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Formation en informatique destinée aux enseignant·e·s au gymnase

Revealing Programming Language Abstractions

An Excerpt of nand-to-tetris – in Reverse – Using Smalltalk

GymInf Individual Project

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Abstract

This thesis develops an empirically validated tool for programming classes at high school level which allows students to experience and explore interactively various abstraction layers involved in running a program.

Didactic literature suggests that exploring different abstraction layers (called *Sichtenwechsel*) improves students' understanding of both programming and the inner workings of a computer system. Such multi-layered exploration is even considered a foundational idea of computer science and has to be taught, among others because many lower abstraction layers tend to leak through interfaces anyways.

On the basis of the Smalltalk environment "Glamorous Toolkit", an interpreter for the Processing programming language in its Python form was developed and molded with many different views: Tokenization, syntax tree building, transpilation of Processing into Smalltalk, translation to an intermediary language and eventually into Smalltalk bytecode and finally the program's actual output. These views are tied to source code and updated live for seamless exploration and can be composed in interactive teaching material.

This product has been used for various lessons for which both plans and a brief evaluation is included. The evaluation shows on very limited data that the live environment does encourage experimentation and allows for students to work at their own speed and depth, allowing them to profit at their pace. Understanding of the various layers has however not improved significantly in the short period of time the tool could be tested.[1]

[1] A typographical note:

☲ Text prepended by this symbol is a temporary note for the author.

Contents

1 Introduction

In modern digitized society, the importance of computer science has grown to the point where some of its subjects are taught at schools of all levels. Whereas elementary schools focus on introducing digital, connected devices and their applications, high schools also teach fundamentals. And while programming or application use courses have been implemented since decades ago, broader and more theoretical courses have recently become standard. E. g. in Switzerland, computer science has become an obligatory subject for all high school students similar to more traditional sciences starting in 2019.

The curricula used usually contain introductions not only to algorithms and programming, but among others also into encodings, computer architecture, networking and social ramifications such as privacy and security (see e. g. [13]). As such, students not only are taught a high level programming language such as Python, but should also have insights into what happens at various other abstraction layers when such a program is stored and run.

One traditional approach to this consists in teaching a separate assembly-like language during the introduction to computer architecture. This can happen closer to theory like "Von Neumann Simulator" [26] or in a more gamified fashion e. g. with "Human Resource Machine" [4] or even without mnemonics as using the Little Man Computer architecture [5]. While all of these approaches help to show how a microprocessor might approximately work, none of them offer a direct, explorable connection to a high level language.

One suggestion for such a direct connection between high level language and machine code will be presented in this thesis. As high level language, "Processing" based on Python syntax is chosen (which will be introduced in section 3.1), and the implementation is based on "Glamorous Toolkit" (which will be introduced in section 3.3).

Before going into the technical details, we'll first introduce the notion of "leaky abstractions" in chapter 2; motivate why having a direct connection over multiple abstraction layers is helpful from a dictactic point of view in section 2.1; and show how currently used development environments already help exploring such abstractions in section 2.2.2.

The tool introduced in this thesis is called `Processing Abstractions` and will be introduced in chapter 4. In chapter 5, we'll offer suggestions for how to employ it in the high school classroom, and in chapter 6 student feedback from two trial runs is discussed.

All of this wouldn't have been possible without the very helpful support of Prof. em. Oscar Nierstraz

who has finally managed to introduce me to Smalltalk and Prof. Timo Kehrer who has taken this project below his wing. I'd also want to thank my students from the classes 27Ga and 28Ga of Gymnasium Neufeld who have worked with my productions and given helpful feedback. Finally, many thanks go to my kids for letting me work even during their holidays and to my wife for her endless support when morale was low.

- [ ] expand, include full motivation, product overview and results (expanded from abstract)
- [ ] Scoping: Computer Science in High School
- [ ] based on introduction in primary school
- [ ] broad overview, not just programming, but also hardware, networking, encoding, *etc.* (see e. g. [13])
- [ ] here focus on various abstractions involved in programming
- [ ] comparison with other subjects: psychology, natural sciences, ...

2
State of the Art in Computer Science Didactics

Before introducing the product of this thesis in chapter 4, we first introduce the problem it should help solve: How abstractions involved in programming are taught.

In detail, we first discuss didactic literature on teaching computer science at high school level, introducing the notions of "foundational idea" one of which is a *Sichtenwechsel* – a change of perspective in a multitier architecture; then we show the relevance and limits of abstractions in programming and motivate why students should look beyond a single abstraction layer in 2.2.

2.1 Didactic Approaches

Traditional introductions into programming focus on a single programming language, its syntax and the available semantics – introducing them iteratively and practising each element with basic exercises. E. g. Hartinger introduces most of Python in this way so that it can later be used for scientific calculations [30].

This traditional introduction works mainly on the level of the programming language, only barely mentioning a simplified memory model (p. 31) and binary encoding (pp. 114–115). Interestingly, it does not assume an IDE (see section 2.2.2 below), but instead very briefly introduces the command line and the Python REPL. Even though in that way, files are not guaranteed to be UTF-8 encoded (as examples assume, cf. p. 118), encodings are not mentioned beyond pure ASCII. And the Python interpreter is just in the preface briefly characterized as "program which translates source code into electronic instructions"[1].

While the needs of academic teaching and the form of semester courses with lectures and separate lab work tends to suggest such an approach, this is not a good fit with suggestions from current didactic literature [39, 46] (and even past texts [23]):

2.1.1 Foundational Ideas

Schubert and Schwill [46] base their didactic approach around the notion of "foundational ideas" derived from Jerome Bruner and Alfred Schreiber. A foundational idea is a concept which is deeply ingrained in

[1] German original: "[...] das Programm, das den Programmcode in Elektronik-Anweisungen übersetzt."

a specific subject such as computer science and without which the subject would loose part of its core. Additionally, they ask for a foundational idea to have the following properties (pp. 62–63):

- Breadth: the concept is applicable not just in one specific context but can be used more generally.
- Abundance: The concept can be applied in different ways.
- Meaning: The concept is meaningful to the learner beyond the scope of a course.

