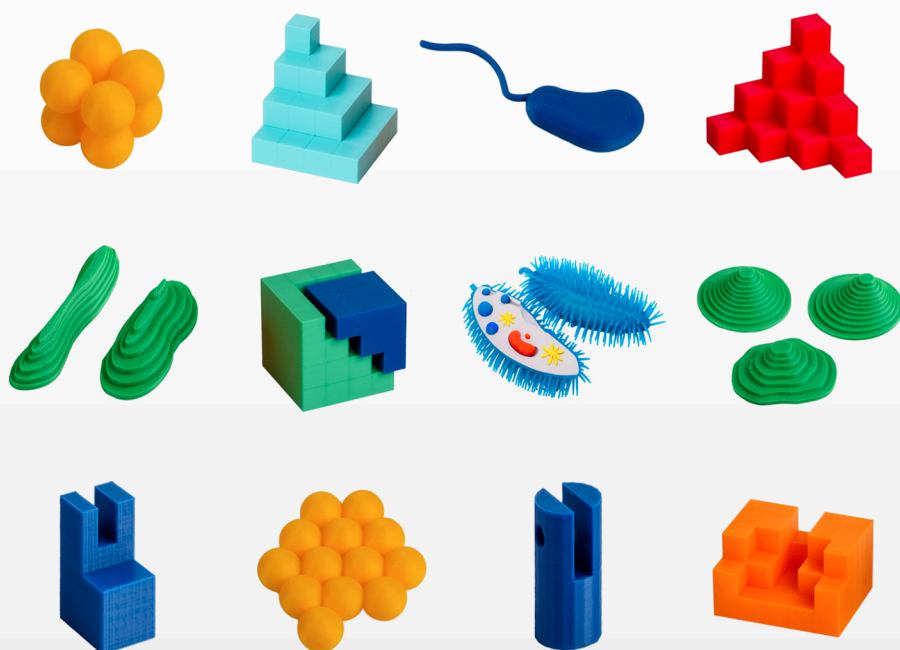


# Implementation of **3D Printing** Technology into Primary and Secondary School Education

Verified Methodology



Martin Dosedla · Zdeněk Hodis · Martina Jančová · Jiří Ledvinka · Leni Lvovská · Kamil Malinka  
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**IMPLEMENTATION  
OF 3D PRINTING  
TECHNOLOGY  
INTO PRIMARY  
AND SECONDARY  
SCHOOL EDUCATION**  
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The development of 3D printing technology caused a significant decrease in the prices of printers, which consequently caused an increase in the availability of this technology. This technology area reveals new possibilities in a wide range of fields, from industry, medicine, construction, and architecture, to the level of common domestic use. 3D technology offers considerable potential, which is currently not exploited. The implementation of 3D technology in primary and secondary education can enable the formation of entirely new types of teaching aids and increase the availability of educational models for pupils and students. Therefore, students can not only work with teaching models in classes, but thanks to methodological support, they can also actively participate in their creation.

For most schools, teaching models might be too difficult to access either financially or in terms of their specific requirements. However, their usage in education has several benefits, such as spatial visualization of structures that are difficult to observe on real objects without the help of an instrument or depiction of hard-to-access products of nature. In addition, students' participation in the process of model production, which 3D printing enables in an accessible way, and their work with the models directly in class, will develop their other skills.

There is a wide range of different types of printers and used materials. For its usage in education, it is necessary to guarantee health safety of the equipment, choose devices that allow printing in sufficient quality, and meet other parameters. It is required to have knowledge about production technology for the creation of aids. For example, printing more complex structures requires specific modifications in 3D models. Similarly, in order to make the most out of the technology, it is necessary to have a good overview of the methods and forms of teaching, the content of subjects, and practical teaching experience, so that the proposed methodology, aids, and procedures were to be created didactically correctly and would reflect the current needs of schools (Friedmann 2018).

According to available studies (Malinka and Schindler 2021, p. 88–96), schools may encounter three fundamental problems when implementing 3D printing in education: setting rights and controlling access to the printer, managing costs, including Return on Investment advocacy, and the appropriate inclusion of 3D printing projects in the curriculum (the issues include lack of teaching materials, lack of technical knowledge, or difficult access to a printer). Provided that schools manage to overcome the initial difficulties and acquire a printer, they still might encounter problems with a lack of quality educational content. Several projects are devoted to the effort to create quality educational content, but they are usually connected with 3D printer manufacturers, who are trying to support sales through this. The size of freely available databases of



3D models is thus constantly expanding, but only a minor part of them has significant didactic potential.

Although the quality of the materials is generally at a good level, the companies do not have the space or pedagogical experience to make significant changes in materials in order to take educational programs and their specificities in individual countries into account (in the Czech Republic - framework educational programs, hereinafter referred to as RVP). It is also considerably time-consuming for teachers to find a suitable model, check whether the printing is of good quality, check whether it corresponds to their ideas, prepare teaching materials, and consider effective integration into the teaching. Even though teachers actively use available teaching materials, we still encounter the following problems: existing materials are not very connected to the RVP (the existing materials have only “extra interest” features), lack of a broader set of teaching materials, lack of teachers’ knowledge frequently leading to a decision not to buy the equipment, and the problem with defining the overall benefit of incorporating 3D printing into education.

This methodology aims to help to solve the mentioned problems. We believe that at this early stage of introducing the technology, a systematic approach will make the integration of this technology into the education system more efficient and ease the way for schools that are new to this technology.

## 1 | 1 Objective of methodology

The methodology was created as part of a project that responds to the recent availability of high-quality 3D printing and the demand for methodical support for 3D printing usage in teaching and didactically accurate topics for the production of teaching aids (models) for individual subjects in primary and secondary schools. The methodology consists of two fundamental units.

The aim of the **technical part** of the methodology is to provide structured and clear information about **3D printing technology**. The goal is also to provide the most effective procedures for its use and to facilitate the adoption of 3D printing in primary and secondary schools that do not have experience with this technology. It also shows reader the **possibilities of creating teaching aids using 3D printing technology** and their integration into specific lessons. The methodology also contains a collection of free lessons, which are adjusted to schools so that they do not require any further adaptations by teachers, and examples and links to **interesting 3D printing models** used to support education in selected fields.

**The educational part** intends to help with orientation in publicly available resources, to guide the systematical **implementation of technology into teaching**, to provide an elementary set of useful lessons, and to discuss technical preparations of teachers and students. It also includes **embedding 3D printing in curriculum documents**. We focus mainly on the obstacles, which are preventing the introduction of 3D printing, as well as on the possibilities of 3D printing and its implementation in the school curriculum. As a part of the analysis of existing materials, there is an evident

dominance of projects in the fields of technical orientation. However, we believe that 3D printing technology has much greater potential and can be incorporated into the teaching of most educational fields. In the methodology, we focus mainly on emphasizing interdisciplinarity and the implementation of this technology in other areas (e.g., projects for fields of mathematics-biology, special education-mathematics, geography-biology, etc.).

The methodology is intended for **primary and secondary school teachers**, creators of school educational programs, university students, and all those who want to use 3D printing for non-formal education. It is designed to support teaching in selected subjects such as biology, geography, or mathematics.

The aim of the methodology application is:

- To inform about 3D printing technology and its use in primary and secondary schools.
- To introduce the possibilities of creating aids using 3D printing.
- To present an overview of teaching model databases and free lesson sets for schools.
- To provide advice on including 3D printing into individual subjects and clarify the current state of embedding 3D printing in curriculum documents.

In order to achieve the above-mentioned objectives, the methodology contains the following:

- The technical part, where you can find an explanation of 3D printing technology altogether with advice and tips on choosing a printer that will meet your requirements, and recommendations for printer operation and maintenance.
- The educational part, where you will get to know more about 3D models as teaching aids, the way 3D printing is embedded in curriculum documents, and above all, how to work with 3D printing in selected teaching subjects

## 1 | 2 Definition of 3d printing

Printers are considered basic computer peripherals. Each user is thus able to print anything from simple texts to complex graphic designs at the push of a button, and the resulting quality relates to the quality of the purchased hardware.

The situation differs with 3D printers. Although 3D printers have been available for many years, they have not become a regular part of human life. 3D printers are starting to catch up on the rest of the technologies only in the latest years of their existence. 3D printers are just becoming a common part of households. However, several factors limit the usability of 3D printers. One of the factors is the complexity of the printing itself, as well as the purchase price of the device.

The 3D printer is becoming affordable for common users in the Czech Republic and abroad. The cheapest 3D printers can be assembled, calibrated, and adjusted all by yourself. These are so-called “entry” level printers, i.e., printers for beginners.

So what is the difference between a regular printer and a 3D printer? What exactly does 3D printing mean? A regular printer works with paper, on which it prints in two axes: X and Y. In contrast, a 3D printer works with another axis, the Z axis, which adds another dimension to the entire process. The X and Y axes determine the base of the printed object, while the Z axis determines its depth.

To put it simply, you can imagine 3D printing as a series of classic 2D prints stacked on top of each other. The number of layers corresponds precisely to the Z value. So how does 3D printing work? Different printers use different methods to create the final product. For the time being, there is no universal printer that would be able to print everything, which is why you need to choose a printer according to its use. Some printers work with powdered materials made of plastic, wood, or metal.

Each printed object thus consists of individual layers that are printed on top of each other. In theory, the principle is quite simple, but in practice, it is necessary to take the software and hardware limits into account. Despite the limitations, 3D printing has several advantages over classical production methods, such as machining or casting. Thanks to 3D printing, it is now possible to save money that would be otherwise spent on casting molds or on residual materials created during machining. The complexity of shapes that cannot be created using classical methods is also worth mentioning (Objects 2017).

Because of the mentioned and other advantages, there is an assumption that 3D printing will become one of the significant manufacturing methods in the future. As a consequence of massively improving technologies and falling prices, 3D printers are gradually getting out of the label of unaffordable devices owned only by large companies and are now getting more available to schools and common users (Horáček 2017).

## 2 | Technical part

The technical part of the methodology aims to provide structured and clear information about 3D printing technology, to inform about the most effective procedures for its use, and to facilitate the adoption of 3D printing in primary and secondary schools that do not have experience with this technology.

We describe the entire **life cycle of 3D printing at school**. First of all, we deal with the issue of choosing and purchasing a printer. We describe the parameters that play a role in choosing the right type of printer. We also consult the adequate number of printers, the need for additional support equipment, the appropriate location of a printer, and its access control. In the next part, we focus on printer operation. In addition to describing the printing material, we also deal with the costs (printing material price, charging, etc.). In the following chapter, we deal with the printing process itself. We describe the individual steps that lead from the digital 3D model to the final product. We name appropriate modeling tools and databases of completed 3D models, then describe the printing process of the acquired models, operating the printer, and finalizing. In the final section, we deal with printer maintenance and the description of common issues and their solutions.

The technical part of the methodology is intended for **administrators and operators of 3D printers** - it contains the necessary information for making the technology accessible. There is also information for pedagogical purposes describing the principles of general usage and Guidelines for efficient use in education.

Technical schools and other specialized schools might have different requirements for 3D printing. These requirements might differ significantly from the described procedures. It might include, for example, the usage of special printing materials and the use of different printing technologies. The following text will not mention these specific requirements any further.

### 2 | 1 Acquiring a printer

Nowadays, there are many different types of printers, which differ mainly in the printing technology, the maximum size of the printable object, the security of the printer, or other advanced functions.

There are several aspects to be considered when using a 3D printer in a school environment, in particular:

- Initial costs (the price of a 3D printer, construction adjustments of the space, and others).

- Operating costs (the price of printing material, service, and energy).
- Safety during operation and manipulation.
- Health Safety.
- Sufficient print quality and speed.

## 2 | 1 | 1 Printer selection

Provided that schools or hobby groups want to use 3D printers, they can choose some of the available printers on the market. Due to the gradual development of technology and greater competition, prices are gradually falling. 3D printers are also becoming more user-friendly and do not require advanced technical skills. Many settings are already fully automated. If not, there are also detailed instructions and manuals that will help in cases where the user does not know what to do.

The first criterion for selecting a printer is **the choice of technology**. For elementary school students, ordinary hobby printers are perfectly sufficient, as they are affordable, illustrative, and easy to operate. Hobby printers usually use material extrusion technology.

We recommend using the **Fused Filament Fabrication (FFF)** printing technology, also known as Fused Deposition Modeling (FDM), see Fig. 1. Its principle consists of extruding the material (filament) with a print head through a heated nozzle that applies the material in thin layers to a heated print bed (heating increases the adhesion of the printed object to the bed). It is currently the most popular technology because the printing costs are low compared to other technologies, and in addition, it allows printing of a sufficiently high quality (Krishnanand and Taufik Mohammad 2021).

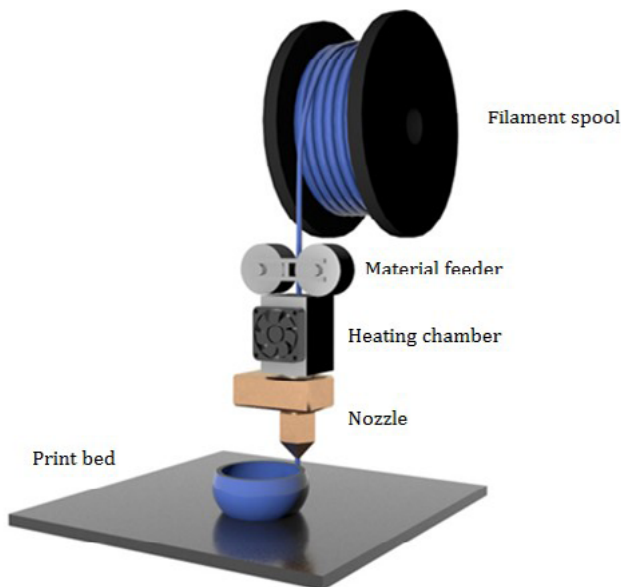


Fig. 1: Principle of FFF/FDM printing technology

Another quite widespread 3D printing technology is SLA (stereolithography) (Salonitis 2014). This technology achieves better printing quality than FFF/FDM but at the expense of more complicated handling and higher operating costs. This method is based on curing liquid resin by using a light source. Printer operation is more demanding, therefore it is necessary to follow safety regulations and precautions when operating the printer and especially when manipulating the resin. Then, the printed objects should be washed from resin residues, most often in a water bath or in isopropyl alcohol, according to the manufacturer's recommendations. Finally, it is advised to cure the objects with UV light in a "curing chamber" for their final strength. These processes and the equipment required for these processes increase the demands for printer operation and the cost of the 3D printer.

The SLS (Selective Laser Sintering) method is a significantly more expensive technology than the two mentioned above. The printing process consists of applying powdered material on the surface of a powder bed and firing laser beams at decisive points, which leads to sintering the powdered material (2020 SLS 3D Printer's Guide Buyer's Guide 2020). The advantage of this method is using materials such as plastic, metal, or ceramics for print production. However, operating these printers is demanding and requires specialized tools and procedures.

Table 1: Comparison of 3D printing technologies

Technology	Print quality	Health hazards	Materials	Price
FFF/FDM	Medium	No/low	Plastics	from approx. 7 000 CZK
SLA	High	Medium	Resin	from approx. 5 000 CZK
SLS	High	Low	Plastics Metals Ceramics	from approx. 200 000 CZK

There are many other technologies available on the market, see Table 1. Further information about FFF/FDM technology and its properties or other popular 3D printing technologies can be found in the following books: Basics of 3D printing with Josef Průša (Stříteský 2019), Understanding Additive Manufacturing by A. Gebhardt (2011), or in the article: Overview of 3D Printing Technologies<sup>1</sup>.

The choice of **printing material** is also an important criterion for selecting a printer. We will deal with the selection of printing materials in Chapter 2.2.

Another relevant requirement to be considered when selecting a printer is **the size of the print area**, which determines the maximum size of the printed model. The size of the print area influences the size of the entire printer, which affects printer placement.

The layer height determines how many detailed shapes and layers appear on the model. Objects with small layer heights have a smooth surface, which makes the clear

1 <http://www.dkmp.cz/o-nas/detail/prehled-technologie-3d-tisku>

distinction of individual layers difficult at first glance. For all that, the printing takes a longer time. The higher the layer height, the more distinct the layers are, but the print might become less detailed. However, the printing is much faster.

3D printers can be divided according to **the number of print heads and print head nozzles**. Printers usually contain one print head and a nozzle, but more advanced printers offer more heads and nozzles, which allows, for example, printing in multiple colors or with different materials (Horáček 2017).

Other features that schools might focus on when choosing a printer are, for example, printing space coverage, access control, connectivity, whether the printer is equipped with a display, or the readiness of the printer, i.e., whether the printer arrives fully assembled or as a kit. Individual items may increase the purchase price, but they can also significantly facilitate work in the workroom.

The last criterion is undoubtedly **the price of the printer**. In this case, it is necessary to approach the problem from the point of view of the school's financial possibilities. Higher initial costs might lead to fewer problems in the future and provide more possibilities for students' creative work as students will be able to create better quality products.

Additional criteria for a printer selection include supporting devices such as a camera monitoring the printing process. The user thus knows whether the printing is proceeding according to the plan without having to wait at the printer and monitor the entire process.

To conclude, the main decisive factor in selecting a printer for schools is often the price of the printer. Ideally, the printer should be able to automatically adjust the plane of the printing surface, thanks to which the first printed layer will always be perfect. You should also monitor the speed and quality of printing, as well as the software equipment of the 3D printer and the quality of the construction. These might be the key factors influencing the life expectancy of printers in schools. Other parameters are not vital but might simplify teachers' and students' work.

## 2 | 1 | 2 Number and availability of 3D printers for efficient use in teaching

As shown by the results of a survey conducted among teachers who use 3D printing in teaching (Babičová 2020, Y Soft 2016, Y Soft 2019), the ideal solution is to have fully equipped classrooms in which there is the same number of 3D printers as there are students in the class. All students proceed through the process at the same time, and they learn and gain experience together. With a lower number of printers, teaching is becoming less effective, as some students only observe the work of others and cannot participate directly. In case there are only a few printers available, it is beneficial to prioritize their placement so that they would be more visible to students. The opportunity to work with the printer or at least to observe it further increases students' interest in 3D printing.

## 2 | 1 | 3 Support equipment for printers

When purchasing a printer, the additional purchase of accessories that can significantly support the operation and administration of the printer is also worth considering. It includes mainly a camera for remote printer monitoring and a backup Uninterruptible Power Supply (UPS).

Any camera that has access to the school network or the Internet can save time and money. Considering the duration of the printing process, there is a possibility of stopping the printing during the process in case of an error, which also leads to an earlier start of the new printing. At the same time, a considerable amount of printing material is spared, which saves money. The user does not have to check the printer regularly, which is practical, especially for a teacher who needs to prepare for the following lessons during breaks or supervision.

After a sudden stop of printing (e.g., during a power failure), some 3D printers refuse to resume printing and must start from the beginning. It means that a partly printed object is practically unusable, even though some materials, energy, and time were invested in printing. Nevertheless, uninterruptible power supplies can temporarily supply electricity to the printer during a power failure. If it is a short-term power failure, the printer does not have to stop at all and can finish the current print.

## 2 | 1 | 4 Printer placement, security, and access control

The appropriate placement of the printer significantly influences the quality of the print and its use.

Due to the long printing time and occasional misprinting errors, students should have the printer as accessible as possible (ideally in the corridor or in freely accessible dedicated rooms). The opportunity to witness the interaction with the printer further stimulates the interest of new students. Unfortunately, it turns out that, during the pilot stages, the printer usually ends up locked in a cabinet with on-demand access, which generally decreases students' interest.

When thinking about the placement of a 3D printer, consider the need for space for the final adjustments of the printed object that some models require (e.g., sanding, sealing, and painting). We recommend preparing public spaces for the printer in advance, for example, during planned school renovations.