In a later refinement, the property of Historical Relevance is added by requiring a foundational idea to also have persisted through time [39, p. 17].

Such foundational ideas are among many others the idea of modularization, the idea of layered archictectures or the idea of encoding information and instructions.

As a consequence, they propose an introduction into programming to use several different programming languages along different paradigma: e. g. Prolog as a declarative language (pp. 91–104) and Python as object oriented language (pp. 157–185), in order to better teach the foundational idea of 'language' and to demonstrate to students already at the level of instructions that the language chosen comes with inherent limitations in expressibility (p. 154, comparing programming languages with natural languages and referring to Wittgenstein's philosophy of language).

2.1.2 *Sichtenwechsel*

Consequently, they propose to explicitly discuss the foundational idea of multitier architectures – and that not only in the context of the networking stack and computer archictecture (pp. 113–116):

They introduce the notion of *Sichtenwechsel*, a change of perspective with relation to the current layer, which should help students better understand concepts of one layer by inspecting lower layers. As an example, they show a live model of a calculator app whose input is translated to both pseudo code and machine code (p. 115); an environment for inspecting live Java objects (pp. 208–209); or the Filius environment for inspecting a virtual computer network at its different layers (p. 284).

They conclude that "it was a fallacy to assume that students would be able to develop a working model of a computer [. . .] by designing small programs" (p. 213),[2] reinforcing the need for going beyond of what traditional programming courses (used to) do.

This conclusion is repeated again and again, e. g. by Jaokar [33, p. 51] or Zhang [52, p. 407].

2.1.3 Manageability

Modrow and Strecker [39] follow Schubert and Schwill [46] in also building upon the concept of foundational ideas. They do however propose to significantly reduce their number and focus on a few very general such ideas such as modelling (*Modellierbarkeit*), connectivity (*Vernetzbarkeit*), digitization (*Digitalisierbarkeit*) and algorithms (*Algorithmisierbarkeit*) (pp. 27–37). As a consequence, they do propose to focus programming exposure for high school students to block based programming languages such as MIT's Scratch [9] or Berkeley's variant Snap! [10] (p. 125).

Their reasoning for this is that students should not (yet) have to deal with syntax errors (as opposed to teaching them as suggested by Bouvier *et al.* [20]) and only have a manageable command palette. Furthermore, they note that block based languages with free form layouting encourages to build complex behavior from simple building blocks which can always be run and inspected individually (pp. 184–185). This allows for a bottom up development approach in which abstractions are incrementally developed out of basic command blocks which they deem more suiteable for students than starting development at the abstract algorithm.

[2] German original: "Es erwies sich als Irrtum, dass Schüler beim Entwerfen kleiner Programme ein tragfähiges kognitives Modell vom Rechner oder von Informatiksystemen im Allgemeinen entwickeln."

While Modrow and Strecker do suggest also including digital circuits in the curriculum as concrete examples of digitization (p. 118), they seem content in programming them without inspecting the layers in between. From their foundational idea of connectivity, treating these layers could however still follow: If students are to see how hardware and software are connected – and that such a connection is even possible –, intermediary steps between program and hardware must be explorable by students.

Following in these footsteps, Chiodini *et al.* [21] similarly state as requirements for programming classes:

- Manageable complexity: IDEs and APIs must not be unnecessarily complex so as to not confuse students.
- Meaningful engagement: Samples and exercises should be introduced such that it's clear what they refer to outside of class. Their usefulness shouldn't end at the exam.
- Clean problem decomposition: Bottom up development should be effortless and code should compose with as little refactoring as possible.

The last point explicitly asks for a clean separation of abstraction levels which might be an ideal to strive for but might not be realistically achievable (cf. 2.2.1).

2.1.4 Teaching Bottom Up

Beyond suggesting to connect multiple abstraction layers in a *Sichtenwechsel* (see 2.1.2), general didactic literature does not offer more specific suggestions. There are however two readily available ways to deal with abstraction layers: Either starting at the bottom and building abstractions on top; or starting at the most abstract and disecting it into its more fundamental forms.

Starting at the bottom conceptually seems to be the more sound way and is e. g. how Mathematics are taught. One rigorous implementation of this approach is offered by Nisan and Schocken [42]: They offer a course which starts with basic logic gates and builds out of them first the parts of and later a fully functioning, basic CPU for which they continue to develop a low level and a high level programming language until reaching the point where applications can be run on the developed hardware (this was originally dubbed as "NAND to Tetris").

Their motivation is the same as the motivation for this thesis: "The most fundamental ideas [. . .] are now hidden under many layers of obscure interfaces" (p. ix). Since the course is taught at university with hundreds of students, once concession is hardware virtualization: The original logic gates are not built out of silicon or electronics but instead simulated in a portable Java app. This does allow skipping intermediary steps and allows to start the course at any desired level.

Since working with logic gates without seeing their eventual purpose may lack motivation, the course starts with an overview from the top (pp. 1–4) which also serves as the table of contents. With this, students keep in sight what they're working towards and can start connecting their own preexisting notions with the new material.

2.1.5 Teaching Top Down

An alternative teaching approach starts directly at the students' experience, e. g. at gaming [51], art [44] or even toy houses requiring intruder alerts [39] and starts exposing lower abstraction layers as required for gaining more control (and understanding) and extending available capabilities.

At this point a rather traditional approach starts with games: Weintrop and Wilensky [51] discuss a variety of games where programming plays a role in either shaping an avatar, improving its available actions or make it move altogether. Whereas such games are specifically created as 'pedagogical' games, many other games have at least part of their logic implemented in scripting languages such as Lua [11]

which allows them to be modified by players. While the content involved is more complex, modifying or creating a game within still popular 'Roblox' might be sufficiently motivating.

While gaming works as an approach into programming, it's rarely used for inspecting further layers in an educational context. Motivation for doing so is usually constricted to performance optimizations for game platform developers.