It is therefore a good idea to think in advance whether the installation at the selected location meets the following requirements:

- Printers always need access to an electrical grid.
- Some types of printers may require a computer network connection - either wired or Wi-Fi.
- A flat and firm surface area is also necessary for the printer to work properly without deforming the object during printing (never underestimate running children).



The best way to secure the printer during printing against unauthorized access is to cover it completely, protecting not only the printer itself, but also the printed object. It also guarantees a constant temperature and humidity. It also ensures the safety of people moving around the printer - the temperature of the nozzle in the printer exceeds 200 °C. The storage of the filament also significantly affects the printing quality - it must be kept dry, preferably in the original packaging or a closed box.



Fig. 2: Secured and fully covered Y Soft Be3D eDee printer

Furthermore, it is very convenient to have security against unauthorized manipulation during printing (e.g., automatic lock) and an access control system (e.g., smart cards, RFID chips). This security enables uninterrupted printing and its successful completion and the possibility of measuring filament consumption for subsequent payment of used materials.

As already mentioned, the most convenient place for a printer is in a fully equipped classroom where one printer is available for each student. Students should have the best possible access to the printer. Therefore, the classroom must not be locked or with on-demand access, as this generally leads to a decrease in student interest in 3D printing. Rather than locking up the classroom or the place where the printer is placed, it is more appropriate to purchase a secured printer (see Fig. 2).

In case there is no possibility of placing the printer in a classroom dedicated to this purpose, or if only a small number of printers are available, we recommend placing them in a visible and accessible place, for example, in a corridor or the entrance hall. Although placing the printer in a public space seems risky at first glance, a covered printer (for example, with an automatic lock) minimizes the risk of damage.

## 2 | 2 Printer operation, printing materials, and cost

Apart from the direct use of 3D printers in teaching, i.e., under the supervision of a teacher or printer administrator, printers can also be provided to students for personal printing. They can thus create a teaching aid, a toy, or a decoration for the classroom or home. Not many students have access to a 3D printer. If students show interest in working with a printer, it is a good idea to encourage them as much as possible. At first, they will probably require guidance from a more experienced printer user. Afterwards, it is possible to leave the elementary operation of the printer to the students themselves – provided, of course, that they are able to work with it independently. Independent work with a 3D printer obliges students to follow the principles of safety and health protection.

In Chapter 2.1. Acquiring a printer, we recommend using FFF/FDM technology printer. In the following section, we describe several of the most commonly used printing materials - filaments, which are usable in printers with this printing technology. These currently involve mainly PLA, PET-G, and ABS/ASA materials. When choosing materials, it is also necessary to emphasize health and manipulation safety.

Some filaments may contain various additives that further affect their properties. It does not have to be just a change of color, but also, for example, luminescence (glow effect in the dark), adjustment of hardness, flexibility, or temperature resistance. Because of the extra additives, the filaments can imitate the appearance of other materials, such as wood, bronze, and many others.

Proper storage ensures the filaments last longer than the manufacturer's guaranteed minimum. On the other hand, with improper storage, filaments degrade quickly. They can break, a large number of dust particles on the filament can clog the print head, etc. Therefore, it is necessary to store filaments that aren't used ideally in their original packing, to protect them from excessive heat and moisture, direct sunlight, and dust.

### 2 | 2 | 1 PLA

The most popular and probably most commonly used material is PLA. It is a very suitable material for getting started with 3D printing and gaining experience. The individual layers of the molten filament stick together and form fused layers, and the material is well attached to the substrate. PLA is a strong but brittle material, which cracks rather than bends under mechanical stress. During printing, the object practically does not deform

under the influence of heat. However, it is not temperature resistant – it starts to soften around 60 °C, which means it can be deformed even by direct sunlight.

In general, PLA is an ideal material with wide use, especially in schools, because it is cheap, safe, and harmless to health, and its quality is usually sufficient. For these reasons, we recommend using it. The filament is produced from renewable resources and is also affordable.

## 2 | 2 | 2 ABS/ASA

If PLA material lacks desired properties, ABS or its successor ASA is used. Both materials (ABS and ASA) are quite similar. However, ASA has better resistance to the effects of sunlight. Compared to PLA, ASA/ABS has better flexibility and mechanical and temperature resistance (it softens up to around 100 °C). Due to their higher mechanical resistance, they can be easily machined and further adjusted. There are many variants with different additives, e.g., ABSi, which glows in the dark.

On the other hand, ABS/ASA is more demanding in terms of printing than PLA because it can deform during printing. Without a special PEI sheet, there is a high chance of being separated from it during printing. Especially printing large objects as a whole is very problematic, and it produces harmful fumes during printing, which can, in exceptional circumstances, irritate eyes or mucous membranes.

## 2 | 2 | 3 Other materials

Countless other materials can be used in 3D printers. Each one of them is used for a slightly different purpose. PET-G material (a modification of PET) provides easier printing than ABS/ASA and has better temperature and mechanical resistance than PLA.

TPU or TPE plastics (sometimes referred to as Flex or Elasto) have similar properties to rubber. They are flexible and produced in different hardnesses (the softer, the more difficult to print). They are often used to create regularly deformed objects (mobile phone cases, toy wheels).

Polycarbonate (PC) is an extremely resistant printing material, which makes it an excellent choice for printing mechanically stressed objects, such as carabiners. PEEK and PEI (also known under the trade name ULTEM) are chemically resistant materials used in places with high temperatures (up to 210 °C). Another printing material is Nylon, which use includes the production of some industrial components. All materials are hard to print and require a more powerful printer due to their high melting temperature.

Materials made from recycled wood and binder are also available on the market. With their help, the user can print objects that have properties of wood, such as appearance or smell. These materials are handled similarly to ABS or PLA. You can find more information about the mentioned and other materials, for example, on the Simplify3D website[1] or the Prusament website[2].

## 2 | 2 | 4 Table of comparison of materials

A comparison of the properties of the printing materials is shown in Table 2. A comparison of other parameters of the printing materials is shown in Table 3.

**Table 2: A comparison of the properties of the printing materials for 3D printers using FFF/FDM technology**

Material	Difficulty of printing	Resistance		
		Temperature	Chemical	Mechanical
PLA	Easy	Very low	Low	Low
PET-G	Easy	Low	Low	Low
ABS/ASA	Medium	Medium	Low	Medium
Flex	Medium/Hard	Medium	Low	High
PP	Hard	High	Medium	High
Nylon	Hard	High	Medium	High
PC	Very hard	High	Medium	Very high
PEEK	Very hard	Very high (up to 250 °C)	High	High

**Table 3: A comparison of use, health hazards, and prize of printing materials for 3D printers using FFF/FDM technology**

Material	Use	Health hazards	Price
PLA	General	None	Cheap
PET-G	General	None	Cheap
ABS/ASA	General	Low	Cheap/Medium
Flex	Regular deformances	None	Medium
PP	Mechanically stressed components	None	Medium
Nylon	Resistant components	None	Expensive
PC	Resistant components	Low	Medium
PEEK	High temperature	Low	Expensive

## 2 | 2 | 5 Printing costs

The cheapest printers using FFF/FDM technology are currently available from CZK 2,500. However, the rule applies that durability and quality are reflected in the final price. High-quality, certified, covered, and safe printers can be purchased for a price between 10,000 and 20,000 CZK. Some of them even offer more advanced functions, such as an Internet connection or an access control system.




In addition to the initial investment in the printer, regular costs cannot be neglected, especially for printing materials, maintenance, and electricity. The price of the most used PLA filaments starts at 600 CZK per 1 kg. The prices of other materials vary significantly depending on the type or manufacturer. Maintenance costs and the frequency of maintenance depend on the gentle handling and quality of the printer. Generally, however, it does not exceed several hundred crowns per year. The electrical

energy used varies again for different printers. On average, it is tens, at most hundreds, of W/h.

Another parameter affecting the final price is the proper setting of the printing parameters, such as the infill percentage, the number of walls of the object, the height of the layer, and the thickness of the top layer (Friš 2019). Another important parameter is the proper orientation of the model on the print bed, which can reduce the number of supports needed to create the model and increase the resulting print quality.

Table 4 shows the frame parameters of printing models of different complexity.

**Table 4:** Comparison of printing costs depending on the model size and printing time using FFF/FDM technology. In the example, all models have the same layer height of 0.2 mm, and the filament used is PLA.

	Small model	Medium model	Large model
Illustrative picture			
Printing time	23 minutes	1 hour and 23 minutes	39 hours and 45 minutes
Filament consumption	0,86 m (2,6 g)	4,29 m (12,8 g)	112,6 m (344 g)
Filament price*	1,56 CZK	7,8 CZK	204,73 CZK
Electricity costs*	0,95 CZK	3,46 CZK	99,38 CZK

\* The price is derived from the purchase of 1 kg of PLA filament for 600 CZK.

\*\* Electricity consumption is different for each printer. In this case, we are considering CZK 2.50 per hour of printing operation (at a power consumption of 50-150 W during printing). The calculation takes into account the warm-up time before the start of the printing.

## 2 | 2 | 6 Printer accounting

If the printer is also available for private printing services, it is necessary to deal with printer accounting. The price for each print can be calculated according to the parameters offered by each printer. These parameters include the consumption of filament linked to its price, printing time (which also takes electricity consumption into account), amortization of equipment (the prize of the print head, etc.), and possibly others. Direct costs can be calculated by the following calculation: weight of the printed model × filament prize + printing time × electricity consumption. It is also necessary to support authentication before printing (e.g., using a school smart card) to assign the prints to individual users. Even though creating a price list is not complicated, completing the entire process, from monitoring the print to collecting the money, is a certain organizational burden. In addition, the resulting price is often not motivating. In the case of a limited number of printers, it is often more efficient for the school to provide everything for free and bear the costs (there is a limitation primarily due to the time-consuming nature of the printing) or find a sponsor to help with them.

## 2 | 3 Printing process

This chapter describes the individual steps leading from the digital 3D model to the final product (see Fig. 3).

The first step is **to obtain a 3D model** of the object itself. One of the options is to create a 3D object using 3D modeling tool. Another option is to download the model from databases on the Internet.

The second step includes **slicing** the selected model into individual layers, which are then printed. Within each layer, the path of the print head is also specified. This step is provided by a software called “slicer”. In the application, different operations can be done with the object (move, resize, etc.). In addition to that, various print parameters are defined (layer height, padding, etc.). During slicing, it is often necessary to add model supports to print potential overhangs.

Slicer **will generate** instruction for the printer, according to which the printer will print.

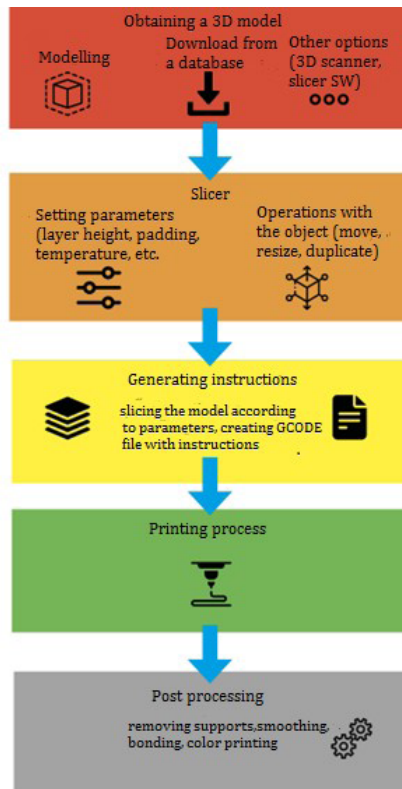


Fig. 3: Description of the printing process

Another step is **the printing process** itself.

**Post-processing** is the final step, it involves removing supports, and smoothing the surface of the printed object. If the product consists of several parts, it is necessary to glue or bond them together. The most realistic appearance of the object might be achieved by implementing final surface treatments, such as caulking, sealing, and color painting.

## 2 | 3 | 1 Acquiring models for printing

Although obtaining a 3D model is the first step in the entire process, it is often the most time-consuming. The model can be obtained in two ways: by creating it yourself (in 3D modeling software, using a 3D scanner, etc.) or by getting it from another author. There are large databases on the internet containing millions of models. In addition to freely available models, some objects can also be purchased. Paid models are usually of higher quality, more accurate, generally more sophisticated, and often contain a description with parameters for a slicer for successful printing. Their prices start at about two US dollars and reach up to several tens or hundreds. However, we will not deal with paid models because, in the vast majority of cases, there are sufficiently accurate alternatives that are free for the needs of schools.

### Modeling tools

If you want to create or modify a 3D model, you will need to use appropriate modeling software. If you already have a program for creating 3D objects in school, you will likely be able to use it for 3D printing. The main requirement for the modeling program is the ability to export the resulting model to the STL format file, which is the most widely used format.

Tinkercad was found to be the least complicated and most user-friendly modeling tool. There is no need to install it as it runs in a web browser. Models are created by combining simple shapes (cubes, spheres, cones). Although Tinkercad lacks some advanced features, it can import and edit STL files, which means that complex models can be prepared in advance (e.g., downloaded from an internet database) and later only edited in class. More information, including instructions and training, can be found on the website<sup>2</sup>.

If Tinkercad's functionalities are not sufficient for the model we want to create, we can choose from several other programs. Among the most famous there are SketchUp, Blender, Cinema 4D, SolidWorks, AutoCAD, and Fusion 360. The programs **Blender** and **Fusion 360** have proven to be the best for us. Fusion 360 is technically oriented and allows the creation of accurate models and components. On the contrary, Blender

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<sup>2</sup> <https://www.tinkercad.com/>

focuses more on the artistic modeling of irregular objects. However, both programs are more complicated than Tinkercad. Especially Blender's user interface is very complex.

You can learn more about these modeling tools on the **Blender**<sup>3</sup> and **Fusion 360**<sup>4</sup> websites. Fusion 360 offers a free license for schools and students. Blender is available for free.

## Online databases of freely available models

The fastest way to get a printable model is to download it from one of the online databases. Several models suitable to be used for the teaching of individual subjects can be found in **Chapter 3 of this methodology**.

In the following list of portals, we mention those that contain free models and models free for non-commercial purposes. If you decide to use models from other internet portals, always check the distribution license. If the models are used in teaching, a violation of copyright might easily occur.

### Y Soft Be3D Academy<sup>5</sup>

Online school lesson collections are prepared in all aspects. Each lesson includes the necessary materials for immediate use in teaching. In addition to the 3D models, there are detailed instructions and information about printer settings and material selection. They also contain a lesson plan, which includes its position in the curriculum, a video or presentation to be used in class, or worksheets for students. The lessons we developed and other sample lessons are free, but the rest of them are included in a paid package.

### MakerBot's Thingiverse<sup>6</sup>

Thingiverse is the largest and most popular online database of 3D models. It currently contains over two million 3D models, and the number of newly added models is constantly rising. If you're looking for a random model of anything, you'll probably find it right here. However, not all models are scientifically accurate, which is why we recommend checking them before using. Models suitable for teaching purposes are in the Education section, including a suggestion for use in teaching.

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3 <https://www.blender.org/>

4 <https://www.fusion360.cz/>

5 <https://be3dacademy.ysoft.com/>

6 <https://www.thingiverse.com/>



## Printables<sup>7</sup>

The portal of the well-known 3D printer manufacturer Josef Průša currently includes over 32,000 models. There is also an **Education** section with 3D models that are potentially usable in teaching. These models are provided only with a basic description of use.

## YouImagine<sup>8</sup>

YouImagine is a community portal that contains over 18,000 models divided into popular categories.

## MyMiniFactory<sup>9</sup>

MyMiniFactory is a community portal with several thousand models in many categories.

## NIH 3D print exchange<sup>10</sup>

NIH 3D print exchange is a US Institute of Health portal that contains scientifically accurate models in the fields of biology and medicine.

## Create Education<sup>11</sup>

A community portal with resources for inspiration with 3D printing and related technologies for STEAM.

## 2 | 3 | 2 Preparation of printing

Before importing the model into the printer, it is necessary to “cut” the 3D model into individual layers that the printer will apply. This process is called *Slicing*. Its output includes instructions for the printer, which are converted in a program called *Slicer*. The program can be a part of the printer software, but it is more often an external tool. The best-known slicers for FFF/FDM printers are **Cura**, **PrusaSlicer**, its predecessor **Slic3r**, or the paid Simplify3D (Stříteský 2019). The limitations of printing itself should be considered when creating and selecting a model. Detailed and small models with too many supports are not very suitable for this type of printer.

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7 <https://www.printables.com/>

8 <https://www.youmagine.com/>

9 <https://www.myminifactory.com/>

10 <https://3dprint.nih.gov/>

11 <https://www.createeducation.com/>

In the slicer, it is possible to make the prepared model rotate, change its size or divide it into several parts, which are easier to print. If several objects are printed concurrently, their mutual position on the printing surface can also be adjusted. The most relevant print settings to be considered before printing include the layer height, the ratio of the filling of the object, the material used, and the temperatures of the print head and substrate, which are related. Last but not least, the creation and properties of the supports are set in the slicer, which enables the printing of overhanging parts of the model that would otherwise be impossible to print. A print preview containing all settings (including supports) is important for checking the correctness of the slicing and the resulting outcome of the print.

Most slicers contain pre-prepared profiles for different printer models and used materials. We recommend using these profiles, as they have been tested for a long time. They also optimize the print settings for a specific combination of printer and material.

### Basic slicer settings:

**Layer height** – determines how high one layer of the final print will be and significantly affects the quality and printing time (see Fig. 4).

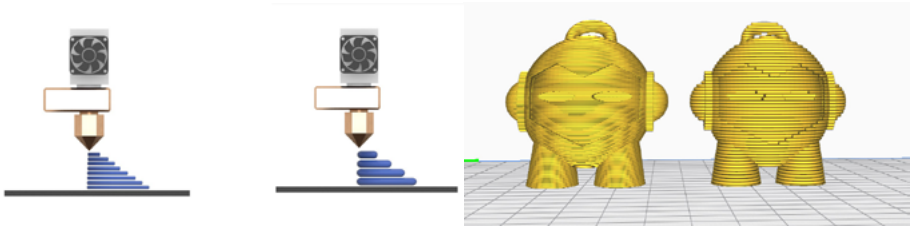


Fig. 4: Layer height

**Perimeters** (shell thickness) – defines the thickness (number of layers) of the side walls.

**Top & Bottom Layers** – determine the thickness (number of layers) of the top and bottom of the 3D object.

**Temperature** – setting the temperature of the print head and the print bed. We recommend using slicer profiles with preset temperatures for different materials. In the case of self-adjustment of the temperature, follow the instructions of the manufacturer of the materials.

**Printing Infill** (Infill Density) – a percentage value that determines the fill ratio of the object. In addition, the infill pattern can also be set. The infill pattern is the structure and shape of the material inside the object. Infill patterns can affect the strength, weight (material consumption), print time, and even the flexibility of the object. Slicers offer a choice from simple lines to more complex geometric shapes. For basic printing, the default settings are sufficient (see Fig. 5).

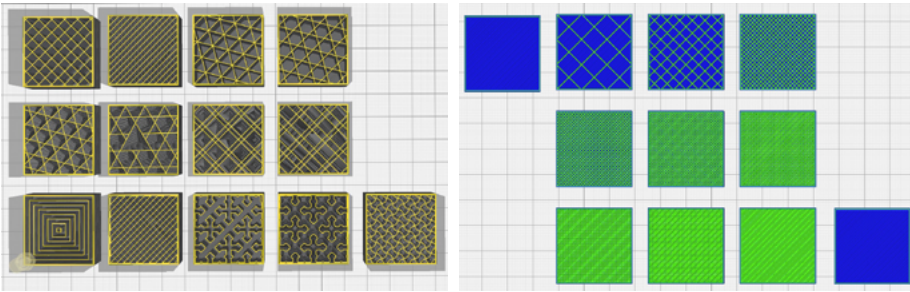


Fig. 5: Infill patterns and density

**Skirt** – determines the height and the separation distance between the skirt and the object. It is printed first and in several layers around the first layer of the object. Although the skirt does not directly help to adhere the model to the print bed, it prepares the nozzle before printing and shows the stability of the print bed (bed leveling). Provided that the skirt adheres well to the print bed, the print bed leveling in the places of the first layers of the model is correct. It is, therefore, probable that the entire first layer of the model will adhere well to the print bed.