An alternative approach which was originally targetted at art students but works well at high school as well is proposed by Reas and Fry [44]: Starting from visual arts and extending the capabilities of the artist through digital means. While the involved programming language, Processing, will be discussed in its own merit in 3.1, their didactic approach is notable as well:

A work of art on its own is something abstract which can not only be interpreted but also created. For (re)creating it, various painting techniques are needed which can be further broken down to basic movements. At this abstraction layer, they set in with high-level programming primitives for creating basic shapes. This allows them to achieve pleasing visual results with just a few commands and initially barely any programming knowledge. Afterwards, the question as to how to achieve more complex output is naturally motivated by already discussed more complex works of art.

Additionally, as art can be considered as individual expression, the parallel to programming as individual expression (as also proposed by Modrow and Strecker [39]) and programming as art is easily drawn: "To use a tool on a computer, you need do little more than point and click; to create a tool, you must understand the arcane art of computer programming." (p. 3). Finally, programmed art must not remain purely digital and can be extended into physical sculptures, for which at least some considerations about hardware can be introduced.

While in both approaches – gaming and art –, stepping further down to lower abstraction levels is a possibility, only one or two such steps are naturally motivated from the source material. Nonetheless, in both cases a *Sichtenwechsel* is possible.

2.1.6 Exploratory and Live Programming

Live programming refers to output and other intermediary products being adapted or recalculated every time source code changes, without any explicit saving and/or rerunning required by the programmer [45]. This gives students the quickest results, as otherwise they might tend to work on code too long without occasionally testing it, if doing so requires additional interactions (for the same reason, many applications have switched to auto-saving instead of relying on users to do so manually from time to time). Live programming also gives students immediate feedback about their code and modifications.

Exploratory programming on the other hand refers to students being given sample code and then modifying said code in order to figure out what effects their modifications have, building like this a mental model of what the code performs.

Both Schubert and Schwill [46, p. 367] and Modrow and Strecker [39, p. 167] suggest exploratory programming for allowing students to work at their own speed and depth: With given examples, less experienced students can stay closer to the given – simple but working – code, while more experienced students can use their knowledge for testing more complicated hypotheses.

While live programming requires explicit support from the programming environment (see 2.2.2), exploratory programming can be done without. Apps can still support exploration better by providing a form of REPL[3] which most scripting languages do, an interactive notebook (such as Jupyter or Lepiter, see 3.3) or a way of direclty running any part of a program, as Scratch does (see 2.1.3).

The didactic reasons for using both exploratory and live programming also apply outside or pure programming, such as when inspecting and modifying live systems, networks, *etc.*.

[3]REPL is short for *Read-Evaluate-Print-Loop* i. e. an interactive interpreter.

2.1.7 Computational Thinking

Since other disciplines have started to rely on computers as more than a glorified typewriter and filing system, the notion of preparing students for working in academia and industry has shifted from teaching applications to teaching "Computational Thinking". Lee *et al.* [37] have assembled cases from schools where programming is used in physics, biology, chemistry and other sciences, linking it to the role that mathematics have had in the past centuries.

As a basis for employing programming, simulation or data transformations to solve problems in other domains, students must be versed in dealing with different abstraction levels in order to connect the abilities of a computer with the subject at hand. Buitrago *et al.* [25] also point out that students must know the limits of computers and not attribute them understanding and intelligence.

With the sudden rise of large language models in the past decade, computational thinking even refers back to programming: Martini [38] argues that with LLMs being able to write programs on their own, programming curricula have to be adjusted accordingly. Students will still have to be able to understand the basics, in order to be able to instruct an LLM towards a desired result.

Also, recent studies seem to suggest that relying on LLMs for coding does not lead to better developer performance [17] nor to better code [40], as cognitive offloading has been observed. This effect is likely even more pronounced for students, as getting quick results for simple tasks might lull them into overconfidence with relation to the available LLM.

As a consequence, the functioning and limits of large language models must not only be taught as part of computational thinking but also used as another example for examining different abstraction levels in a computer system.

2.2 Multitier Architectures / Abstractions

In order to handle complexities arising in both theoretical and practical computer science, subjects are split into multiple layers or tiers to be described, investigated and used separatedly.

Common such multitier architectures taught at high school level are the networking stack (either the seven layered OSI model or the simplified four layered DoD architecture) or the software-hardware stack ranging from apps and hardware abstracting OS down to transistors consisting of e. g. silicium atoms (see figure 2.1).

Ideally, in such architectures all layers above the layer to be investigated can be ignored (beyond what the layer will be used for) and all the layers below can be abstracted away into a nicely defined interface.

As such, programming should be possible to be done independently of hardware and even the operating system, in the same way that natural languages can be taught independently of body or mind of the students.

This analogy however shows that even in computer science, the philosophical mind-body problem persists, albeit in a different form: "At the grossest physical level, a computer process is a series of changes in the state of a machine" [22, p. 12]. In contrast to the human mind, where the interaction between objectively observable brain matter and subjective thought is at the core of an ongoing philosophical and neuroscientific debate, in computer science this duality of having electrical currenty on the one hand and a running program on the other is decomposable all the way through.

And as has been shown in 2.1, didactic literature suggests that this feature should be discussed, as this is a foundational idea of computer science.

2.2.1 Leaky Abstractions

In his article "The Law of Leaky Abstractions" [47] introduces the concept of *leaky abstractions*, claiming that for all non-trivial such architectures, details of lower layers are to some degree bound to bleed through

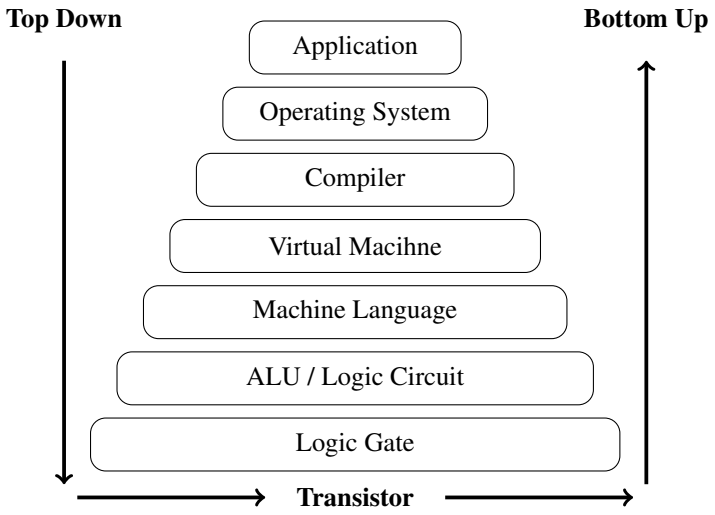


Figure 2.1: Multitier model of a computer system [42, p. xii].

to upper layers. In other words, in practice complex interfaces tend to be incomplete or 'leaky'.

In teaching computer science, such leaky abstractions occur repeatedly, e. g. when an app doesn't run on a different device (with either the OS or the processor architecture leaking); or when a document seemingly can't be saved (with either the file system or differences between apps leaking).

More specifically, in programming there are several ways of abstracting away technical details:

- Programming instructions consist of source code which consists of encoded bits which are stored in memory or on a drive.
- Source code consists of tokens which are usually parsed into an abstract syntax tree (AST) which are either directly or via intermediary representations translated into machine code to be run on a virtual or actual machine.
- When programming instructions through the above abstractions are executed, variable values are encoded and stored in memory, function calls are tracked through a call stack, input state is continually mapped into memory and output is generated in several forms – where e. g. textual output causes a font renderer to interpret glyph instructions for every character; or graphical output is anti-aliased before any pixel data is produced.

Of these different layers, students usually focus on turining instructions into source code and then checking the program's output – or any error messages produced by the compiler or interpreter (see section 2.1). Still, several of the lower layered abstractions might leak through, such as:

- Missing a stop condition in a recursive function leads to a cryptic "Stack overflow" error – leaking information about the call stack.
- If a program outputs emojis, they might look notably differently in source code and output – leaking font rendering.
- Similarly, programs containing emojis might have emojis garbled depending on the app used for inspecting the source code – leaking text encoding.

- If a program contains an endless loop, there might be neither error message nor output, so that it might wrongly seem that the computer isn't doing anything. This isn't an abstraction leak in the above sense but a related student misconception.

Besides the above rather easily observable abstraction leaks, the issue might also have to be discussed itself, since recently one class of leaky abstractions has been shown to be security critical: timing attacks. Since programs might be compiled differently and optimized differently and run on different hardware, runtime timing is not considered to be inherent to a particular source code.[4]

In cryptography, timing attacks have been successfully used for extracting passwords from insufficiently protected webservers [43]. More recently, another class of timing attacks taking advantage of modern CPU's branch prediction optimizations has been demonstrated [36]. In the latter case, an implementation detail of the CPU managed to leak. And in both cases, at least implementors of cryptographic programs must be aware of lower abstraction layers.

Further examples of leaky abstractions are discussed by Egger [24] and many others [12, 34]. These show that knowledge of lower layers are particularly important for developers of compilers and other performance-critical programs: In order to optimize a program, the specifics of the platform architecture and the implementation of processors and networking become crucial.

Since abstraction leaks are unavoidable in programming – even with block based languages such as Scratch –, they have to be discussed anyway. Instead of tackling them one by one as separate exceptional cases, literature discussed above suggests to use this opportunity to work out the foundational idea of a multitier architecture and of the interconnectivity of computer systems.

2.2.2 Abstractions in IDEs

Integrated development environments used for programming offer a variety of different views on a program beyond its source code and its runtime output. The popular Visual Studio Code offers e. g. through extensions step-by-step debugging with variables and the call stack listed [8]. This is mirrored in most other full fledged IDEs such as PyCharm [2] or Eclipse [7].

And while such IDEs through appropriate extensions even allow inspecting Python bytecode, the respective views are usually overwhelming for programming novices and thus rather targetted at professional developers than high school students.

As a remedy, several teaching oriented IDEs have been developped, such as "Code with Mu" which offers a minimal command set and still allows runtime inspection [50]; or Thonny which had the goal to visualize runtime concepts beyond what IDEs offered at the time [16, p. 119]:

On the one hand, Thonny shows intermediary steps during expression evaluation. This demonstrates that statements are not evaluated in one go, but indeed in a predetermined order operation by operation.[5]

On the other hand, Thonny visualizes recursion by showing code in a new pop-up for every function call, so that multiple recursive function calls lead to an equivalent number of visible pop-ups. Most other IDEs rather show a call stack as in a separate view, which abstracts the stack into a list.[6]

Finally, Thonny distinguishes between values on the stack and on the heap, showing the pointer to the heap as the value actually pushed on the stack and in a separate view the actual object on the heap at the given address.

Thus, the Thonny IDE set out to and indeed nicely visualizes several concepts on lower runtime layers.

[4] At least beyond generic complexity considerations on an algorithmic level.

[5] In professional IDEs, intermediary results are usually available by hovering over a specific operator with the order of evaluation being left to the user to determine.

[6] As a compromise, Glamorous Toolkit presented in chapter 3 displays the call stack as a list of expandable method sources with the call location highlighted.

Jalalitabar and Wang [32] have assembled a list of tools targetted at visualizing some of these concepts outside of an IDE. One noteable such alternative approach is taken by Python Tutor [6] which combines a visualization of stack frames variable values as pointers and deconstructed objects.

Sychev [49] suggests as an additional IDE feature hints for syntax errors which show students a side-by-side view of their entered code and the corrected code with all required transformations highlighted. They have implemented this feature for Moodle.

Bouvier *et al.* [20] ask for an extension of this: a view to show details about any form of errors, helping students to better understand the issue at hand. In particular, they suggest including an LLM assistant which can further help explain an error to a novice student. How effective such an assistant would be, remains to be seen (see 2.1.7).

Comparing to programming IDEs, the web development consoles offered by modern web browsers also provide a variety of views into the various layers of the network stack. These views are however tailored to answer the most common questions of a web developer instead of providing a coherent overview of how the network layers interact.