**Brim** – determines the width of the brim that will be printed in the first layer around the object. The brim is very similar to the skirt. Unlike a skirt, it consists of just one layer and forms a perimeter around the first layer of the printed model. However, unlike the skirt, the brim is always directly connected to the first layer of the object. It means that the brim expands the area that is in contact with the print bed, helping to keep the printing on the print bed. After printing, it breaks off.

**Raft** – works by printing extra layers on which the object is to be printed. Compared to the brim and skirt, the intensity of adhesion, material consumption, and printing time are the highest. Raft provides excellent first-layer adhesion for any model as the print material best adheres to itself. It is used mainly for ABS/ASA material (see Fig. 6).

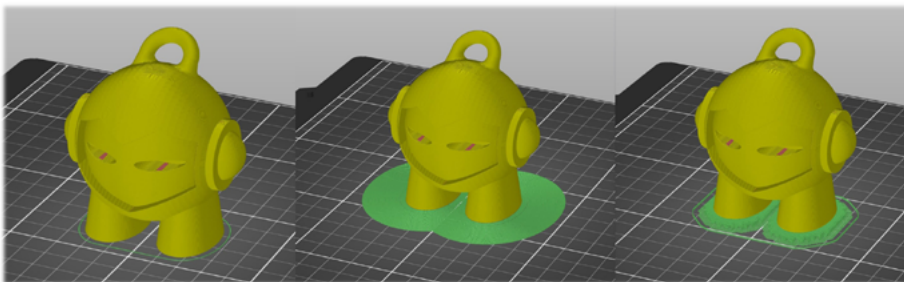


Fig. 6: Skirt, brim, raft (from left to right)

**Supports** – various settings for generating supports, especially the shape of the supports, the filling ratio, or the distance of the supports from the model in all three axes (see Fig. 7).

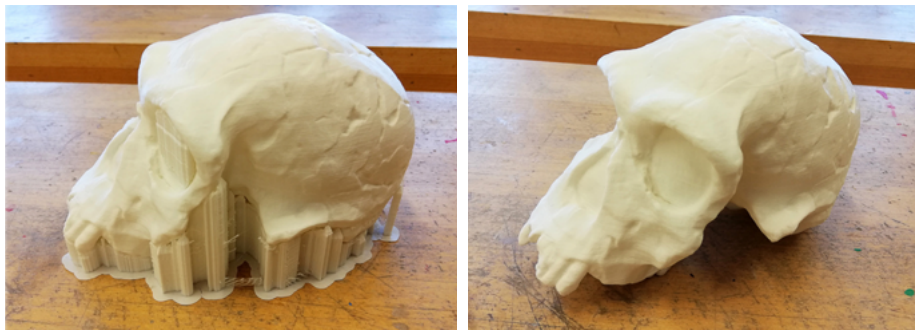


Fig. 7: Print with supports and brim; supports removed

## 2 | 3 | 3 Printer operation

Before printing, the print bed must be cleaned from the remains of previous prints, dirt, grease, and possible adhesive residues. A clean palette knife can be used for removing large residues on selected types of print beds. In order to eliminate grease, the print bed can be washed with soap and water and then dried, or you can use technical alcohol. Degreasing the pad is essential for proper adhesion of the most commonly used materials (especially when using materials with less adhesion, such as ABS). Therefore, cleaning should not be underestimated.

The instructions generated from the slicer are usually inserted into the printer on an SD card or other portable medium. Some printers also support other data transfer methods, such as an Ethernet or Wi-Fi connection, which can be especially practical when working in a school network environment. All settings from the slicer are part of the generated instructions, so there is no need to modify anything after starting the printing.

We recommend checking the entire process regularly during printing. The most important thing to check is the adhesion of the first layer of the object to the print bed. Checking the adhesion of the individual layers to each other is also relevant. In the case of printing more complex models, it is also advisable to check the printing of critical parts, such as bridging the gaps between two parts of the model. If there is an error during printing, we recommend stopping the process as soon as possible to avoid unnecessary energy and material consumption or causing damage to the printer itself. After stopping the printer, remove the failed printout, clean the print bed and, if necessary, change the printer or the slicer settings (see Chapter 2.5.). Then you can start a new printing again.

## 2 | 3 | 4 Finishing 3D prints

Simple objects are ready to be used immediately after printing. More complex objects usually require the removal of the supports. Although the supports are connected to the model, they can be easily broken off, cut off, or chipped off with pliers. If sufficient padding and wall thickness of the object is set, it should not be damaged.

Furthermore, it is possible to sand the print so that the differences in the heights of the individual layers even out. We recommend 200 to 4000 grit sandpapers. Avoid sanding machines, as they heat up and deform the print.

For connecting objects printed with PLA, ABS/ASA, and PET-G materials, it is best to use UHU All Plastics or ordinary cyanoacrylate (secondary) glue. Other materials may require the use of special adhesives or solvents. If the surface of the contact surfaces is not smooth, it is a good idea to sand it with fine sandpaper. The contact surfaces must be as flat and clean as possible, do not forget to remove the remains of adhesives, paints, and sealants. A detailed description of the use of adhesives for joining different materials together can be found, for example, on the Printables blog<sup>12</sup>.

Finally, the print can be colored and painted. Before coloring, we recommend using an acrylic putty, ideally in the form of a spray, which will cover small irregularities and mask the printed layers. After the sanding, it is almost impossible to tell that the object was printed on a 3D printer. Acrylic paints are suitable for coloring because they cover well and have excellent adhesion. Spray paints can be used as well. It is also possible to use other components to complete the model and to make the resulting model look realistic (see Fig. 8).

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12 [https://blog.prusa3d.com/cs/velky-clanek-o-lepeni-a-kompletaci-3d-vytisku\\_44908/](https://blog.prusa3d.com/cs/velky-clanek-o-lepeni-a-kompletaci-3d-vytisku_44908/)



Fig. 8: Skull model before and after surface finishing; a model of a paramecium before and after surface treatment and the use of colored filaments

## 2 | 4 Printer maintenance

Individual printer models can differ significantly from each other in terms of their operation and maintenance. Therefore, it is not possible to create universal and accurate instructions for their maintenance. In this chapter, we will focus on the most common tasks that must be done regularly to ensure that the printer works properly. Always follow the instructions in your printer manual.

Printing material replacement or replenishment is among the most common printer maintenance procedures. Some printers can run a procedure that firstly heats the print head to the correct temperature, then releases the filament, and guides you through the following steps to insert another. In general, the filament needs to be heated, loosened, and pulled out in this order. After that, it is necessary to insert a new filament, with which the printer will push out any remains of the previous material. To ensure there are no residues left in the nozzle, it is important to set the printhead temperature correctly. If you replace one material with another, for example, ABS to PLA, always set the higher of the two temperatures these materials require. For example, if ABS requires 235 °C and PLA only 210 °C, the resulting set temperature will be 235 °C.

Keep all mechanical parts, including the printhead, clean to prevent filament snagging. That also applies to the nozzle, in which the filament can get stuck because of dirt. It is advisable to check the tension of the belts regularly, as they move the print head and the print bed. They may loosen slightly after a long period of use. Loose belt tension can cause defects in the print. A regular inspection of bearings and lubrication of moving parts is necessary to maintain good print quality. Each manufacturer lists the most suitable lubricant for their printer, but universal machine oil or plastic grease will also suffice (WD40 is not a suitable lubricant).

Before the first print, it is necessary to calibrate the printer. Although the process is automatic for some printers, always follow the instructions in the manufacturer's manual. Perform a calibration check regularly to ensure good print quality.

## 2 | 5 Common 3D PRINTING PROBLEMS and their solutions

### **Nothing happens at the start of the print.**

Wait a while after the start of print. It can take up to several minutes for the print head and bed to heat up. If printing has not started even after a long time, check the display or other mechanism by which the printer reports errors. According to the error message or fault code, identify the problem and proceed according to the manual. In case of more complex issues, consult a technician or printer supplier.

### **At the start of the print, the print head moves, but no object is created.**

First, check that the filament is inserted into the print head properly. If the nozzle moves over the bed but nothing prints, check that the filament is not stuck in the print head and that the nozzle temperature is set correctly.

### **At the start of the print, the printer does not print an object but a tangle of threads.**

It is most likely due to poor adhesion of the filament to the print bed or the position of the print head, which is too high above the print bed. You should stop printing, clean the print bed and check the heated bed temperature setting. Check the printer bed nozzle height calibration. Another cause of this error can be printer nozzle clogs or poor cooling of the model.

**After the start of the print, the first layer of the newly formed object begins to lift off the print bed. Subsequently, a deformed object or a tangle of fibers is created.**

This problem can occur for two main reasons. Either the printer calibration is not correct, (especially the distance of the print head from the substrate), or the filament is not sticking to the bed, which means the adhesion is poor. Firstly, check the calibration, or calibrate the printer according to the instructions in the manual. In the second case, clean the print bed and check the heated bed temperature. Consider adding a brim or raft in the slicer. If the problems persist, apply a thin layer of glue on the print bed (an ordinary washable glue stick will suffice). Applying glue to the surface is also usually necessary when printing with less adhesive materials, such as ABS.

**The print started well, as the first layer stuck to the print bed. After a while, however, deformed object or a tangle of fibers started to form.**

Check and adjust the print head settings, especially temperature, speed, or cooling rate. Follow the printer's manual and the production sheet of the material used.

**The print went well for a while, but then the object fell off the print bed, and a tangle of fibers started to form.**

Detachment of the object during printing can be caused by two factors - low adhesion of the first layer to the print bed or lack of supports. In the first case, clean the print bed, check the heated bed, and consider adding a brim or raft in the slicer. In the second case, turn the model in the slicer so that it lies as flat as possible on the print bed. Subsequently, you can add more supports to provide stability and to ensure the parts do not break away.

**The size of the resulting product does not correspond to the slicer settings.**

No printer is 100% accurate. Each printer has a specified print accuracy. Determine the print accuracy (you can probably find it in the printer manual). Then adjust the size in the slicer so that it corresponds to the desired dimensions, even with possible inaccuracy, and print the object again. If the object is only a little larger than expected, you can try sanding it with sandpaper.



## **Some product details are not visible.**

The smallest dimension that the printer can print is determined by the nozzle diameter. The common nozzle size is 0.4 millimeters. It is possible to purchase more precise nozzles with a smaller diameter.

## **The print shows a stair-step effect.**

The value of layer height can be set in the slicer. Common heights are 0.4-0.8 millimeters for fast printing and 0.1-0.2 millimeters for quality printing. The second option to eliminate the step-likeness is subsequent smoothing with sandpaper.

## **Some fibers on the bottom or top layer of the product are not smooth, and holes or bubbles are formed.**

This effect is caused by a too thin bottom or top layer in combination with an insufficiently dense filling. Adjust the number of solid layers in the slicer and increase the fill ratio. Another cause may be faulty cooling of the model, a faulty print head, or poor-quality filament.

## **The filament is stuck in the printhead.**

Once the filament melts, it fills the entire nozzle volume. The solution is to heat the nozzle and thus melt the scrubbing filament, which can then be removed. Nozzle heating is a function of every 3D printer, so there is no need to use external tools. Always replace the filament according to the instructions in the manual.

## **The string breaks when replacing the filament.**

If the filament string is breaking or fraying, this is a clear sign that the filament is at the end of its life. The manufacturer's guaranteed lifetime of PLA material is usually one year, provided that it is stored in suitable conditions without access to air and moisture. Therefore, an airtight sealed container with silicone moisture absorbers is ideal for storage.

You can find other problems and their solutions in the manual of a particular printer and also on many internet forums, especially printer manufacturers' forums (e.g., the Prusa3D forum<sup>13</sup>), or in various articles, for example, on the Simplify3 website<sup>14</sup> or in the All3DP online magazine<sup>15</sup> (both in English).

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13 <https://help.prusa3d.com/cs/>

14 <https://www.simplify3d.com/support/print-quality-troubleshooting/>

15 <https://all3dp.com/1/common-3d-printing-problems-troubleshooting-3d-printer-issues/>

You can find more general information about 3D printing, printing materials, and use in teaching in MakerBot's Educators Guidebook (DeMarco et al. 2017), Basics of 3D printing with Josef Průša (Stříteský 2019) or on the Y Soft Be3D Academy web portal<sup>16</sup>, which includes not only complete lessons, but also many additional materials, guides for teachers and 3D printer administrators.

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<sup>16</sup> <https://be3dacademy.ysoft.com/>

# 3 | Educational part

The teaching part of the methodology aims to provide information on the implementation of 3D printing technology into teaching. The content of the teaching part of the methodology includes information designed primarily for teachers of individual subjects, also for creators or methodists of school educational programs, school director, and their representatives.

In the first chapter of the educational part, we present a comprehensive overview of the issues of 3D models as teaching aids and the specifics of using them in teaching. The benefits and barriers of using 3D models in teaching are analyzed in more detail.

The following section is devoted to the implementation of 3D printing technology into the curriculum. It consists of experiences from abroad and 3D printing in the context of curriculum documents of the Czech Republic. In addition to the connection to the 2030+ Strategy, more attention is paid to framework education programs, specifically the Framework Education Program for Basic Education and the Framework Education Program for Gymnasiums.

The most important parts are the chapters devoted to individual teaching subjects. Each chapter illustrates a connection to the expected outcomes listed in the RVP ZV (The Framework Educational Programme for Basic Education) or the RVP G (The Framework Educational Programme for Secondary General Education). Tips on implementing 3D printing in specific classes and links to available models or teaching lessons are also included.

After reading this section, the reader should have a solid understanding of options to get started with 3D printing in education and be aware of the benefits of starting with 3D printing.

## 3 | 1 USING 3d models in education

In this chapter, we characterize models as teaching aids (Subchapter 3.1.1). Following individual chapters present the benefits of using 3D models in education (Subchapter 3.1.2) and barriers to 3D printing in education (Subchapter 3.1.3).

### 3 | 1 | 1 Models as teaching aids

Models printed by 3D printing technology are material didactic means, specifically teaching aids. According to Obst (2009), a didactic mean refers to everything that can be used by the teacher and students in order to achieve expected outcomes. The adjective

“material” then points to the material essence of these means. A teaching aid is then defined, for example, by Průcha et al. (2003), these are “[ ... ] objects and items mediating or imitating reality, helping to develop visualization or facilitating teaching [ ... ]”.

Considering its use in teaching, models are typically used in science (Petty 2008) and technical subjects. Although they are a mere representation and simplification of real objects and phenomena, they emphasize essential features and enable the observation of objects that are difficult to obtain and that students would not otherwise be able to observe. Models can be used, for example, to illustrate the external or internal structure of natural objects – static models, but also some processes – dynamic models (Altmann 1971, Maslowski 1990).

Typical features of 3D models as teaching aids can be summarized as follows:

- They depict spacial objects or phenomena.
- They allow pupils physical manipulation.
- They help the teacher to achieve learning objectives.
- They support the visualization of teaching (for more, see Subchapter 3.1.2.).
- They stimulate the student’s activity, altogether with sensory perception and abstract thinking (Skalková 2007), and thus create prerequisites for the long-term consolidation of knowledge.

Teachers can obtain 3D models as teaching aids in two ways: by purchasing them in shops with teaching aids or making the models themselves. The obstacle to the first option is the limited offer of commercial teaching models and the high financial cost of their purchasing. The second option is limited by technical means, teachers’ and students’ skills, or the time required to produce the model. In the production of educational models, commonly available materials (paper, plasticine, ceramic clay, etc.) are traditionally used. These materials can limit the final outcome of the model and its resemblance to reality. Providing that we create our own model, we should take the above-mentioned properties of the model into account. However, it is also necessary to consider other parameters of 3D models (Petty 2008):

- **The size of the model** – related to the visualization and usability in the classroom. Models can enlarge real structures (e.g., bacterial model) or reduce them (e.g., cut model of a pyramid).
- **Model decomposition** – models are suitable, for example, for demonstrating the internal structure of nature.
- **The degree of simplification of the model** – it must be adapted to what we want to show the students on the model. All essential structures should be visible and scientifically correctly illustrated.
- **The movement speed of the model** – refers only to dynamic models that depict the operation of devices (e.g., four-stroke engine model) and some time-varying processes (e.g., solar system model) (Petty 2008). In such models, the speed of movement (of the observed phenomenon) needs to be set so that the observer can perceive the changes that occur.

## 3 | 1 | 2 Benefits of using 3D models in education

When using 3D models in teaching, there are many benefits these teaching aids provide:

### Visualization

Visualization is a key benefit of using 3D models in teaching. From the point of view of general didactic, it represents the application of the didactic principle of visibility in teaching.

Models are especially applicable when explaining abstract concepts, which are difficult for students to imagine. In this case, it is necessary to illustrate typical features of objects and phenomena. For students to create **accurate and undistorted images**, the models are required to be expertly and didactically correct. Therefore, not only experts on the technical side of the matter (in the case of models created by 3D printing technology, IT experts) but also experts on specific subjects should participate in the preparation of models. Only in this way is it possible to accurately capture the characteristic properties of an object or phenomenon and, at the same time, simplify them so that the model is “creatable” – in our case, printable – on a 3D printer. Only then can the model be upgraded to a teaching aid. Several instructions for printing 3D models are available on the Internet, but only a few of them meet these characteristics. Chapter 3.3 presents tools and entire teaching lessons that were created and verified by a didactic team and IT experts and have the appropriate quality to support visualization. Another benefit of the aids created in this way is saving the time the teachers need for preparing lessons. If teachers had expertly corrected and verified manuals for printing 3D aids at their disposal, they would not have to revise them themselves. Then, they could simply print aids according to the manuals.

### Availability and variability of models

Another benefit of models printed by 3D printing technology is their **availability and variability**. Commercially offered teaching aids are usually quite expensive to acquire (around thousands of CZK), and at the same time, their offer is limited. 3D printing technology offers the possibility to create realistic and financially affordable models. Models can be made not only by teachers but also students. For a relatively low price, the teacher can thus print a model that corresponds to his requirements and the teaching aims of a particular lesson. Although the offer of manuals for printing 3D models is more extensive than for commercial teaching models, the models must be carefully selected so that they are expertly correct and, at the same time, usable in teaching (consider their size, durability, and work safety). However, thanks to their simplification, models cannot usually completely replace real objects (natural objects). If it is possible to use real objects, they should be used.

## Development of pupils

Including the printing of 3D models in the teaching and allowing the pupils to create their own models should lead to further positive effects on the development of their specific skills. These impacts might be even more important in the long term. Pupils' participation in the preparation, printing, and completion of the model develops a number of specific skills and habits, which can be referred to as so-called key competencies. Pupils will also realize how connected expert knowledge is. What is presented to them in isolation within individual fields (subjects), they will see in context. It will thus help to strengthen and develop **cross-curriculum relations**. Typically, it involves a relationship between a professional educational field (e.g., Natural Sciences, Geography, Physics) and a competence-developing field (e.g., Humans and the World of Work). During the processing of the materials for the design of the 3D model, its preparation for printing, and during the printing itself, a relationship with the educational field of Informatics will be developed. Then, during finishing (e.g., dyeing), a relationship with the educational fields of Fine Art or Human and the World of Work will be developed. The implementation of 3D printing technology in the curriculum can provide students with competencies that will be important for their everyday life and career choice.

## Differentiation and individualization of education

The entire process of students using 3D printing technology to create 3D models by themselves non-violently supports **differentiation and leads to individualization of education**. This approach follows the idea of inclusive education. For the successful education of **pupils with special educational needs and gifted and exceptionally gifted pupils**, applying the principle of the differentiation and individualization of the educational process when organizing activities and determining educational content, forms, and methods, must be ensured. Following the RVP ZV, the implementation of differentiated and individualized education for pupils with special educational needs (RVP ZV 2021, Chapter 8) and gifted and exceptionally gifted pupils (RVP ZV 2021, Chapter 9) must be enabled in every school education program. Pupils can choose the difficulty level of the project they will create according to their interests and abilities. Some of the suggested lessons (e.g., Under the Microscope Lesson) take this into account and offer students different levels of difficulty. Gifted and exceptionally gifted pupils can use 3D printing lessons to enrich their educational content, assign specific tasks and projects, and expand their range of optional and non-compulsory subjects and interests (RVP ZV 2021).

## Inclusive education support

The principle of inclusive education is based on the fact that pupils differ in their individual educational needs and possibilities. The purpose of supporting the education of pupils with special educational needs is their involvement in the educational process

and the maximum use of the educational potential of each of them, taking into account their individual possibilities, abilities, and possible limitations (RVP ZV 2021).

3D models might be one of the support measures for pupils with special educational needs. Specifically, they might be used to support:

- Cognitive abilities (to provide education for pupils with intellectual, visual, or combined disabilities).
- Comprehension of spoken language (for pupils with a hearing impairment, a different mother tongue, developmental language disorder, a phonematic processing disorder, or with autism spectrum disorders).
- Motivation and maintenance of attention (for pupils with learning, attention, and behavior issues, but also for the majority of those mentioned above, and for pupils included in the 1st level of support for reasons other than disability).

For example, when educating pupils with mild intellectual disability we can use 3D models to compensate for some of their learning problems. These can include, for example, their difficulties with distinguishing between the essential and inferior; inability to work with abstraction; issues with understanding the meaning of words; insufficient language skills; lower abilities to read and remember what is read, and the perception of context (RVP ZV 2021).

### 3 | 1 | 3 Barriers to 3D printing in education

The integration of 3D printing into primary and secondary education brings several advantages. On the other hand, it places higher demands on schools and teachers due to the need for equipment (hardware and software), which is connected mainly with higher demands on skills related to the progressive development of this industry. A number of research documents present barriers that can influence and hinder the implementation of 3D printing in primary and secondary schools. Y Soft's 2016 International Education Survey reports the results of a survey in which more than 300 respondents, teachers from various levels of education who used a 3D printer, took part (most numerous being university teachers with a total of 50%, and secondary school teachers with a total of 33% of respondents)<sup>17</sup>. The survey revealed three key barriers that keep 3D printers underutilized in schools:

- The first barrier concerns **access to 3D printers and their management**. These printers are often locked in rooms without free access. They are only available in certain classes, or the 3D model is printed only on request by the teacher, which prevents the development of a number of skills (manipulation, etc.).
- The second barrier points out **the impossibility of managing 3D printing and material prices**. Thus, teachers could not charge expenses for specific prints.

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<sup>17</sup> <https://3dprint.com/162719/y-soft-3d-print-education-survey/>

Today, however, there is already a comprehensive 3D printing solution that combines print management and accounting systems. These are solutions that previously only existed with 2D printers.

- As for the third barrier, the teachers identified **the lack of incorporation of 3D printing in the school curriculum documents** (educational plans, etc.). Educators should have a clearly defined curriculum and goals for 3D printing, especially in STEM subjects. STEM stands for education in Science, Technology, Engineering, and Mathematics.

Another foreign study dealing with barriers to 3D printing (Irwin et al. 2015) reports the results of a survey (see Chart 1) in which workshop participants from among secondary school teachers who use a 3D printer in teaching were interviewed. Teachers' lack of practice in solving technical problems with hardware and software was identified as the biggest obstacle (13.2% of respondents) to achieving the full potential of 3D printing in school. Other barriers mentioned, rated at approximately the same level (about 12%), include the non-functionality of the 3D printer due to software or mechanical issues. It also points out requirements and costs associated with financing the printer from school budgets. Other obstacles were insufficient integration of 3D printing into the curriculum, a limited offer of appropriate lessons, and insufficient training of teachers in 3D printing. The research confirmed that there is no barrier concerning the interests of pupils (Malinka et al. 2021).

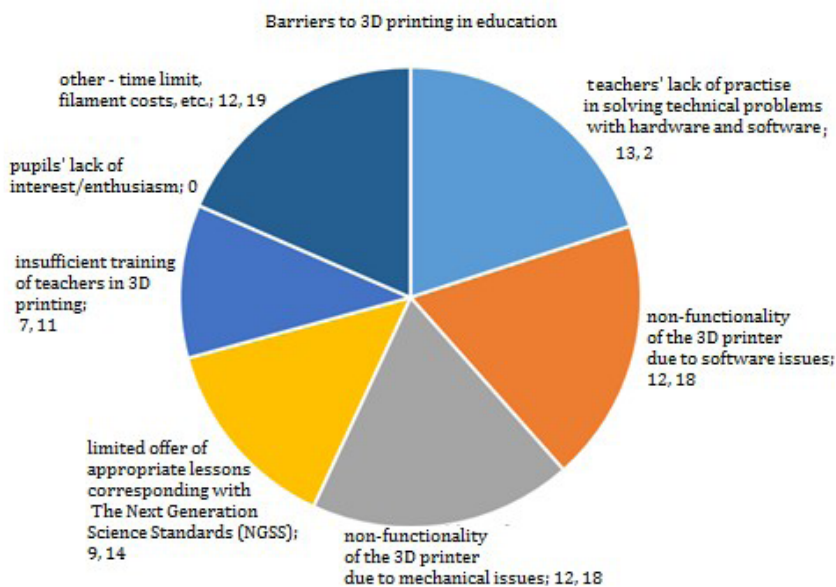


Chart 1: Barriers to 3D printing in research conducted in the USA, n=35 (Irwin et al. 2015).



Further, an online survey was conducted in the Czech Republic (Lepka 2021), in which 234 respondents participated – of which 90% were primary school teachers. 69% of respondents already had some experience with 3D printing, and the rest had not yet come across 3D printing. Graph No. 2 summarizes the results of the survey on barriers to 3D printing.

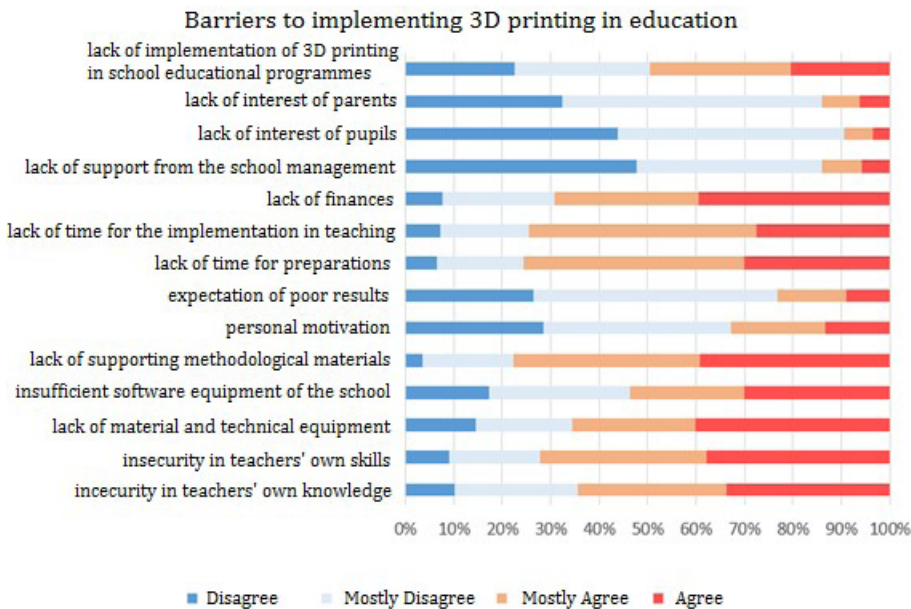


Chart 2: Results of the survey on barriers to the implementation of 3D printing in teaching in Czech schools, n=234 (modified according to Lepka 2021).

The survey results show that the respondents do not consider the lack of interest of parents and pupils or inadequate support from the school management to be the barrier to the implementation of 3D printing in teaching. In addition, personal motivation and the expectation of a poor result are also not considered a barrier. On the contrary, the respondents identified the lack of supporting methodological materials and the time aspect as the most significant barriers. The time aspect includes the time the teacher must devote to preparing 3D printing lessons and to the actual implementation of 3D printing in teaching. Other barriers include, of course, **a lack of material and technical equipment** at many schools. A large number of respondents also cite **insecurity in their knowledge and skills** as a barrier. Approximately 50% of respondents see the lack of implementation of 3D printing in the school educational programmes as an obstacle.

## 3 | 2 Implementation of 3D PRINTING TECHNOLOGY IN THE CURRICULUM

Decades have passed since the creation of the first 3D printer. The users and the way of using the printers have changed over the years – from hobbyist users to professional users from many fields; from a technical novelty through industrial use, 3D printers have recently also reached schools. There are already pilot programs in this direction abroad (see Department for Education UK 2013, Ministère de l'Éducation nationale 2018). On the other hand, in Czech schools, 3D printers are only just becoming established. Provided that pupils should be introduced to their operation, this issue needs to be implemented in documents dealing with the content of education.

### 3 | 2 | 1 Foreign experience with the implementation of 3D printing in education

This sub-chapter presents the effort to implement 3D printing in education in Great Britain and France. The goal of this section was not to provide readers with a complete overview of how individual states approached the implementation of 3D printing in education but rather to illustrate that it is happening.

Until recently, 3D printing technology in Great Britain has been used mainly in the field of design and industrial technologies. However, in 2012–2013, the British Ministry of Education funded a little 3D printer project to explore the possibilities of using 3D printers to enrich teaching across STEM (Science, Technology, Engineering, and Mathematics). The project offered the opportunity to explore innovative ways to enrich teaching and stimulate pupils' interest in these technologies. As using 3D CAD software for modeling was already part of the UK curriculum, the introduction of 3D printing did not rapidly increase the subject matter in the curriculum (Department for Education UK 2013).

Similar to Great Britain, 3D printers are gradually starting to penetrate schools in France. First, it was mainly thanks to enthusiasts - handymen who built them a year ago in the so-called Fab Labs or Makers. 3D printing technology, together with two other technologies (laser cutting and Arduino), enabling the creation of prototypes, was included by the French Ministry of Education among the technologies enabling the development of 21st-century competencies.

In France, teachers started creating places for 3D printers in schools before 2018. These enable them to realize several projects and produce teaching materials in various subjects, especially Mathematics, Physics, Chemistry, History, etc.

The French Ministry of Education sees the potential in the use of 3D printing to support pupils with special educational needs, e.g., those who have an issue with the transformation of three-dimensional objects into a surface or those who require using more senses (e.g., touch) for better understanding. Different possibilities of using 3D printing (from searching for completed models to designing and modeling) allow the teacher to differentiate teaching according to the abilities and needs of individual

students, taking into account their individual requirements (Ministère de l'Éducation nationale 2018).

### **3 | 2 | 2 Current status of 3D printing in Czech schools**

Currently, 3D printing in schools is not widespread and well thought out. The use of 3D printers is not even explicitly embodied in curriculum documents. In general, a 3D printer is an established and readily available technology. It is used not only by high-tech companies but also in various forms in almost every industry. Many schools are aware of this and try to prepare their pupils and students for the labor market demands.

Therefore, the market already offers technical solutions designed specifically for schools. In the Czech Republic, the YSoft and Prusa Research companies deal with the issue of 3D printing and support 3D printing projects in primary and secondary schools. As part of its support, it offers 3D printers to schools for loan and for creating educational projects. If the school is interested in 3D printing, it can get a free-of-charge printer. Both companies declare the provision of a printer and training in 3D printing. Other companies also offer 3D printer loans or rentals. These include Alza.cz, a. s., TriLAB Group, s. r. o., Konica Minolta Business Solutions Czech, s. r. o.

Despite these possibilities, however, a systematic approach is lacking, and 3D printing remains a matter for individual schools. The potential of 3D printing thus remains more or less unused. This situation also causes a lack of quality and well-thought-out didactic content to support the use of 3D printing in teaching. Although the size of freely accessible databases of 3D models is constantly expanding, only a minor fraction of them has significant didactic potential. Although the quality of these models is good, companies usually do not have the space or pedagogical experience to significantly adjust the materials according to curriculum documents and their use in teaching. First, teachers must find a suitable model, prepare teaching materials for the selected model, and consider effective integration into the classroom. All this is a huge time burden (Malinka and Schindler 2021).

### **3 | 2 | 3 Problems of 3D printing in curricular documents of the Czech Republic Strategy 2030+**

Strategy 2030+ is the key document of education policy in the Czech Republic. This document, created for the period 2020–2030, aims to determine the future direction of Czech education and set investment priorities for the decade (Fryč et al. 2020).

The implementation of 3D printing technology into Czech schools is not directly expressed in the document, but because of the relatively broad formulation of support activities that strengthen the teachers' ability to work with diverse digital educational resources and to use digital technologies in various stages of the learning process, the inclusion of 3D printing technology can be counted on. In addition, using 3D printing in schools develops specific skills that fulfill the aims of this strategy to create a place responding to technological and social changes associated with global megatrends and

the concept of the fourth industrial revolution and to take into account the requirements for sustainable development (Fryč et al., 2020).

## Framework Educational Programme for Basic Education

Although 3D printing and 3D printers are not implicitly mentioned in the current version of the Framework Educational Program for Basic Education (hereinafter referred to as RVP ZV) a careful and informed reader will find this issue within context. For example, as part of **the objectives of basic education**: “[...] guide pupils to the safe, self-confident, critical and creative use of digital technologies at work, during learning, in their free time and when participating in society and civic life [...]” (RVP ZV 2021, p. 9). Another part of the RVP ZV, in which we could see the applicability of 3D printing technology, are key competencies. The 2021 revision brought new competencies – **digital competencies**. These assume, among other things, that at the end of basic education, the pupil will: “[...] control commonly used digital devices, applications, and services; use them when learning and when participating in school life and society; independently decide which technologies to use, for which activity, or a problem. The pupil will also understand the importance of digital technologies for human society, get acquainted with new technologies, critically evaluate their benefits and reflect on the risks of their use [...]” (full text of digital competencies - see Box 1).

Box 1: Digital competencies (RVP ZV 2021, p. 13).

At the end of primary education, the pupil will:

- Control commonly used digital devices, applications, and services; use them when learning and participating in school life and society; independently decide which technologies to use, for which activity, or a problem.
- Acquire, search for, critically assess, manage, and share data, information, and digital content, while choosing procedures, methods, and means that correspond to the specific situation and purpose
- Create and edit digital content, combine different formats, and express himself by using digital technologies
- Use digital technology to make work easier, make routine activities more automatic, streamline or simplify work processes, and improve the quality of work results.
- Understand the importance of digital technologies for human society, learn about new technologies, critically evaluate their benefits and reflect on the risks of their use.
- Prevent situations threatening the security of equipment and data, situations with a negative impact on his physical and mental health, and the health of others; behave ethically when collaborating, communicating, and sharing information in the digital environment.

**3D printers and 3D printing technologies** fit well into the above-mentioned digital competence framework. 3D printers are slowly becoming commonly used digital devices, and it is, therefore, appropriate to teach pupils their operation and applicability from both a technical and IT perspective. At the same time, 3D printers also make it possible to convert the created digital content into a tangible form, which increases students' motivation to make their digital content independently. Last but not least, they also teach pupils to understand the importance of digital technologies and to critically evaluate their benefits and risks.

3D printing and related activities (3D modeling, 3D scanning, etc.) help develop these competencies practically in all aspects, including operating digital devices (3D printer), applications (slicer, 3D modeling software), or services (database of models and projects). The pupil can also obtain ready-made digital content for printing or create and edit models. 3D printers currently facilitate a number of procedures by printing 3D parts of models quickly. At the same time, it is also necessary to perceive the continuity of the other key competencies. 3D printing also helps to develop working competencies. The pupil learns to safely and efficiently work with materials, tools, and equipment while operating the 3D printer and complying with guidelines and rules (RVP ZV 2021, p. 13).

The procedures and knowledge acquired in this way will increase pupils' competitiveness in the labor market later in life. 3D printing also teaches pupils how to price 3D prints and deal with licensing rights of 3D models available on the Internet, which helps them orient in the activities necessary for the realization of a business plan and its subsequent implementation. 3D printing leads pupils to independence, responsibility, and critical thinking, thus fulfilling not only **problem-solving competencies** but also **learning competencies**. Through 3D printing, pupils can improve their knowledge and skills in technology and informatics fields.

These new and modern technologies (and their functioning in the world and around the student) can also be found in the expected outcomes and the curriculum of the innovative **educational field of Informatics** (in more detail, see subsection 3.3.1), which replaced the original educational field of Information and Communication Technologies. In the RVP ZV, we can also find the connection of modern technologies with the educational areas of Humans and Nature and Humans and the World of Work (RVP ZV, 2021).

Last but not least, it is essential to see the importance of all didactic aids, information and communication technologies, digital technologies with an Internet connection, and other means that **support** pupils' activity and creativity. In the RVP ZV, these are listed as part of "[...] material, personnel, sanitary, organizational and other conditions for implementing the RVP ZV [...]" (RVP ZV, part D, ch. 10), while they are considered necessary for the education of pupils with recognized supporting measures and gifted and exceptionally gifted pupils (RVP ZV 2021, p. 149).

## Framework Education Programme for Secondary General Education (Grammar Schools)

In the revised Framework Educational Program for Gymnasiums (hereafter RVP G), there are also no connections to 3D printing and 3D printers. However, we can find a specific mention in the background study on revisions of the RVP, the author of which is doc. Jiří Dostál, Ph.D. from Palacky University. Despite these obstacles, it is possible to imagine the implementation of 3D technologies in teaching at gymnasiums. During a detailed analysis of RVP G, we found terms such as “digital technologies” or “new technologies,” which could cover the umbrella term 3D technologies.

**The objectives of education at grammar schools** state that this type of education should: “[...] provide the pupils with key competencies on the level which is required by the RVP G [...]” and also “[...] provide the pupils with a wide knowledge base on the level described by the RVP G [...]” and, last but not least, it should “[...] prepare the pupils for lifelong learning, for their professional, civic as well as personal lives [...]” (RVP G 2021). 3D printing technology could help fulfill all three of these goals. The fulfillment of the first and third goals could be realized in the form of tasks developing **key competencies** (in relation to 3D printing, these include mainly digital competencies, working competences, and problem-solving competencies). Digital competencies are a new addition to the curriculum document as they are part of the RVP G from 2021. The importance of new technologies is emphasized, among other things, in digital competencies: “The pupil understands the importance of digital technologies for human society, learns about new technologies, critically evaluates their benefits, and reflects on the risks of their use.” (RVP G 2021, p. 11).

The second objective of grammar school education is implemented through **educational areas and fields**. 3D printing technology is most closely related to the educational field of Informatics, which, among other things, counts on mastering the basic principles of modeling. The pupils will then discuss the functioning of digital technologies that determine trends in the world. Within other educational areas, 3D printing technology can also be applied in the educational field of Mathematics and Its Application, thanks to which students are guided to use digital technologies in modeling mathematical situations to solve problems effectively and present results. Even here, it is possible to classify 3D printing as not only a tool but also as a motivational aspect. Similar to the RVP ZV, we find the connection between modern technologies and the educational areas of Man and Nature and Man and the World of Work (RVP G 2021).

Although 3D printing is not embodied directly in RVP G, schools can incorporate 3D printing into their school education programs individually. For example, within the optional subject Computer graphics or the non-compulsory subject Polytechnic seminar, which includes the topics “3D Modelling (Fusion360, ArchiCAD) – creation and design of your model or its modification” and “Preparation of a model for further processing on a 3D printer.” It is also in the expected outcomes stated in the ŠVP (= School curriculum) “[...] the student will create 3D models of organic compounds [...]” using

computing technology during the teaching of chemistry (ŠVP GML 2009, ŠVP Polička Gymnasium 2015).