- [1]
- Conclusion

3 Technical Background

The product of this thesis is implemented in Glamorous Toolkit and bases teaching material on the "Processing" programming language. A brief overview of both is given in this chapter for readers unaware of either of them.

3.1 Processing

"Processing" is a programming language consisting of a graphics API built upon a mainstream language as a base. Development started between 1997 and 2004 at the MIT Media Lab with the goal of creating a language for teaching art students the fundamentals of programming as basis for creating digital, visual art.

Its authors, Reas and Fry [44], wanted to create a unified teaching system consisting of art, language and a matching IDE. They based the language upon then popular and portable Java, removing much of the boilerplate required for object orientation, enhancing it with visual primitives and implicitly showing an output window, allowing for quick results (see figure 3.1).

As elaborated in 2.1.5, Processing was meant to be taught top down, starting from art and then decomposing it. As such, its main introduction features several chapters focused on exhibits of digital or hybrid art such as Manfred Mohr's *Une esthétique programmée* or Steph Thirion's *Eliss*.

Apart from graphical primitives (see appendix B for the API subset implemented for this thesis), Processing features an implicit event loop which allows for creating (interactive) animations within a dozen lines of code (see figure 3.2).

```
// Output canvas dimensions
size(200, 200);
// (Default white) square
rect(50, 50, 100, 100);
// Red inner rectangle
fill(255, 0, 0);
rect(50, 50 + 100 / 3, 100, 100 / 3);
```

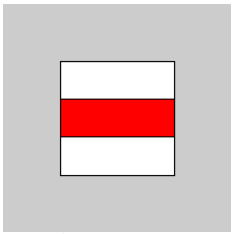


Figure 3.1: Example code (with Java syntax) and output

```
y = 50; dy = 0

# called once after global code
def setup():
    size(100, 200)

# called repeatedly for every frame
def draw():
    global y, dy
    background(192)
    circle(50, y, 50)
    y += dy; dy += 1
    if y > height - 25:
        dy = -0.9 * dy
```

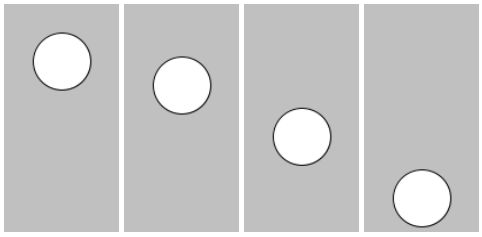


Figure 3.2: Example code (with Python syntax) and one output frames

Reacting to input happens either by pulling state while painting a frame (implicit global variables `mousePressed`, *etc.*) or by defining event handlers alongside `setup` and `draw`.

Since Python has become the prevalent teaching language ([14]), Processing has been extended with a Python mode which leads to Processing code reading like Python code with the additional Processing API calls and exposes most of Python's libraries to Processing code. This allows using Processing as a starting language and later seamlessly transitioning to pure Python code, which remains part of the motivation for students: learning an "actually useful" language.

As the official Processing IDE continues to be written in Java, Processing's official Python mode uses Jython for compiling the code to Java Bytecode. Since developers have started moving away from Java, there are now several reimplementations of Processing such as p5.js for running Processing on top of JavaScript in a web environment, p5.py for running Processing in a pure Python environment[1] or a version of Processing for microcontrollers such as Arduino. With this thesis, a limited version for a Smalltalk environment is also available.

Initially in the early 2010s, we ran our own IDE based on p5.js with custom error handling[2] before changing to the official IDE for its Python mode.

Our experience of working with Processing over the past decade has shown that it allows novice programmers in the first year of high school to learn enough of the language within a month that they're able to write a clone of a game like "Pong", "Flappy Bird" or "Geometry Dash" as a group project. Feedback from the various student groups about this part of the computer science curriculum has always been positive to very positive. This aligns with what didactics states about student motivation (see 2.1).

3.2 Moldable Development

"Moldable development" is a term coined by Nierstrasz and Gîrba [27, 41] for a collection of development patterns which should make it easier to understand a computer system by extending ('molding') it with views and features. The goal of moldable development is to quickly get feedback on code and objects being worked on so that a programmer can confidently make appropriate changes.

In traditional IDEs, a running system is inspected either through its source code or its live runtime objects. Available views (see 2.2.2) are static and new views are added through non-trivial extensions. Moldable development asks for an environment in which a tool is more easily adaptable to data, making it

[1] Requiring two additional lines: `from p5 import *` at the top and `run()` at the bottom.

[2] This is still available from `https://software.zeniko.ch/ProcessingIDE.zip`. Note that it's targeted at `mshta.exe` and as such runs best under Windows.

simple to write either one-off throw-away views and tools but also allowing to refactor such throw-away code into reusable components when needed.

Moldable development is thus a form of exploratory programming (cf. 2.1.6) on live objects where tools, whether one-off or reusable, are created in a bottom up approach with immediate feedback available at every step.

In order to support this, a moldable environment must have extensibility in its core, allowing to register tools and views e. g. through a simple code annotation of a few characters which the environment can use to detect and include it (instead of having to write a lot of configuration boilerplate and overhead which IDE extensions meant for independent distribution usually involve).

One core pattern of moldable development is the "Moldable Object": Objects should be implementable incrementally with live object states and previously developed views remaining available throughout the whole process. An object consisting of little more than a data wrapper is thus extended with new functionality as it fits the available live data – instead of designing an object on a clean slate or along tests. Exploration code can then be extracted into tests, ensuring that what worked once will continue to work. Extending objects iteratively based on actual needs ensures that they remain transparent and that code is cleanly separated.

Having a moldable environment also allows for working on code and documentation intertwined, similar to literate programming [35]. Opposed to literate programming where code has to be extracted first, in moldable development every code snippet should be runnable on its own and beside code and documentation also live results can be included. This allows a moldable environment to be used to either first document ideas and then add matching code but also to document progress or explain written code (which can then easily be extracted into a test case).