### 3 | 2 | 4 Aspects of 3D printing implementation in education

However, the implementation of 3D printing in education should not be random. It is vital to clarify the goals that the school wants to achieve. If the school decides to use 3D printing, it should consider its material and personnel capabilities and set the implementation method accordingly. When creating a certain concept for the implementation of 3D printing, it is advisable to consider the aspects listed below.

#### Implementation in the school curriculum

The introduction to 3D printing in schools is usually in the form of **optional subjects, clubs, or projects**. Schools approach the introduction of working with a 3D printer in different ways. Some schools do not have 3D printers yet, so their existence is taught only in Informatics. A number of schools have already acquired a 3D printer, but for the time being, they only present 3D printing on the school's website, and meantime, the printer is located in the teacher's office or other closed spaces. Only a limited number of teachers use this printer to print their models. Only a limited number of teachers use this printer to print their models. It is ideal to have placed the 3D printer visibly so that pupils could see it. You can choose a computer science classroom or public spaces in school corridors. However, you should consider the noise of printing and the production of fumes during printing. If the school has several 3D printers (the ideal solution is a classroom fully equipped with 3D printers), then there is a way to implement these technologies into the school curriculum.

If you are considering using 3D printing in school, see the decision process in Fig. 9. If you have not come to the end of this process, think about whether or how to solve the problem that prevents you from implementing 3D printing in education.

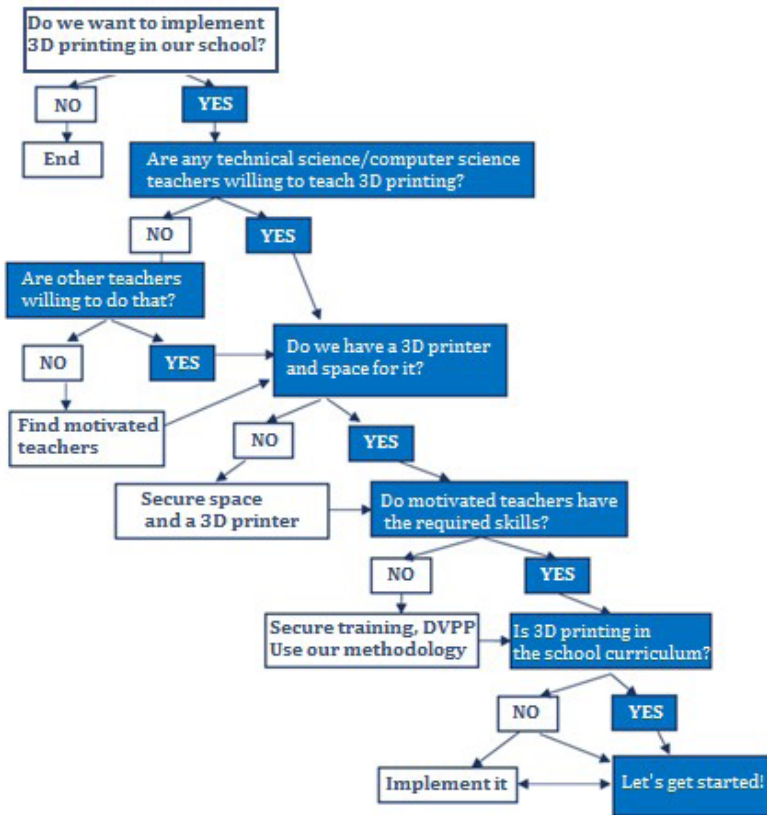


Fig. 9: Decision-making process for implementing 3D printing into teaching

### The follow-up to the development of digital competences

The implementation of 3D printing can contribute to the development of **digital competencies** formulated in framework educational programs, which, together with other competencies, create a basis for lifelong learning, students' entry into life, or the work process. In addition to digital competencies, 3D printing helps to develop **work competencies** (operating a 3D printer, using various materials, tools, or equipment), **problem-solving competencies** (recognizing and understanding a problem when a 3D model is printed incorrectly, thinking through and planning a solution, etc.) and **learning competencies** (knowledge and skills in the field of technology and informatics).



## Cross-curricularity

All educational areas can include the application of 3D printing. Within educational areas of **Informatics** and **Humans and the World of Work**, 3D printing fulfills several expected RVP outputs. If we appropriately connect the mentioned educational areas (fields) with the other educational areas, then great possibilities for developing both digital and field competencies of pupils open up. 3D models can help facilitate the creation of ideas of spatial objects and the relationships between them. They make it easier to interpret and compare objects, phenomena, and various processes of different disciplines. Models created by 3D printing technology and students' modeling can be used to accomplish a whole range of expected outputs of all disciplines. Thus, there is an open space for the implementation of 3D printing in all educational areas and their fields.

## Ways of using 3D printing

There are two basic ways of using 3D printing in schools:

- If, as teachers, you decide to print models, these models can serve you well as a means of supporting visualization in teaching. With the help of models, you can create students' ideas about specific objects, phenomena, and processes across educational fields.
- A different approach involves the students' activity in modeling and printing 3D objects. In this case, students learn and develop several skills and achieve the expected outcomes primarily from IT and technical subjects but also from a number of other educational fields, provided that students use the model afterward.

## Difficulty level of tasks (progression)

During the initial introduction to the 3D printer, we should print models obtained by downloading from the online database of freely available models (see Chapter 2.3.1).

The only thing we do is open these models in the appropriate application for preparing commands for the printer (so-called slicer), export in the required format for the given type of printer, and print. Creating your models is a more demanding type of task. For this, we initially use simple modeling programs, e.g., Tinkercad. To make such models, we combine simple shapes that are available in the application and then modify them. If we want to create more complex and accurate models, components, etc., we need to use programs that provide a wider range of tools and functions, e.g., Blender or Fusion 360. To print these more complex models, we also need to set the necessary parameters in the slicer, including the use of support printing, etc. (for more, see Chapter 2.3.).

## Role of teacher and student

When implementing 3D printing, we aim to develop students' modeling and 3D printing skills. However, for the teacher to develop these skills in the students, the teacher must acquire them first. In the sample educational lessons for individual subjects, which you can find in the clear tables in the appendices of this methodology, we offer several types of materials intended both for teachers and students, including pictorial and video instructions.

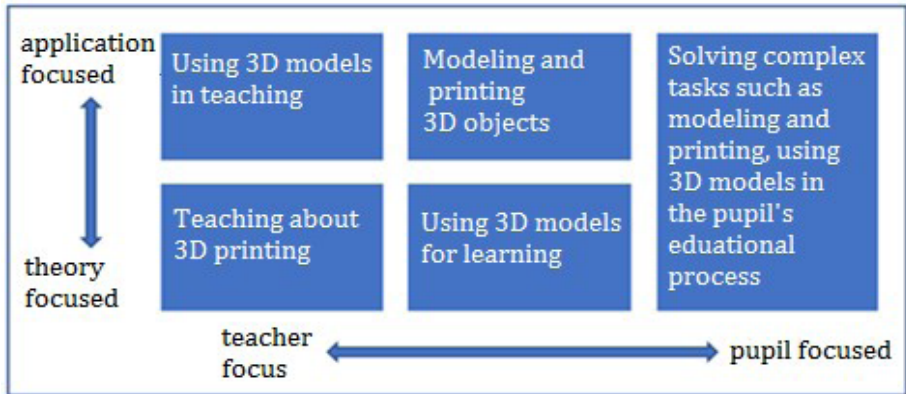


Fig. 10: Possibilities of integrating 3D printing into teaching

Teachers' roles should gradually transform during the implementation of 3D printing. From a mere mediator of information about 3D printers (teaching about 3D printing), they should eventually become the ones who only supervise the independent work of pupils, their modeling, and the operation of the 3D printer (see Fig. 10). The students should gradually acquire basic technical skills and modeling tools. The role of the teachers should recede into the background. The aim is, therefore, for the pupils to be able to solve complex tasks, i.e., independently model, print the model, and thus use the whole process to help develop key skills and relevant field knowledge.

## Securing the materials

If schools or interest groups are interested in using 3D printers for work, they can choose from some of the devices on the market. Because of the development of technology, and greater competition, prices are gradually falling. 3D printers are also becoming more user-friendly as they do not require too many technical skills. A number of settings are already fully automated, and some extensive instructions and manuals will help if the user does not know what to do.

Based on our own experience, we recommend using Fused Filament Fabrication (FFF) printing technology, also known as Fused Deposition Modeling (FDM). At present, it is the most popular technology, as the printing costs are low compared to other technologies, but at the same time, it allows printing of sufficient quality.

We have to mention the regular costs, apart from the initial investment in the printer, especially of printing materials, maintenance, or consumed electricity. The price of the most used PLA filaments starts at 600 CZK per 1 kg. If the printer is also available for private printing services, it is necessary to deal with printer accounting.

For more information on this issue, see chapters 2.1.–2.3.

## Recommended tools/applications/software

If you are interested in creating or modifying a 3D model, you will need to purchase appropriate modeling software. If you already use a program for creating 3D objects in school, you will likely be able to use it when creating models for 3D printing. The fastest way to get a printable model is to download it from an online database. Before importing the model into the printer, it is necessary to “cut” the 3D model into individual layers that the printer will apply. This process is called **Slicing**. Its output is instructions for the printer, the conversion of which takes place in a program called **Slicer**. For more information on this issue, see Chapter 2.3.

## 3 | 3 EXAMPLES OF 3D PRINTING IMPLEMENTATION IN MODEL EDUCATIONAL FIELDS

In this chapter, we point out the possibilities of implementing 3D printing into the existing curriculum of primary and secondary schools on the examples of selected educational fields (Informatics, Humans and the World of Work, Mathematics and Its Applications, Geography, Natural Sciences).

### 3 | 3 | 1 Educational fields: Informatics and Humans and the World of Work

By applying 3D printing in teaching, we can essentially include all educational areas. In this case, we will focus only on those that interest us from the point of view of technology and informatics, which are part of **Informatics** and **Humans and the World of Work**.

#### Informatics

Within the educational field of Informatics, several expected outputs are being fulfilled at elementary schools thanks to 3D printing. The 3D printer is included in Stage 1 subject matter, as it is a part of computer output hardware, which is often part

of computer networks. All the outcomes of the thematic area **Digital technologies** correspond to this:

- Pupils will find and run an application and work with data of various types.
- Pupils will connect digital devices and state the possible risks associated with such a connection.
- Pupils will observe safety and other rules for working with digital technologies.

The thematic area Digital technology appears again in Stage 2. By using 3D printers, it is possible to fulfill several of the expected outputs:

- Pupils will describe how a computer works in terms of hardware and operating systems; will discuss the functioning of digital technologies that determine trends in the world), and will also choose a suitable format - this includes the discussion of 3D printing as a digital technology that determines trends in the world.
- Pupils will store and manage data in a format that is suitable for further processing or transmission.
- Pupils will choose the most appropriate way to connect digital devices to a computer network; will give examples of networks and describe their characteristics.

The fulfillment of this outcome can be formulated by the following words: “[...] from several possible connections of the 3D printer to the network, it selects the most suitable one in terms of security and transfer speed[...].”

**RVP G**, in the revised version with effect from 1 September 2022, follows up on RVP ZV in the thematic area of **Digital technologies**. Within the expected outcomes, it is possible to use 3D printers to identify and solve problems and challenges that arise during working with digital devices. In the thematic area of **Data, information and modeling** placed in the RVP ZV, a student acquires models, critically considers their usability, possibilities, and shortcomings, and achieves the outcome:

- Pupils will obtain information from the data, interpret the data, and reveal errors in other people’s interpretations of the data.

We also get access to the individual data formats used in 3D printing (such as STL, OBJ, AMF, 3DM for 3D models, and GCODE containing instructions for 3D printers), which fulfills the following outcome:

- Pupils will propose and compare different ways of encoding data to store and transmit them.

From the complex point of view of solving the problem, using 3D printing to find information needed to solve it partially fulfills the outcome:

- Pupils will define the problem and determine what information they need to solve it [...].

In the same area within **RVP G**, it is possible to expand and deepen the work with 3D models for data visualization.

The entire 3D printing process can then be divided into individual outcomes of the thematic area of Algorithmization and programming:

- Pupils will divide the problem into individually solvable parts and propose and describe the steps to solve them.

- Pupils will verify the correctness of the procedure and find and correct any errors in it.

Problem analysis, decomposition, and algorithmic thinking, which **RVP G** develops in the educational area of **Algorithmization and programming**, can also be applied to 3D model creation processes, even to printing or post-processing processes of prints. During computer science education, 3D printing is often taught in separate blocks, in which students learn all the knowledge and skills related to 3D printing. It includes searching for suitable models, modeling, modifying existing models, preview rendering, preparing a model in the slicer, and operating the 3D printer to achieve successful printing.

Apart from this block, we can often use a 3D printer in informatics to print various boxes and packaging for single-board computers such as Arduino or Raspberry. Furthermore, for example, for producing attachments and accessories for school robots. An example could be a pen holder, thanks to which Ozobot can draw, or various attachments for the Fable robot. It is a very complex and useful technology, suitable to be implemented in informatics at primary school.

### Ideas for computer science educational activities

- Principles of 3D printers, printing materials – theory and practical use.
- Preparing the printer for printing – installation, and commissioning of the printer, printing bed, material, nozzle, etc.
- Basic 3D printer maintenance – replacing nozzles, cleaning and lubricating components, solving common problems (material jams, etc.).
- Searching 3D model databases, critically assessing the model suitability for printing and its purpose.
- Working with 3D modeling software (recommended free software for schools – Tinkercad, Fusion360, Blender, SketchUp, etc.) – principles of 3D modeling, creating a basic model, adjusting a downloaded model.
- 3D models file formats for printing – conversion, usability.
- Working with the slicer (according to the used printer) – settings for printing, resolution, speed, temperature, supports, printing mat, filling, etc.
- Safety rules for working with a 3D printer (hot-end, electrical equipment).
- Starting the print – print – removing the print from the bed.

### Humans and the World of Work

Technology and technical education within the RVP ZV primarily refer to the educational field **Human and the World of Work**. As part of the thematic area **Working with technical materials**, the following expected outputs are fulfilled:

- Pupils will perform simple work with technical materials and observe proper technological procedures.

- Pupils will solve simple technological tasks using an appropriate selection of materials, tools and implements.

It might also aim at the knowledge of individual printable plastics, choosing a suitable assignment, or finishing 3D prints (sanding, gluing, sealing, etc.). Concurrently, when using 3D printing and 3D prints, we can fulfill the other remaining expected outcomes:

- Pupils will organize and plan their work activities, make use of technical documentation, create their own simple product diagram, observe fundamental health and safety rules as well as basic safety and protective measures while working with tools; provide first aid in case of injury.

Further use can be found in the outcomes of the thematic area **Design and construction**:

- Pupils will design and construct simple constructional elements and inspect and compare their functionality, load-bearing ability, stability etc.

The following outcome is fulfilled in a very similar way:

- Pupils will perform assembly, disassembly and maintenance of simple objects and equipment.

Both of these outcomes must be accompanied by the outcome listed below:

- Pupils will observe fundamental health and safety rules and regulations; provide first aid in case of injury.

To completely fulfill the thematic area **Design and construction**, we can also include the outcome:

- Pupils will assemble a specific model according to instructions, sketches, plans or a simple programme.

Considering its current expansion, it is almost necessary to include 3D printing in the thematic area **Use of digital technologies**. Pupils are guided to be able to operate 3D printers and solve problems that may arise during printing. The printer must be kept in working order and calibrated by the students. Thanks to this, other outcomes are fulfilled:

- Pupils will manage to control the basic functions of digital technology; diagnose and eliminate common problems in the operation of digital technology.
- Pupils will treat digital technology accordingly and protect it from damage.
- Pupils will connect individual digital devices to each other - within this outcome, it is possible (depending on the 3D printer used) to connect the printer to a PC, LAN, or WLAN and configure network printing.

Although 3D printing cannot fulfill all of the outcomes in the thematic area of World of Work, its knowledge will nevertheless be valid in the fulfillment of the following outcomes:

- Pupils will orientate in the work activities of selected professions and will benefit from assigning other working activities to certain professions.
- Pupils will demonstrate, in model situations, their ability to present themselves when entering the labor market, in which they can take advantage of the fact that their knowledge and skills portfolio includes 3D printing and 3D modeling.

3D printing methods are used not only for hobby activities but also in many areas of the educational field of **Humans and the World of Work** – e.g., in rapid prototyping of products, design suggestions, etc. In the context of **RVP G**, the educational field of **Man and the World of Work** is focused, among other things, on the thematic area **Labor market and career choice**, where mastering modern technologies (such as a 3D printer) represents an advantage on the labor market, even when choosing another career path.

### Ideas for educational activities in technics:

- Principles of 3D printers, printing materials – theory and practical use.
- Calibration of the 3D printer – leveling the print bed and loading filament.
- Basic 3D printer maintenance – replacing nozzles, cleaning and lubricating components, solving common problems (material jams, etc.).
- Working with 3D modeling software (recommended free software for schools – Tinkercad, Fusion360, Blender, SketchUp, etc.) – principles of 3D modeling, creating a basic model, adjusting a downloaded model.
- Safety rules for working with a 3D printer (hot-end, electrical equipment, toxic fumes).
- Starting the print – print – removing the print from the bed.
- Surface treatment of 3D prints – joints, smoothing, coloring, gluing.
- Production of gift and souvenir items for school markets or fairs.
- Production of didactic aids for other first and second-stage subjects.

### Overview of available 3D models and educational lessons in the field of informatics and technology (educational field of Humans and the World of Work)

In online databases, repositories, and portals, we can find a lot of suitable models and even completely prepared lessons that are suitable for teaching in the field of technology and informatics.

The already mentioned accessories for single-board computers are mostly very simple to print and design.

One of the options is printing an Arduino Nano V3 case by b-shu (see Fig. 11). It fulfills not only protective but also a design function – the Arduino case looks nice in the box (you can even add the school logo or anything else). It does not even have exposed pins or components, so there is a lower risk of damage.

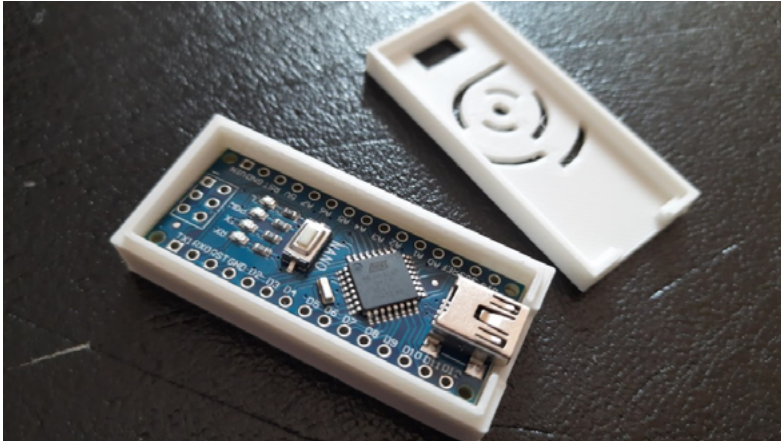


Fig. 11: Arduino Nano V3 case<sup>18</sup>

The second interesting category is accessories for robots and robotic kits. These are usually more complex both in terms of design and printing. However, they increase the number and variability of activities we can perform with the robotic kit.

Thanks to 3D printing, the Ozobot can draw lines, wear a cap or carry small objects. For a Fable robot, which works on the principle of modular blocks, a wide range of modules is available on the Internet, created directly by its creators – Shape Robotics. These printed modules can be simple, as in the case of a ping-pong ball stand (see Fig. 12), a spoon, or a joint. However, there are complex prints available, such as the balance maze.

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<sup>18</sup> <https://www.thingiverse.com/thing:608121>



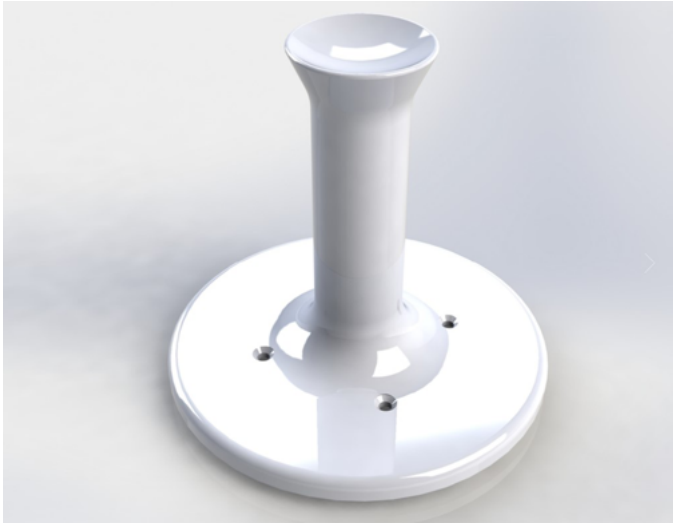


Fig. 12: Fable Ping-Pong ball stand<sup>19</sup>

In technical activities, 3D printing finds use mainly in the creation of molds, tools, fixtures, and packaging or covers for electronics. One of the available models is a shrew, used to create a line parallel to the edge of the material (see Fig. 13). The student thus makes his own instrument, which he can then use.

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<sup>19</sup> <https://www.thingiverse.com/thing:2516762>

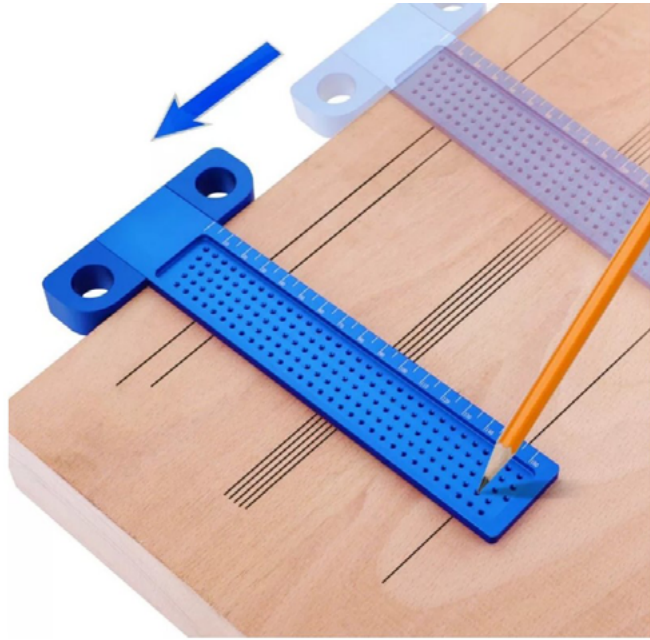


Fig. 13: Gauge<sup>20</sup>

From an educational point of view, prepared teaching lessons interest us a lot. We can find them in several places. BE3D Academy by Ysoft and MakerBot SKETCH Classroom are available in Czech. These company portals offer the implementation of 3D printing in the form of printers, printing solutions, and accompanying lessons to schools. Their main advantage is high-quality processing and a large number of documents (i.e., not only a printable file but also worksheets or a lesson plan, including its connection to RVP). Both of these projects are subject to a fee.

One of the lessons available at the BE3D Academy suitable for teaching technical activities is printing and subsequent making of molds for casting soap, chocolate, or wax (see Fig. 14). The lesson includes a summary, lesson objectives, timetable, list of equipment and knowledge, instructional videos, worksheets, and 3D models.

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<sup>20</sup> <https://www.thingiverse.com/thing:4186423>



Fig. 14: Molds for casting<sup>21</sup>

Other sources of online lessons include the models in the **Prusa printers** repository under the education tab. Labels are often in English. Comprehensive additional materials are thus not available. However, the models divided according to the fields are available for free. The education tab on the **Thingiverse** website works on the same principle (see Fig. 15). The advantage of these options is also much greater variability in the choice of the printed model.

Filter Lessons by Subject				Filter Lessons by Grade	
<input type="text" value="Art"/>	Engineering	Geography	History	<input type="text" value="K-6"/>	7-12
Science	Special Ed	Technology	Languages	University	Reset
Math	Reset				

Fig. 15: Lessons Filter – a table listing lessons by field of study<sup>22</sup>

Repository recommendations and models for technology and informatics are in the relevant chapter.

### 3 | 3 | 2 Educational field: Mathematics and Its Application

Due to its characteristic features, the educational field of **Mathematics and Its Application** offers many opportunities for the implementation of 3D printing. RVP G

21 <https://be3dacademy.ysoft.com/cs/lekce-3d-tisku/forma-na-odlevani>  
 22 <http://www.thingiverse.com/education>

mentions that: “Mathematical education helps cultivate abstract and analytical thinking, develops logical judgment, and teaches clear and factual reasoning aimed at finding objective truths rather than defending one’s own opinion.” The focus of the instruction lies in mastering the ability to formulate a problem along with a strategy to solve it, in actively mastering mathematical tools and skills, and in cultivating the capability of applying these skills.

Mathematics contributes to the pupil’s being capable of evaluating the correctness of his/her approach when deducing theses and recognising false conclusions. During their studies, pupils discover that “[...] that modern technologies are a useful aid to mathematics [...]” (RVP G 2013). These characteristic features are reflected in the expected outcomes to which the implementation of 3D printing contributes.

Similarly, in the RVP ZV (RVP ZV, revision 2021) in the educational field of **Mathematics and Its Application**, the outcomes listed are indirectly related to the development of digital competencies and naturally offer scope for the implementation of 3D printing. Let’s list at least a few where 3D printing models and students’ modeling can be effectively used:

Pupils will solve simple practical word problems and problems which may to a large degree be solved independently of usual approaches and algorithms of the mathematics taught at school.

- Pupils will estimate and calculate the area and circumference of basic two-dimensional figures.
- Pupils will estimate and calculate the volume and surface area of bodies.
- Pupils will sketch and construct basic bodies.
- Pupils will sketch and construct simple bodies in a plane.
- Pupils will analyse and solve applied geometric tasks using newly acquired mathematical skills.

3D models generally increase students’ interest in the issue, help them understand the relationships presented, support logical thinking, the ability to estimate the result, and the ability to construct and analyze mathematics.

## Demonstration of educational 3D models

Educational 3D models facilitate not only the creation of ideas of spatial objects and the relationships between them but also help solve situations where it is necessary to reach the result through several steps. 3D models are (and have always been) a part of quality mathematics education in elementary and grammar schools. 3D printing offers a diametrically different variability of such models, their quick availability in larger quantities, and other advantages (see Chapter 3.1.2.).

## Ideas for educational activities

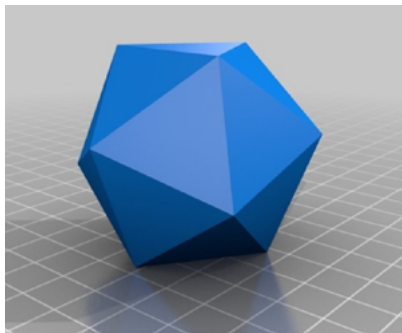


Fig. 16: Convex polyhedrons<sup>23</sup>

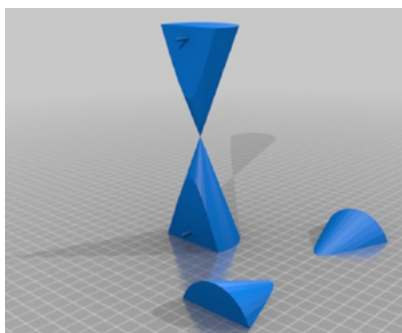


Fig. 17: Conic sections<sup>24</sup>

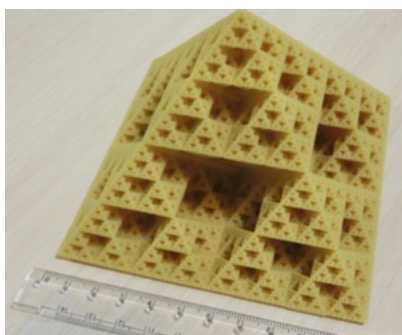


Fig. 18: Fractals<sup>25</sup>

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23 <https://www.thingiverse.com/thing:233540>, <https://www.thingiverse.com/thing:23354>

24 <https://www.thingiverse.com/thing:1260776>

25 <https://www.thingiverse.com/thing:1356547>

## Students' own creation of models

Here, we enter an area where 3D technologies and 3D printing offer new possibilities. We can compare this qualitative step to the situation in which the manual ink drawing was replaced by CAD systems. Although it is possible, and in many cases even desirable, for students to create their own mathematic models using paper, sticks, and so on, 3D technologies bring a revolutionary possibility in this field to prepare assignments and modeling of such tasks, on which students can effectively practice several competencies at the same time and also discover relationships and connections, and practically convince themselves of their reasoning (see Fig. 16, 17, 18).

### 3 | 3 | 3 Educational field: Geography

Geography is, together with other educational fields (Physics, Chemistry, and Natural Sciences), part of the educational area of **Humans and Nature**. These educational fields “[...] provide pupils with the tools and methods for a deeper understanding of natural phenomena and natural laws. It also gives them the necessary foundation for a better understanding and use of contemporary technology and helps them better orient themselves in everyday life [...]” (RVP ZV, p. 63).

Expected outcomes that would develop digital competencies or specific skills in connection with 3D printing are not directly stated in the educational field of Geography in RVP ZV (RVP ZV, revision 2021), nor the educational field of **Geography** in RVP G (RVP G 2007). Nevertheless, it is possible to appropriately implement the teaching of 3D printing in science subjects, even from Stage 1 of elementary school. Models created by 3D printing technology and students' own modeling can be used to fulfill a whole range of expected outcomes that are listed in the educational area of **Humans and their World**. This educational area is designed only for Stage 1 of basic education. Furthermore, these models can be used in all thematic areas connected to the educational field of Geography in Stage 2 of basic education and within secondary general education. Provided that the educational field of Informatics/Information and Communication Technology was appropriately linked with Geography at primary and secondary schools, there could be a wide range of opportunities to work with (geo)information technologies, and thus the development of pupils' digital and field competencies.

Using physical 3D models in geography lessons, thanks to which students have the opportunity to “touch” the model, arouses their interest in the issue, and enables easier interpretation or comparison of objects, phenomena, and processes. When implementing 3D printing for the field of geography, the thematic area of Geographical information, data sources, cartography and topography (at primary school), Geographical information and field teaching (at secondary school) appears to be pivotal. These should connect all other thematic units through work with information, data, and maps.

A 3D map, compared to classic 2D maps, offers an extra dimension, which can facilitate orientation and a credible interpretation of the surface of the Earth. 3D maps

can be used for the visual presentation of a certain locality and thus visualize the image of a place that can be located on the opposite side of the Earth or in an otherwise inaccessible area. However, 3D models can be used to represent a number of real phenomena from other thematic areas as well. For example, in the thematic area of the Natural image of the Earth, you can use a model of the internal structure of the planet Earth, a volcano model, an erosion model, models showing individual relief shapes, etc. In thematic areas dedicated to regions of the world or the Czech Republic, you can use models to practice and consolidate knowledge about the location of individual regions (e.g., models of administrative units, etc.).

## **Ideas for educational activities**

Educational activities created for the field of geography can be divided into three groups:

### **Using 3D (geo) aids**

Physical models depicting specific objects or phenomena of the real world can be considered educational (geo) aids. Thanks to the mentioned (geo) aids, students can interact with the model and get an idea about the given object or phenomenon. All this with the aim of a better understanding of a specific issue. It includes, for example, models whose subject matter is part of physical geography – a model of a volcano, a model of the internal structure of the Earth, a model of a karst cave, a model of a globe showing the distribution of land and landmasses, etc. From the field of social geography, we can illustrate specific administrative units or model different social surfaces. 3D models in the form of puzzles (puzzles of regions of the Czech Republic, European states, etc.) are especially attractive to younger children. With the help of the model, it is also possible to visualize a series of maps with a specific theme, which is represented, for example, by the cartogram method (see Cartogram).

It seems beneficial to create models illustrating certain dynamically changing phenomena and processes, for example, models of floodplains – floods, models of glacier movement, etc. 3D models are also used in teaching, which can make it easier for students to learn to correctly read contour lines, which are most commonly used to capture elevation on topographic maps. With the help of contour lines (their shape and density), it is possible to determine relief shapes. A large number of these models are available for download in Thingiverse databases.

### **3D Terrain models**

In the past, 3D relief and surface models could be used mainly for military purposes, navigation, or property management. Currently, they are widely used in architecture and typhlocartography and can be also used to visualize tourist or other attractive places (Brus and Barvř 2016).

Creating a 3D terrain model requires height data. Data for the territory of the Czech Republic are currently part of freely available databases. The ArcČR® 500<sup>26</sup> database contains a digital relief model that can be used to create a 3D model of the Czech Republic<sup>27</sup>. This web application offers downloads of European height data. The website of the American company “The United States Geological Survey<sup>28</sup>” provides available altitude data for the whole world. Unfortunately, there is currently no functional connection between the Geographical Information System (GIS) and 3D printing, meaning the production of high-quality 3D relief models requires specialized knowledge.

There are several tools that are user-friendly, free, and allow you to create your own 3D terrain model by using only a web browser. For example, the **Terrain2STL**<sup>29</sup> web application offers the possibility to use Google Maps for relief creation. We locate the relief that we want to model using latitude and longitude. After selecting the area of interest and defining the parameters, the resulting STL file can be simply downloaded. The other free app available is the **TouchTerrain**<sup>30</sup> application. In its left part is a map in which we select an area for 3D printing, and in its right part, there is a toolbar, which we use to set the parameters of the resulting model. This application is well-arranged and very user-friendly, so it only takes a few steps to set the parameters for 3D printing. In this application, we need to set up the following: elevation data source, transparency, tile width, nozzle diameter, tiles to print, model base thickness, and vertical exaggeration. **Application Map2stl**<sup>31</sup>, which deals with the creation of relief models, is similar to the above-mentioned.

Models created on a 3D printer have limitations given by the extent of the printing surface. It is possible to fold the individual parts (tiles) of the relief models after printing in order to assemble relatively large folded models (see Fig. 19). Complete terrain models can be found on Thingiverse.com. Downloaded models can be individually edited and supplemented, e.g., with compositional elements of the map and other descriptive information.

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26 <https://www.arcdata.cz/produkty/geograficka-data/arccr-4-0>

27 <https://www.mapsforeurope.org/access-data>

28 [https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-1-arc?qt-science\\_center\\_objects=0#qt-science\\_center\\_objects](https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-1-arc?qt-science_center_objects=0#qt-science_center_objects)

29 <https://jthatch.com/Terrain2STL/2021>

30 <https://touchterrain.geol.iastate.edu/>

31 <https://map2stl.com/>





Fig. 19: The digital model of the relief of the Czech Republic printed on a Prusa i3 3D printer. Model size 700 × 400 × 32 mm. Source: Brus and Barviř 2016

We can use 3D terrain models to solve several practical tasks. As an example of the use of 3D terrain models in a specific situation, let's mention raising awareness of landslides among residents in Peru<sup>32</sup>.

3D printing technology and its outcomes can also bring a whole range of new stimuli to geography lessons, whether it is about understanding the overall process of creating models, the basics of 3D modeling, or developing students' spatial imagination. We can arouse the interest of pupils and students in the issue of 3D printing and also give meaning to the created 3D models by connecting them with various geographical topics.

## Typhlomap

These teaching aids are referred to as tactile maps. People with visual impairments can primarily use these maps. Typhlomap is a map base that conveys information to the user by touching it. People with vision loss have opportunity to create an idea of the surrounding world, of a specific area or place. Typhlomap can be practically used not only as a teaching aid for the blind but also as an aid for better orientation in space/terrain. Tactile maps can reflect a dual way of representing information. The first of the ways is to illustrate the height of the mountain range by using the different heights of individual areas, i.e., without using Braille. The second option is to demonstrate the phenomenon

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32 <https://3dprint.com/126631/3d-printing-landslide-maps/>

on the map through the Braille font. Working with printed models can thus bring visually impaired pupils, or students, completely new experiences and understanding of the world around us.

### 3 | 3 | 4 Educational field: Natural Sciences

In primary schools, biology is taught together with geology within the field of **Natural Sciences**. Together with Geography, Physics, and Chemistry, they form the educational area of **Humans and Nature**.

In secondary schools, such as gymnasiums, biological subjects are taught within **Biology**, which also falls under the educational field of **Man and Nature**. Compared to basic education, there is a separate educational field of Geology. This educational area consists of five educational fields: Biology, Geography, Geology, Chemistry, and Physics.

#### Natural Sciences in primary school

The curriculum of the educational field of Natural Sciences is divided into eight **thematic areas**: General Biology and Genetics, Fungal Biology, Plant Biology, Animal Biology, Human Biology, Inanimate Nature and Fundamentals of Ecology (RVP ZV 2021). By going through their expected outcomes, we will not find any mention of the implementation of 3D printing technology in education.

The emphasis lies on the educational content (curriculum and expected outcomes), not on how to achieve these outcomes. However, it is certainly possible to incorporate 3D printing technology into teaching, e.g., by producing models that illustrate selected natural phenomena. The models could be applied especially in the curriculum passages devoted to the internal and external structures of organisms and their reproduction (e.g., illustrating developmental stages). Depending on the specific printed models, it would then be possible to fulfill, for example, the following expected outcomes related to the structure of organisms:

- Pupils will recognize the best-known edible and poisonous mushrooms, including fruiting bodies, and compare their characteristic features.
- Pupils will on the basis of observations, infer the organization of a plant's body from cells and tissues to individual organs.
- Pupils will compare the basic internal and external structure of selected animals and explain the functioning of individual organs.
- Pupils will identify the location, structure and function of organs and organ systems of the human body and explain their relationships.

## Biology at grammar school

In RVP G, the curriculum of the educational field of Biology is divided into ten **thematic areas**: General Biology, Viral Biology, Bacterial Biology, Protist Biology, Fungal Biology, Plant Biology, Animal Biology, Human Biology, Genetics and Ecology (RVP G 2021). Similarly to the Natural Sciences curriculum, 3D printing technology is not mentioned in the expected outcomes here either. Even here, however, it is possible to create 3D models that would be used to represent typical structures, especially structures of organisms, but also their developmental stages.

This way, it is possible to use tools printed with 3D printing technology in all ten thematic areas. Due to the expected outcomes listed in RVP G, the potential applicability of models produced by 3D printing technology in some of the thematic areas is, at first glance, more apparent than in others.

For example, in the thematic area of General Biology, it is clearly stated that the pupil shall “[...] explain the arrangement and function of the structural components and life manifestations of prokaryotic and eukaryotic cells [...]”, which makes the use of illustrative demonstration aids such as models obvious. On the other hand, the expected outcome of the thematic area of Genetics “[...] the pupil shall use his/her knowledge of genetic principles to understand the diversity of organisms [...]”, the need for visualization of DNA and chromosome structure, and therefore also the potential use of a 3D model, can only be inferred from the context. Below, there are expected outcomes with an obvious connection to the visual demonstration device:

- The pupil shall explain the arrangement and function of the structural components and life manifestations of prokaryotic and eukaryotic cells.
- The pupil shall recognise and name (relying on various information sources if necessary) significant representatives of fungi and lichens.
- The pupil shall describe the plant-body structure and the structure and function of plant organs.
- The pupil shall elucidate the principle of life cycles and how plants reproduce.