For students, such a "Project Diary" pattern could be used as a learning journal (similar to Microsoft OneNote), for project exploration (similar to Jupyter notebooks) or for project documentation. Another useful pattern for teaching is the "Composed Narrative" which visualizes object relations through side-by-side views tailored towards explaining a relation or interaction.

3.3 Glamorous Toolkit

"Glamorous Toolkit" (GT) is a fully programmable environment optimized for moldable development (see 3.2). It is programmed in Smalltalk and by default persists its entire state into an `.image` file when shut down so that live objects don't have to be recreated at restart [28].

Smalltalk environments have had that property since the early days in the 1970s, when Alan Kay sketched out the original Smalltalk which he eventually standardized at Xerox into Smalltalk-80. Based on a Smalltalk-80 virtual machine by Apple, Ingals, Kay *et al.* started developing a new virtual machine and development environment, Squeak, which had the goal to also be customizable by non-programmers [31]. Squeak inherited its built-in capabilites for live and exploratory coding from the original Smalltalk and its back to this point that GT's heritage is tied directly.

While Squeak was further developed at Walt Disney Media Labs and among others included in the "One Laptop per Child" laptops, it remained a niche product – likely due to missing interoperability between the live environment inside its virtual machine and outside code. Still, Squeak and its later fork Pharo continued being worked on and were actively being used in academia and related spin-offs. Eventually, a team around Tudor Gîrba – including this thesis' supporter Oscar Nierstrasz – set out to implement their idea of a moldable environment on the basis of Pharo, thus creating Glamorous Toolkit [3]. Version 1.0 has been released in 2023 and is still being actively worked on.

Glamorous Toolkit thus has an illustrious lineage and has achieved support for many concepts asked for by literature (as outlined in 2.1 and 3.2): It's a moldable environment, supports a clean object-oriented language, allows for live and exploratory programming, still remains comparatively manageable and –

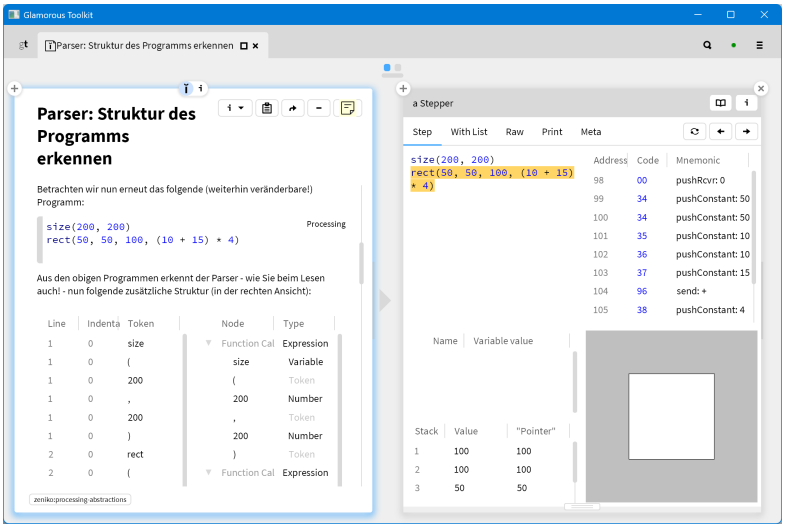


Figure 3.3: GT with a live notebook page (left) and inspectable object view (right)

particularly relevant for this thesis – allows for reflection at various levels, including for every object access to its method's source code, its compiled form and even its memory layout inside the virtual machine.

GT provides a tabbed interface which can show one of several tools: an object viewer, a notebook (dubbed "Lepiter"), a code browser, a git interface and many more. While such tools are about as difficult to implement as an IDE extension, the object viewer – a tabbed interface itself – is extended by annotating an object method which returns a `GtPhlowView` object with `<gtView>`:

```
ProcessingCodeBase >> gtOutputFor: aView [
   <gtView>
   ^ aView explicit
      title: 'Output' translated;
      priority: 40;
      stencil: [ (ProcessingRunner new
            limitTo: (self gtIsAnimation ifTrue: [ 30 ] ifFalse: [ 2 ]) seconds;
            run: self clone;
            canvas) asElement ]
]
```

The element passed to the `stencil:` message – here the canvas resulting from running a Processing program – could instead also be displayed inside a notebook page, with no annotations needed at all.

Annotations are thus only required to allow GT to discover messages of a certain type. Similarly, methods annotated with `<gtExample>` are considered tests and can be collectively inspected and run for a class or an entire package. This achieves several goals of moldable development: What starts as throw-away code can be extracted into a method, annotated and remains then permanently available for repeated testing. Examples are also includable by name in notebooks, where they do function as (tested and thus guaranteed working) examples for documentation.

While GT is based on a Smalltalk virtual machine, support for other modern languages such as Python, JavaScript or Java has been added through a language bridge connecting to an external virtual machine and allowing for inspection and visualization of objects originating there. Unfortunately, these language bridges are one example where one of GT's drawbacks starts showing.

3.3.1 Bleeding Edge

GT follows a trunk-only development style without release branches. This means that downloading GT on two different days might result in subtle differences. If GT with an app is to be distributed, the best way to do this is by downloading the latest version, loading the app into it, testing it and then distributing *this known good* image (as is described in A). Also, GT is mainly developed under macOS and makes some platform assumptions with relation to its host operating system. This isn't noteable when working purely within GT but occasionally shows at its seams.

What might also take some getting used to: All the code in GT and all live objects are stored in its `.image` file and are updated whenever GT is closed with saving. Synchronization of Smalltalk code thus happens best through GT's built-in git client. Preexisting notebook pages are also stored within one of GT's subdirectories. Users can however create new pages in the "Local knowledge base"[3] which can be backed up separatedly and which are stored even when GT is quit without saving. All notebook pages indicate where they're stored in their footer and can be moved between databases through that footer. This allows students to take an existing page from teaching material and move it locally where it's separately backed up, in case they later delete or update GT.

[3] By default, this is located in the `lepiter` subdirectory of the user's documents or home folder.