## 3D models in the teaching of Natural sciences and Biology

Altmann (1971), among others, dealt with using 3D models in teaching Natural sciences. Teaching models replace products of nature, especially in the following cases:

**As a substitute for microorganisms** that students can only observe under a microscope. Students might develop distorted ideas because they cannot see the third dimension of the observed structures during microscopy. Below, there are some examples of models that fall into this category:

- **Cell models** (plant × animal; eukaryotic × prokaryotic) with an emphasis on their differences, internal structure, and functions. The model can take the form of a kit from which the cell can be assembled.

- **Models of cell organelles and other cellular compartments** such as mitochondria, chloroplasts, nucleus, DNA double helix, etc. These models can also be disassembled in a way that makes it possible to describe important structures and explain their function.
- **Models of plant and animal tissues and organs** (e.g., the structure of the leaf, stem, etc.). These models are more complex as they consist of shape- and functionally-specialized cells. It is offering to use a foldable model in this case as well.
- **Microscopic algae model** are especially needed to demonstrate brown algae, which are the most represented taxonomic group of algae in our nature but are often neglected in teaching. Algae models could also be used in laboratory exercises focused on the microscopic observation of green and brown algae. Students could also compare the algae under the microscope with the algae model.
- **Models of crystal systems and crystals** would find application in the teaching of the geological curriculum. They could help students understand the basic principles of crystallography.
- **Models of invertebrate animals or parts of their bodies** could be used wherever it is impossible to obtain and observe real natural ones. Their unavailability, protection, or fragility makes it impossible to use them directly.

**As a substitute for large structures and organisms** that the teacher cannot bring to the classroom. These include, for example:

- **Models of geological structures** (volcanoes, folds, ridges, ditches, etc.)
- **Models of large vertebrates or their parts** (e.g., mammoth model, whale skeleton model, etc.)
- **Natural products that are difficult to obtain.** These include organisms that either do not occur in the Czech Republic because they are protected or endangered or because of ethical restrictions (e.g., human organs). They could find application in the teaching of Natural Science and Biology, for example:
- **Models of skulls or other parts of skeletons of fossil representatives.** For the teaching of anthropology, it is of great importance to show the differences in the brain capacity of the ancestors of anatomically modern humans (Ardipithecus, Australopithecus, *Homo habilis*, *H. ergaster*, *H. erectus*, etc.).
- **Models of skulls illustrating the closest recent relatives of man** (i.e., gorilla, chimpanzee, orangutan).
- **Models of skulls, possibly also complete skeletons** illustrating individual classes of vertebrates.
- **Models of representatives of reptiles, amphibians, and fish.** Reptiles and amphibians are protected animals, and some are also poisonous. At the same time, it is allowed to make stuffed animals from these vertebrates.
- **Models of human body organs** can illustrate the structure of organs or organ systems (e.g., heart model, stomach model, liver, etc.) or their function (so-called functional 3D models). Functional 3D models include, for example, a model of blood circulation,

a model of the excretory tract, a model of the female pelvis and a human fetus (to explain the mechanism of childbirth on it), a model of the spine with a herniated disc for teaching prevention, a model of a newborn with FAS (fetal alcohol syndrome) for teaching prevention or a model of a lower or upper limb with an injury for teaching first aid in case of accidents.

**As a substitute for natural products that are not available all year round.**

These natural products are available during a limited part of the year, or they occur in nature during the time when classes are not taking place. If the teacher wants to show them, he has to preserve them. These typically involve fungi or some plants or their parts (e.g., reproductive organs).

- **Models of fungal fruiting bodies** have the advantage that they are not limited to a season, and it is possible to demonstrate species that do not occur in nature at the same time
- **Models of individual developmental stages of plants and animals.** Typically, these involve individual developmental stages of complete and incomplete metamorphosis of insects or models illustrating reproduction in plants (e.g., bryophyte or horsetail reproduction).

## Designs of models for the educational content of the field of Natural Sciences

### General Biology and Genetics

- a model of a prokaryotic cell (bacteria, cyanobacteria) and eukaryotic cell, both linked to the topic of unicellular organisms (e.g., altogether with cells of euglena, diatom, amoeba, bacteria)

There is, for example, a multi-layered interactive animal cell model on which the student will learn to recognize the individual parts of an animal cell, their functions, and how they are related to each other. The teacher can continue to work with the cell model in different ways with different time allocations in the lesson.

- viruses (e.g., influenza virus, coronavirus, HIV)
- protein and DNA structure model (DNA sequence, non-coding strand, RNA, protein)

A variety of DNA models are available on which students can discuss the structure of the DNA molecule and its specific properties (sequence and pairing of nitrogenous bases) that allow the molecule to carry and transmit information related to the inheritance of traits. These types of nucleic acid and whole chromosome models help students understand that chromosomes are structures in the nucleus of a cell that carry genes and that genes are smaller units of DNA that contain the genetic code of heredity. Using models, students can describe the structure of a molecule and explain the rules

of base pairing. Students will understand that information is stored in a DNA molecule in the form of a sequence of chemical bases, each labeled with the first letter of its name (A, T, C, and G).

### **Fungal Biology**

- fungi models (the exhibition of real mushrooms lasts only a few days, 3D models are durable; it is possible to model both mushrooms without fruiting bodies and with fruiting bodies, which corresponds to the RVP ZV curriculum)

### **Plant Biology**

- models of different types of stomata (textbooks usually show only the gramineous type, others are missing) and models of different types of vascular bundles – these are structures that are not visible to the naked eye and are more difficult for students to imagine

### **Animal Biology**

- within this area of biology, it is possible to create complete animal models (a number of them are freely available and already made) or only some parts of animal bodies for a better understanding of the shape and function of organs
- complete and incomplete metamorphosis – models of individual developmental stages to compare these two types of metamorphosis

For example, the frog dissection model is freely available. Actual autopsies at elementary schools are problematic and often prohibited due to animals' protection from abuse or their unavailability in large numbers. By dissecting a 3D model, students will learn about animal anatomy, the location of individual organs, and their spatial relationships.

### **Human Biology**

- several modeled organs of the human body are available (skull, skeleton, stomach, heart, hearing-equilibrium system, lungs, etc.) Although commercial models of these organs are usually available on the market, the cost of their acquisition is high; in addition, even microscopic parts that cannot be seen with the naked eye can be modeled; these models make it easier for students to understand the function of a structure in the body, e.g., nerve synapse models

## Inanimate Nature

- crystal models of individual minerals illustrating the system in which they crystallize

In accordance with these competencies, it is necessary to familiarize students with the possibility of using 3D printers in bioprinting within the natural sciences. Three-dimensional (3D) bioprinting uses techniques similar to 3D printing to combine cells, growth factors, and biomaterials to fabricate biomedical parts, often to imitate natural tissue properties. With this technology, various prostheses of limbs, noses, ears, eyes, etc., can be produced at a very favorable price, but their hand-made production is quite expensive. In the SkinPrint project, the possibility of bioprinting skin using stem cells, which are directly part of the 3D printer, is being tested. All around the world, hearing aids and bone replacements (skull, pelvis, etc.) with a layer supporting the growth of surrounding tissues are commonly printed all around the world. Some companies are also working on developing prints of various human organs that could be used in a patient's body in case of failure.

### 3 | 4 EDUCATIONAL LESSONS ON BE3D ACADEMY

This methodology is part of the so-called “starter package” for schools. The package contains publicly accessible sets of lessons customized for schools. These lessons are ready to be incorporated into teaching without excessive time demands on the teacher or necessary changes in the teaching concept. Some of these lessons build a greater curriculum connection by connecting several subjects within one lesson.

In addition, verified teaching aids and models are also available as additional support material for teachers and pupils. Apart from that, other publicly available models underwent testing from the point of view of their usability in teaching. Selected recommended models suitable for use can be found in Appendix 6.2.

All lessons that were designed, processed, and tested within the “3D printing and its application in primary and secondary schools” project (TAČR, TL03000425) are listed on the Be3D Academy portal<sup>33</sup> and marked with a logo created in cooperation with Masaryk University (see Fig. 20). The individual lessons are presented in more detail below.

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33 <https://be3dacademy.ysoft.com/cs/>



Fig. 20: Logo indicating this lesson was created in cooperation with Masaryk University

Experts in natural sciences, information technology, and didactics participated in creating the lessons. The lessons are designed so that an ordinary user interested in 3D printing can work with them. However, they are also to be used in the relevant subjects at primary and secondary schools. The lessons are always created in accordance with specific educational content.

All lessons have a uniform structure. The proposed structure should make it easier for teachers to prepare for teaching and be methodical support in facilitating the printing of the given model (e.g., instructional videos, detailed printing instructions, etc.). Individual lessons have two levels of access on the “Be3D Academy” portal. An ordinary (unregistered) user can familiarize himself with the basic structure of the lesson (see Fig. 21).





## TOPOGRAPHY

Topography refers to the shape, height, and depth of the land surface in a place or region. Physical features that make up the topography of an area include mountains, hills, valleys, gorges, etc. In this lesson, pupils will design and print a 3D relief model for a chosen natural landscape.

**Subjects** | Design and Technology | Science | Geography | Computing | Mathematics | Masaryk University  
**Years** | 7th Grade | 11-12 years | 8th Grade | 12-13 years | 9th Grade | 13-14 years  
**Duration** | Lesson 1: 90 minutes | Print Time: 0.5-2 hours

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## TOPOGRAPHY TRAILER

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### OBJECTIVES

- Use a map to explain the relief of an area.
- Create a 3D representation of their relief.
  - convex hill, plateau, mountain ridge, saddle, terrace.
  - concave conditions: valley, depression, gorge, basin, abyss.
- Determine other characteristics of their terrain: ridge, valley, slope, foot, slope ridge.

### TOOLS AND EQUIPMENT

- Be3D E3DE Printer.
- Set of example models.
- Access to a computer that can access the Internet and TrinkerCAD.
- Paper and pencil.
- Printed lesson resources.
- Pictures of contour diagrams of relief shapes (See presentation).
- Shapefinder / topographic maps (at a scale of 1:50,000).
- ShapeSchematic images of relief shapes (See presentation).

### SKILL REQUIREMENTS

- To participate in the lesson, students should be able to:
- Use TrinkerCAD, Fusion 360 or similar CAD software at an intermediate level.
  - Comfortably use CorelDraw software, including adjusting print settings.
  - Use the Be3D E3DE 3D printer.

Fig. 21: Example of the lesson structure listed on the Be3D Academy portal

- brief annotation
- specific subjects and grades in which the lesson can be used
- learning objectives that determine what the student should be able to do after completing the given lesson
- time requirement of the lesson
- tool and equipment requirements
- knowledge, skills and abilities that students should have before they start working on the lesson (so-called initial knowledge and skills)

- an overview of the models with photos, with the time requirement of the printing and the amount of material consumed
- video demonstration and instructional video

More detailed materials needed for the implementation of the lesson are available for download only to registered users of the portal. However, registration is completely free for teachers. After registration, a set of documents will be made available. It contains:

- compliance with RVP
- step-by-step instructions on how to create a model in a modeling software/application
- worksheets for pupils
- accompanying presentation with the content of the lesson
- detailed instructions for printing and setting up the printer

There are two recommended variants of using the lessons. The easier option is intended for those who do not know printing technology yet or for those who are just getting started with it. They can use pre-modeled components that they only print out using the appropriate application and use them as an aid for their lesson. In a second, more complex variant, students model the individual components in the suitable software/application and then print the entire model.

## Presenting teaching lessons:

### Under the microscope:

In this lesson (see Fig. 22), pupils will learn about the classification of bacteria, as well as the effects of a range of good and bad bacteria and pathogens. Students will then be asked to observe and analyze the *Streptococcus lactis* bacteria under a microscope before reproducing them as a 3D printing model. The objectives of the entire lesson are primarily to design a bacterial model, demonstrate how to align objects, employ tolerances and offsets, understand and execute the boolean operation in CAD, understand and practice bacterial modeling, correctly identify and classify bacteria, and define the meaning of the word pathogenic.

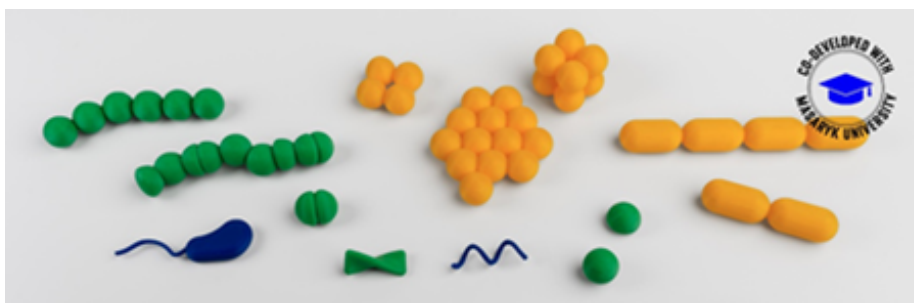


Fig. 22: Educational lesson Under the microscope

## Stereometry

Stereometry is a branch of mathematics dealing with the study of three-dimensional bodies and the relationships between them. When a plane intersects a cube, several types of polygons can result. In this lesson, pupils will learn how to construct a cube section in free parallel projection before creating the resulting polygon (cube section) in CAD software. The objectives of this lesson are to construct a cube cut in a free parallel projection, construct a section polygon in its actual size, check the result on the 3D model by selecting the correct polygon, construct the result using TinkerCAD software, and print a 3D model of the cube (see Fig. 23).



Fig. 23: Educational lesson, Stereometry

## Cartogram

A cartogram is a map. But it is a unique type of map because it combines statistical information with geographic location. In this lesson, pupils will design and print a 3D cartogram model using statistical data sourced from the Internet (see Fig. 24). After printing the 3D cartogram model, students assemble and complete the other elements of the map (heading, legend, scale, etc.). The aim of the lesson suitable for elementary school geography is primarily to create a model of administrative units (regions, states), where it uses the Z-coordinate (height) to show the chosen topic (e.g., unemployment, population density, urbanization rate, average wage, GDP...).

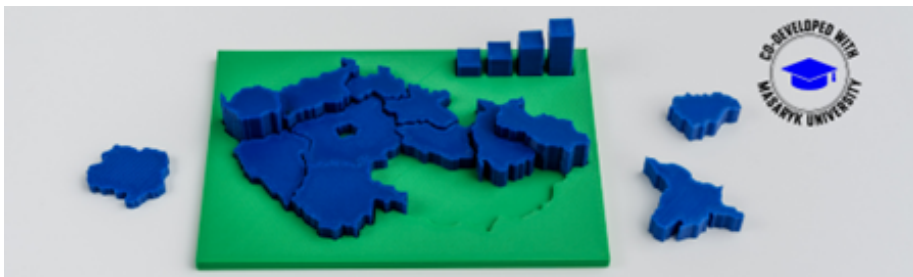


Fig. 24: Educational lesson Cartogram

## Orthographic projection

Educational lesson orthographic projection is suitable for technical education. In this lesson, your pupil's challenge is to create a technical drawing that measures up to professional standards. They will start by designing a 3D model of their choice and then 3D printing it as an object. They will then use a corner projection station to produce three 1st angle orthographic projections of their object (see Fig. 25). Finally, they will use these projections to produce a detailed technical drawing of their object. The objectives of this lesson are to understand and demonstrate the process of creating technical documentation, to design and sketch a target object, to create an accurate 3D model of the object (basic geometric bodies, prisms, rotating bodies), to 3D print the modeled object, and to create a triple elevation technical drawing of the 3D printed object using 1st angle orthographic projection views.

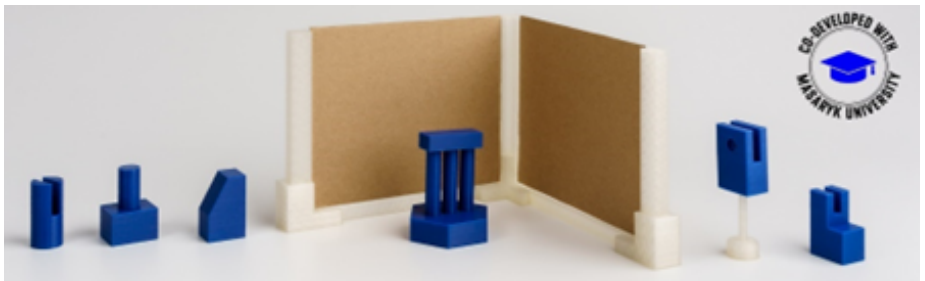


Fig. 25: Educational lesson Orthographic projection

## Braille cube

In this lesson, pupils will be challenged to design and print a braille cube. To start, they will learn about braille, its history and origin and how it is used today. They will then design the 3D model and print it (see Fig. 26). Using their model, they will create letters to challenge their friends and to write their first name.

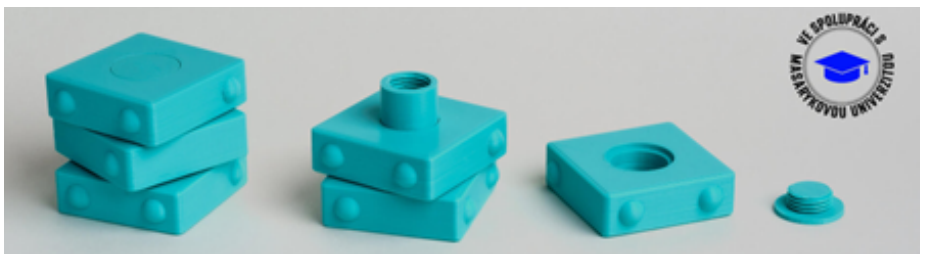


Fig. 26: Educational lesson Braille cube

## Units of a cube

In geometry, cubic units can be defined as the units used to measure volume. In this lesson, pupils will learn how to calculate the volume and area of a variety of complex 4x 4 x 4 rectangular prisms before modelling the missing parts of each rectangular prism in Tinkercad (see Fig. 27).

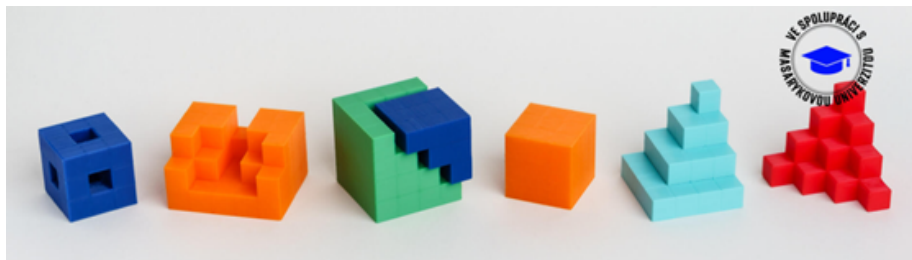


Fig. 27: Educational lesson Units of a cube

## Promethean processing

In part one of this lesson, pupils will learn about Promethean thinking and the four-step problem-solving cycle. They will then be challenged to model a standard six-sided die, before breaking it down into nine cuboid components. In part two of the lesson, they will be challenged to reassemble their die from its components, firstly on instinct, and secondly by following the problem-solving cycle. Once they have successfully reassembled their own die, it's time to swap with their classmates and see who is the quickest in the class (see Fig. 28).

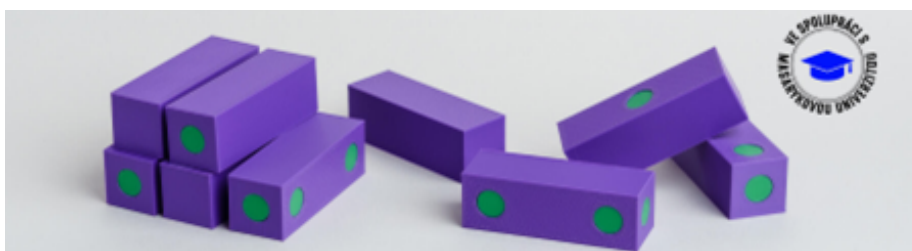


Fig. 28: Educational lesson Promethean processing

## Topography

Topography refers to the shape, height, and depth of the land surface in a place or region. The shape (appearance) of the earth's surface is called relief. In a topographic/tourist map, contour lines are most often used to capture the shape of the earth's surface. Contour lines connect places of the same elevation. Physical features that make up the topography of an area include mountains, hills, saddles, valleys, gorges, etc. In this lesson, pupils will design and print a 3D relief model for a chosen natural landscape (see Fig. 29).



Fig. 29: Educational lesson Topography

3D printing technology is currently a preferred manufacturing technology. We find its usefulness not only in practice but also in the field of education. This methodology tries to bring basic information about the possibilities of applying 3D printing to primary and secondary schools. To get the most out of 3D printing, you need to understand the basics of how 3D printing works. It is very important to understand which printer to choose and how to place it, what the printer operation entails, and how the printing process works. Maintaining the printer and solving common problems are no less important. Working with a 3D printer needs to be taken from a broader point of view. In addition to the technical solution, you should even consider the educational aspects. Among the benefits of 3D printing is the support of visualization, the individualization of teaching, and the support of student creativity in primary or secondary schools. Most students find working with 3D printing interesting. However, 3D printing needs to be appropriately integrated into the school curriculum. This methodology shows how to grasp and implement this technology in selected fields - Informatics, Humans and the Worlds of Work, Mathematics and Its Application, Geography, and Natural Sciences. Similarly, 3D printing can be implemented in other areas of education, such as physics, chemistry, foreign languages, and many others. The methodology does not aim to cover all areas of human activity and education but to show how to grasp 3D printing in selected fields from a didactic point of view.

3D printing can help teachers to create teaching aids but also provide a gateway to contemporary advanced technologies. Pupils' focus on new technologies can support their orientation towards choosing a career in technical, natural science, and IT fields. There is an expected massive boom in advanced technologies, including 3D printing.

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## 6 | 1 List of created educational lessons

Currently available lessons:

Braille cube	<a href="https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_braille-cube">https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_braille-cube</a>
Units of a cube	<a href="https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_units-of-a-cube">https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_units-of-a-cube</a>
Promethean processing	<a href="https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_promethean-processing">https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_promethean-processing</a>
Topography	<a href="https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_topography">https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_topography</a>
Under the microscope	<a href="https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_under-the-microscope">https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_under-the-microscope</a>
Stereometry	<a href="https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_stereometry">https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_stereometry</a>
Cartogram	<a href="https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_cartogram">https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_cartogram</a>
Orthographic projection	<a href="https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_orthographic-projection">https://be3dacademy.ysoft.com/cs/3d-lesson-plans/mu_orthographic-projection</a>

## 6 | 2 List of applicable models for individual subjects

### 6 | 2 | 1 Overview of available 3D models and educational lessons in the field of Humans and the World of Work

TITLE	LINK
Arduino Nano V3 case	<a href="https://www.thingiverse.com/thing:608121">https://www.thingiverse.com/thing:608121</a>
Sleeve case for Raspberry pi	<a href="https://www.thingiverse.com/thing:604915">https://www.thingiverse.com/thing:604915</a>
Ozobot Bit, side slung pen holder	<a href="https://www.thingiverse.com/thing:3317899">https://www.thingiverse.com/thing:3317899</a>
QR code	<a href="https://be3dacademy.ysoft.com/cs/3d-lesson-plans/qr-code">https://be3dacademy.ysoft.com/cs/3d-lesson-plans/qr-code</a>
Tesla valve	<a href="https://be3dacademy.ysoft.com/cs/3d-lesson-plans/tesla-valve">https://be3dacademy.ysoft.com/cs/3d-lesson-plans/tesla-valve</a>
Credit card kits	<a href="https://be3dacademy.ysoft.com/cs/lekce-3d-tisku/plastikovy-model-v-ramecku">https://be3dacademy.ysoft.com/cs/lekce-3d-tisku/plastikovy-model-v-ramecku</a>
Maze	<a href="https://www.thingiverse.com/thing:2594440">https://www.thingiverse.com/thing:2594440</a>
Fable passive joint angle	<a href="https://www.thingiverse.com/thing:2828382">https://www.thingiverse.com/thing:2828382</a>
Desktop vise	<a href="https://www.thingiverse.com/thing:2702273">https://www.thingiverse.com/thing:2702273</a>
Fractals	<a href="https://www.thingiverse.com/thing:4904044">https://www.thingiverse.com/thing:4904044</a>

## 6 | 2 | 2 Overview of available 3D models and educational lessons in the field of Mathematics and Its Application

TITLE	THEME	LINK
Platonic solid in Euclidean geometry	Geometric figures	<a href="https://www.thingiverse.com/thing:37797">https://www.thingiverse.com/thing:37797</a>
Conic sections	Trigonometric functions	<a href="https://www.thingiverse.com/thing:1260776">https://www.thingiverse.com/thing:1260776</a>
Gearing up	Circles	<a href="https://be3dacademysoft.com/cs/lekce-3d-tisku/ozubena-kola">https://be3dacademysoft.com/cs/lekce-3d-tisku/ozubena-kola</a>
Puzzle box		<a href="https://be3dacademysoft.com/cs/3d-lesson-plans/puzzle-box">https://be3dacademysoft.com/cs/3d-lesson-plans/puzzle-box</a>
Geometric shapes	Polygons, Polyhedrons	<a href="https://be3dacademysoft.com/cs/lekce-3d-tisku/geometricka-stavebnice">https://be3dacademysoft.com/cs/lekce-3d-tisku/geometricka-stavebnice</a>
Pythagorean theorem	Relation in Euclidean geometry	<a href="https://www.thingiverse.com/thing:245202">https://www.thingiverse.com/thing:245202</a>

## 6 | 2 | 3 Overview of available 3D models and educational lessons in the field of Geography

TITLE	THEME	LINK
Stone Landmarks, Buildings and Structures	Population	<a href="https://www.thingiverse.com/thing:2240259">https://www.thingiverse.com/thing:2240259</a>
Erosion	Environment	<a href="https://www.thingiverse.com/thing:2709566">https://www.thingiverse.com/thing:2709566</a>
Layers of the Earth	Earth and universe	<a href="https://www.thingiverse.com/thing:1717364">https://www.thingiverse.com/thing:1717364</a>
Microscop	Geology, pedogeography	<a href="https://www.thingiverse.com/thing:3783857">https://www.thingiverse.com/thing:3783857</a>
Volcanos	Geology	<a href="https://be3dacademysoft.com/cs/3d-model-database/volcanos">https://be3dacademysoft.com/cs/3d-model-database/volcanos</a>
Landforms	Geomorfology	<a href="https://www.thingiverse.com/thing:1277448">https://www.thingiverse.com/thing:1277448</a>
Pyramids	Population	<a href="https://www.thingiverse.com/thing:306097">https://www.thingiverse.com/thing:306097</a>
Model of the Earth	Earth and universe	<a href="https://be3dacademysoft.com/cs/3d-model-database/a-model-of-the-earth">https://be3dacademysoft.com/cs/3d-model-database/a-model-of-the-earth</a>
Scafell pike – a mountain	Relief	<a href="https://www.thingiverse.com/thing:524153">https://www.thingiverse.com/thing:524153</a>
Solar system	Earth and universe	<a href="https://be3dacademysoft.com/cs/3d-model-database/the-solar-system">https://be3dacademysoft.com/cs/3d-model-database/the-solar-system</a>
Inside Earth	Earth and universe	<a href="https://www.thingiverse.com/thing:1178717">https://www.thingiverse.com/thing:1178717</a>
Snowdonia topographic model	Relief	<a href="https://www.thingiverse.com/thing:558561/comments">https://www.thingiverse.com/thing:558561/comments</a>
Map of europe puzzle	Population	<a href="https://be3dacademysoft.com/cs/3d-model-database/map-of-europe-puzzle">https://be3dacademysoft.com/cs/3d-model-database/map-of-europe-puzzle</a>
Galdhoppigen	Relief, land surface	<a href="https://www.printables.com/cs/model/22115-galdhoppigen">https://www.printables.com/cs/model/22115-galdhoppigen</a>
Comparison of mountain elevations in the world	Relief, land surface	<a href="https://www.printables.com/cs/model/22113-the-eight-thousanders">https://www.printables.com/cs/model/22113-the-eight-thousanders</a>
Meteor crater	Earth and universe	<a href="https://www.printables.com/cs/model/19850-meteor-crater">https://www.printables.com/cs/model/19850-meteor-crater</a>
Trollveggen	Relief, land surface	<a href="https://www.printables.com/cs/model/22116-trollveggen-troll-wall">https://www.printables.com/cs/model/22116-trollveggen-troll-wall</a>
Sedan crater	Earth and universe	<a href="https://www.printables.com/cs/model/19849-sedan-crater">https://www.printables.com/cs/model/19849-sedan-crater</a>

TITLE	THEME	LINK
A house made to withstand a tsunami	Geology, lithospheric plate movement	<a href="https://www.printables.com/cs/model/21377-tsunami-pod">https://www.printables.com/cs/model/21377-tsunami-pod</a>
Danube bend	Relief, land surface	<a href="https://www.printables.com/cs/model/14929-topographic-3d-map-danube-bend-dunakanyar">https://www.printables.com/cs/model/14929-topographic-3d-map-danube-bend-dunakanyar</a>

## 6 | 2 | 4 Overview of available 3D models and educational lessons in the field of Natural Sciences

TITLE	THEME	LINK
Animal cell	Cell biology	<a href="https://be3dacademyysoft.com/cs/3d-model-database/model-zivocisne-bunky">https://be3dacademyysoft.com/cs/3d-model-database/model-zivocisne-bunky</a>
Plant cell	Cell biology	<a href="https://be3dacademyysoft.com/cs/3d-model-database/multi-color-mini-plant-cell">https://be3dacademyysoft.com/cs/3d-model-database/multi-color-mini-plant-cell</a>
Chloroplast	Cell biology	<a href="https://be3dacademyysoft.com/cs/3d-model-database/model-chloroplastu">https://be3dacademyysoft.com/cs/3d-model-database/model-chloroplastu</a>
Chromosomes	General Biology and Genetics	<a href="https://be3dacademyysoft.com/cs/3d-model-database/chromosomes">https://be3dacademyysoft.com/cs/3d-model-database/chromosomes</a>
Blood cells	Tissues and binders	<a href="https://www.cgtrader.com/free-3d-print-models/science/biology/printable-models-for-blood-cells-a48981d6cb2487a9b197920075a6a5c3">https://www.cgtrader.com/free-3d-print-models/science/biology/printable-models-for-blood-cells-a48981d6cb2487a9b197920075a6a5c3</a>
Blood capillary and red blood cells	Circulatory system	<a href="https://be3dacademyysoft.com/cs/3d-model-database/blood-capillary">https://be3dacademyysoft.com/cs/3d-model-database/blood-capillary</a>
Ovary	Reproductive system	<a href="https://be3dacademyysoft.com/cs/3d-model-database/ovary">https://be3dacademyysoft.com/cs/3d-model-database/ovary</a>
Plasma membrane	Cell biology	<a href="https://be3dacademyysoft.com/cs/3d-model-database/model-biomembrany">https://be3dacademyysoft.com/cs/3d-model-database/model-biomembrany</a>
Rhesus macaque skull and brain	Vertebrate zoology	<a href="https://be3dacademyysoft.com/cs/3d-model-database/model-lebky-a-mozku-makaka-rhesus">https://be3dacademyysoft.com/cs/3d-model-database/model-lebky-a-mozku-makaka-rhesus</a>
Polar bear skull	Vertebrate zoology	<a href="https://be3dacademyysoft.com/cs/3d-model-database/polar-bear-skull">https://be3dacademyysoft.com/cs/3d-model-database/polar-bear-skull</a>
DNA double helix	General Biology and Genetics	<a href="https://be3dacademyysoft.com/cs/3d-model-database/model-dvousroubovice-dna">https://be3dacademyysoft.com/cs/3d-model-database/model-dvousroubovice-dna</a>
Hive for solitary bees	Pollinators	<a href="https://be3dacademyysoft.com/cs/3d-model-database/ul-provcely-samotarky">https://be3dacademyysoft.com/cs/3d-model-database/ul-provcely-samotarky</a>
Prokaryotic cell (bacteria)	Unicellular organisms	<a href="https://be3dacademyysoft.com/cs/3d-model-database/model-prokaryotni-bunky-gram-negativni-bakterie">https://be3dacademyysoft.com/cs/3d-model-database/model-prokaryotni-bunky-gram-negativni-bakterie</a>

## 6 | 3 Glossary of terms

**PLA, PET-G, ABS/ASA** – printing materials/filaments

**Filament** – printing material used in FFF/FDM 3D printers

**Slicing** – cutting/slicing the selected model into individual layers, which are then printed

**Slicer** – application that slices the model into individual layers

**Layer height** – determines how high one layer of the final print will be and significantly affects the quality and printing time

**Perimeters (shell thickness)** – defines the thickness (number of layers) of the side walls.

**Top & Bottom Layers** – determine the thickness (number of layers) of the top and bottom of the 3D object.

**Printing Infill (Infill Density)** – a percentage value that determines the fill ratio of the object. In addition, the infill pattern can also be set. The infill pattern is the structure and shape of the material inside the object. Infill patterns can affect the strength, weight (material consumption), print time, and even the flexibility of the object. Slicers offer a choice from simple lines to more complex geometric shapes. For basic printing, the default settings are sufficient (see Fig. 5).

**Temperature** – setting the temperature of the print head and the print bed. We recommend using slicer profiles with preset temperatures for different materials. In the case of self-adjustment of the temperature, follow the instructions of the manufacturer of the materials.

**Brim** – determines the width of the brim that will be printed in the first layer around the object. Brim is always directly connected to the first layer of the object. It increases adhesion to the substrate and breaks away from the object after printing.

**Skirt** – determines the height and the separation distance between the skirt and the object. It is printed first and in several layers around the first layer of the object. It enables checking adherence of the model to the print bed.

**Raft** – works by printing extra layers on which the object is to be printed. It provides excellent first-layer adhesion for any model as the print material best adheres to itself. It is used mainly for ABS/ASA material to prevent the print from curling.

**Supports** – various settings for generating supports, especially the shape of the supports, the filling ratio, or the distance of the support between each of the axes.

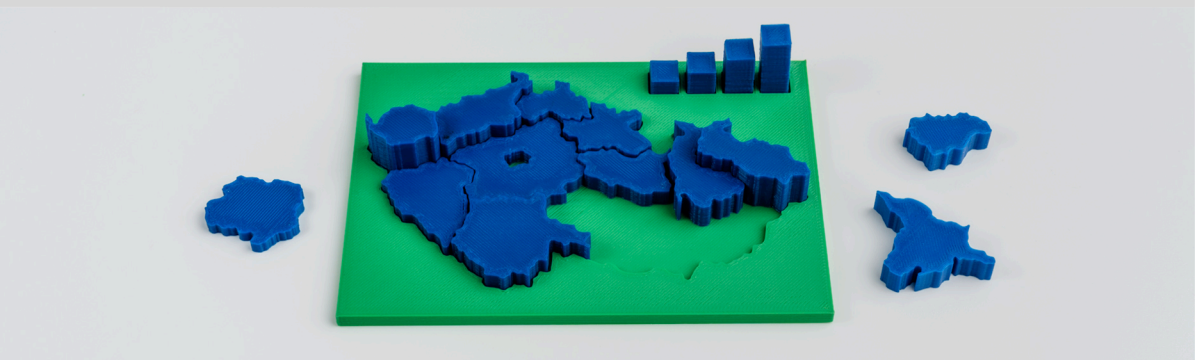
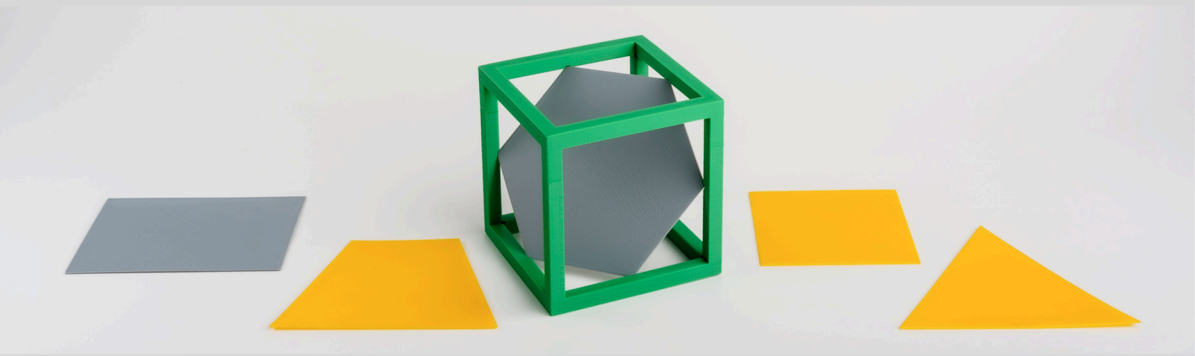
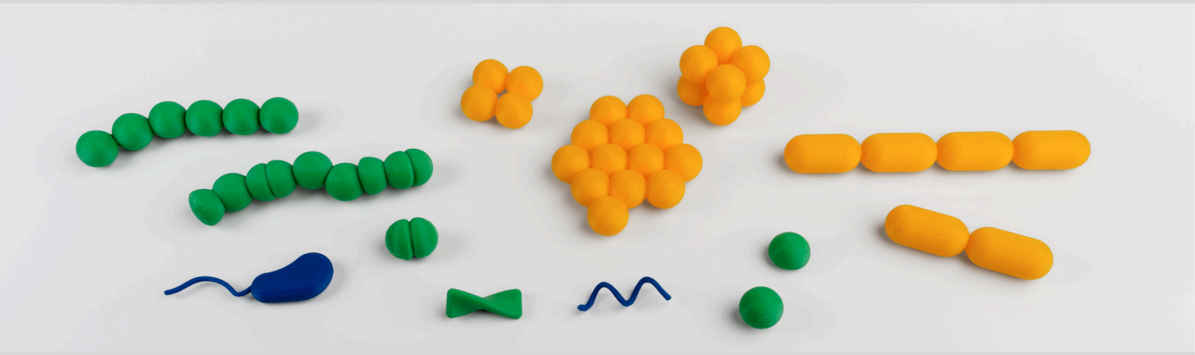
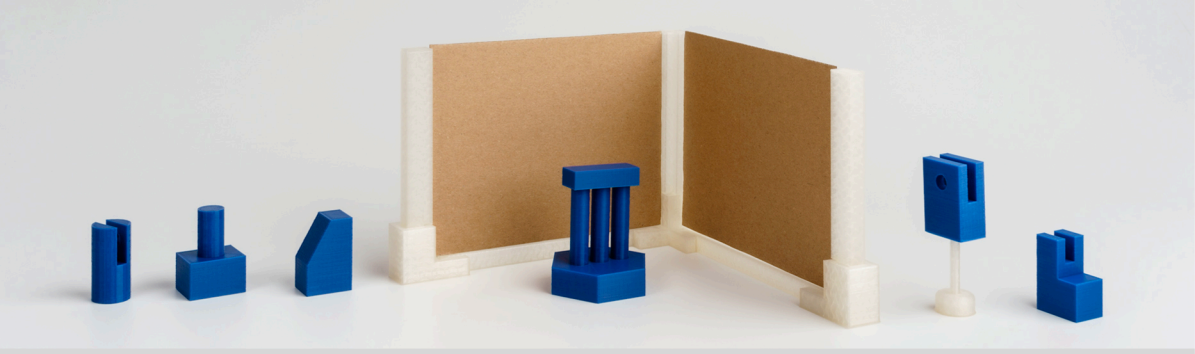
# **IMPLEMENTATION OF 3D PRINTING TECHNOLOGY INTO PRIMARY AND SECONDARY SCHOOL EDUCATION**

## **Verified Methodology**

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