4

Proposed Solution: A New Teaching Environment for Programming

In order to let students have a *Sichtenwechsel* with relation to programming, i. e. have them experience several different abstraction layers involved between a program's source code and its execution, a new teaching environment dubbed "Processing Abstractions" is proposed:

Within Glamorous Toolkit, we've implemented support for the Processing programming language and molded views for every implementation step along the way. This allows for creating interactive notebook pages containing source code and a variety of these views, showing e. g. the abstract syntax tree (AST) and resulting bytecode for the GT virtual machine side-by-side (see figure 3.3).

In this chapter, we document the development of this environment and the reasons for the approaches chosen. If you want to try things out directly, see appendix A for how to install all referenced code[1] A stable snapshot of the code discussed here is available on Github [**?** , Bue25, Bue25a]

4.1 Reasons for Using Processing and Glamorous Toolkit

For the past decade, we've taught the introduction to programming using Processing to ninth graders. This consisted of an introduction into the language along relatively simple examples inspired by minimalist art and games (similar to the approach by Reas and Fry [44] described in 2.1.5). In a separate sequence, we've taught computer architecture in a bottom up approach (inspired by Nisan and Schocken [42] as described in 2.1.4 but much abbreviated).

While the introduction to programming was usually quite well received by students and also led to satisfying results, the sequence on computer architecture did less so. The two sequences also didn't fit together as nicely as we'd have liked and processor and memory remained a mystery for too many students. Hence the decision to look into combining the two sequences.

At this point, we've briefly evaluated whether staying with Processing was reasonable. Reasons to do so were manyfold: As seen in 3.1, Processing allows a top down approach starting at visual arts, which allows to motivate students with less interest in mathematics and natural sciences; Processing also quickly yields

[1] Remove the line `GtExplorationHomeSection studentMode: true.` in order to also see our implementation notes.

```
ProcessingCanvas >> circle: x y: y d: d
   self
      ellipse: d
      by: d
      at: x @ y
```

```
def circle(x, y, d):
   ellipse(x, y, d, d)
```

Figure 4.1: Implementation of `circle` as built-in API and in user code

pleasant looking results, which also adds to initial motivation [21]; then it can be based on still popular and widely used Python, which allows using it as a stepping stone and makes it a 'real' programming language in the eyes of novices; on the other hand, Processing itself is sufficiently unknown that even students already experienced with programming will have something new to discover; additionally, Processing has a large community sharing sketches and ideas which can be used as inspiration for both students and teachers; finally, its proven itself in our own experience over the years.

While Modrow and Strecker prefer a block based language, we feel that at least parts of their issue with a text based programming language can be remedied by having a live environment with custom error messages. For remedying their remaining issue about allowing individual bits of code to be called independently, that could be achieved in one of the ways Glamorous Toolkit does this: either by offering separate playgrounds which do work similarly to a REPL; by allowing multiple code snippets to access the same environment (as it also works in Jupyter notebooks); or by allowing only selected code to be executed. The last option would be easiest to implement.[2]

Chiodini *et al.* [21] also propose starting with visual programming but have different requirements: In order to keep an introductionary language manageable, they ask among others for a limited API which should be expandable by students (see also 2.1.3). And the full Processing API can indeed be quite overwhelming, so only a subset must be introduced at the start. Indeed also for this reason only a subset has been implemented in GT (see B), although already including some seemingly unnecessary functions: E. g. the `circle` function is easily implemented in terms of the more generic `ellipse` function (see figure 4.1) – either in the implementation of the Processing API or by students.

Another requirement by Chiodini *et al.* is for problems to be transparently decomposed and solutions recomposed. This is indeed an issue with Processing: Moving a composed shape to a different location requires adjusting the coordinates of all basic shapes involved, therefore variables and even functions have to be introduced sooner rather than latter to allow the examples shown [21] to work. Similar to how they introduce a library to achieve their desired API, the same functionality could be implemented on top of Processing at a later stage if desired.[3]

The main reason for not introducing a new API as proposed by Chiodini *et al.* is the same as the reason for not introducing an entirely new programming language optimized for teaching (as done e. g. by Black and Bruce [19]): This prevents benefiting from the large community and preexisting documentation and example code.

As development framework, Glamorous Toolkit was chosen for its moldable environment: As shown in 3.3, different views are quick to implement and can be combined freely with interactions and updates between them.

Of course, since GT is based on Smalltalk, an initial effort is required to learn language and environment before these benefits can be used. This is helped by Smalltalk's regular syntax and GT's reflection

[2] It hasn't been implemented for three reasons: At least in the beginning, it might confuse students more than it helps, which goes against manageability (see 2.1.3); most visual commands can't be executed entirely independently in Processing, as output always depends on `size` and maybe other stateful commands; and interaction with the animation loop would have to be figured out: whether it's has to be paused during the entire interaction, just between two user commands or even not at all.

[3] In the provided teaching materials, an example of how to implement a simpler Turtle based API is provided (see "Schildkröten und Rekursion").

capabilities, which allows finding API, documentation and examples easily.[4]

Implementing a new language in GT can happen along the moldable patterns documented in 3.2: Starting with concrete samples, classes and views for handling them are molded in steps until the desired behavior is reached; then code is refactored into permanent methods on the one hand and a concrete example serving as test case on the other. Whenever the need for a different view into the program or one of its intermediary forms (such as AST, bytecode or output) arises, the view is constructed in the same way by first iteratively shaping the data into the desired form and then either passing this to one of GT's standard views (text, list, tree, table, forward) or composing the view's layout in the same way iteratively.

4.2 Development of "Processing Abstractions"

Within Glamorous Toolkit, Processing is implemented through transpilation to Smalltalk. This allows reusing several of GT's libraries: `PythonParser` for parsing Processing with Python syntax and `OpalCompiler` for compiling Smalltalk with bytecode extractable through `CompiledCode>>>symbolicBytecodes`.

Since Processing implemented on top of Python is a strongly but dynamically typed language, it maps well onto Smalltalk which is the same. Still, initially three other approaches were considered:

Processing could be run either in the original JRE and then accessed through Python or directly run using one of several Python libraries [15]. In all cases, its objects would be accessed through `PythonBridge`. Since at the time of writing, support for PythonBridge under Windows was difficult to achieve in a portable manner (i. e. without requiring students to install multiple different packages which increases the risk of accidental breaking and thus potential support issues), this approach was rejected.

Alternatively, Processing could have been implemented through an interpreter in GT[5]. This would have required to write a separate compiler for creating bytecode just for demonstration purposes. Instead, a compiler from Processing to Smalltalk bytecode could have been written.[6] While this would have allowed for closer control over optimizations, it would effectively have become a reimplementation of most of `OpalCompiler`.

4.2.1 Implemented Classes

☰ Shorten this chapter, move the details into an appendix

The product consists of the following main classes which can be found in GT through the spotter (🔍):

`ProcessingCanvas` provides the implementation of most of the Processing API for rendering the various shapes in the form of `BlElement`s (wrapped through `ProcessingCanvasShape`). It does this through `ProcessingCanvasPresenter` into a `ProcessingCanvasElement` of which there can be multiple, allowing to use a canvas for multiple views. The canvas also provides access to the individual shapes and all of its state. Rendering onto the canvas happens through the transpiled and compiled Processing program for which a new canvas is created for every separate run.

Processing programs can be written either inside GT's notebook in form of a "Processing/Python" snippet, in form of a Smalltalk string or in separate files. All forms are loaded through the `ProcessingSource` class. Since we mostly want Processing source and its various views to be seen in a notebook page, the most common way to process a Processing program will be inside the page through[7]

```
(ProcessingSource fromPage: thisSnippet page at: 1) renderLive
```

[4] For Smalltalk and GT's ancestor Pharo, there are sufficient resources available online, for GT itself, there's the "Glamorous Toolkit Book" [28] and a Discord server.

[5] Remnants of which are available as `ProcessingInterpreter`

[6] A compiler for a tiny subset of Processing is included as `ProcessingCompiler`.

[7] The `at: 1` part of the message may also be omitted, if there's only one snippet on a notebook page. Omit the `renderLive` message, if you want access to any of the intermediary states or different views.

For a pure introduction to programming, it's even enough to rely on the Processing snippet to produce output, as that allows for the most common forms of output:

- ▶ (or its shortcut `Ctrl+R` for "Run") runs the program and either display its visual output or an inline error message.
- ▶`i` (or its shortcut `Ctrl+G` for "debuG") runs the program, recording all individual steps at the level of (nested) Python expressions – allowing to step through the program and inspecting among others the values of variables and the current state of the output.
- ▶`a` (or its shortcut `Ctrl+D` for "Details") shows the program in its main decomposed states: source, abstract syntax tree, bytecode and output.
- ϟ (or its shortcut `Ctrl+Shift+D`) opens GT's Smalltalk debugger at the `gtRun` entry point of the transpiled code for live debugging for either advanced students or for looking under the hood of the API calls.

The snippet is implemented in `LeProcessingSnippet` which builds upon GT's `LePythonSnippet` for syntax highlighting but accesses Processing through `ProcessingSource` instead of Python through `PythonBridge`.

For embedding output or any other view inside a notebook page, an "Element" is added with either the code from above or with `renderLive` replaced with `renderLiveView:` with the symbol of the desired view appended (`#gtTreeFor:`, `#gtTranspilationFor:`, `#gtBytecodeFor:`, *etc.*; see the "views" category of `ProcessingSource` and `ProcessingProgram` for all available views).

For all the views, a `ProcessingProgram` is created through `ProcessingSource>>>program` which transforms it into its various forms:

- `ProcessingParser` is used for parsing the source into an AST. Since Processing shares Python's syntax, the parser is a very thin wrapper around GT's `PythonParser`. The AST is then slightly modified through `ProcessingAstCleaner` to better map Python to Smalltalk: Since statements after a `return` are allowed in Python but not supported in Smalltalk, they're silently dropped (a warning about unreachable code could be added); and parenthesized expressions are parsed into `PyTupleExpressionNode` which complicate later optimizations with relation to operator chains, in particular logical operators `and` and `or`.
- `ProcessingTranspiler` then walks through the cleaned AST and transpiles Python expressions to the corresponding Smalltalk, recording a `ProcessingTranspilationSlice` for every (sub)expression, thus later allowing to map bytecode its mapping into Smalltalk code back to the corresponding Processing source. If `setup` and/or `draw` functions are defined in Processing code, the implicit animation loop is added to the end of top-level code. Processing API calls – if not overwritten by user code – are translated through messages of the form `ProcessingTranspiler>>>emit_...:` which the transpiler detects through reflection.
- The transpiled code is compiled to methods of an anonymous subclass of `ProcessingCodeBase`. This base class provides views at the lower abstraction levels from transpiled code to bytecode and also the entry point to the user supplied program `gtRun` which contains top-level code. Global variables are turned into instance variables, thus being available to all Processing functions in the form of Smalltalk methods.[8]

[8] In order to prevent overriding of `gtRun` and the different view messages, Processing names starting with `gt` are renamed to starting with `gt_` during transpilation.

While compiled Processing programs can be run directly, `ProcessingRunner` is used for ensuring the presence of an output canvas, for allowing program execution to be interrupted and for extracting `ProcessingRunStep` instances for every Processing (sub)expression.

From these, `ProcessingProgram` provides all views corresponding to Processing code and combined views. In order not to overwhelm students with too many views, `gtDefaultInspectorTool` has been implemented for hiding all but the main four views behind the same symbols as used by the snippet.

During compilation, most common exceptions are `SmaCCParserError` during parsing, `ProcessingCompileTimeException` during transpilation and `ProcessingRunTimeException` during execution. At this point, exceptions occurring in the transpiled code are not translated yet. Since most programs are meant to be re-run live, a heuristic has been implemented for catching endless loops which may naturally occur while a program's source is modified where e. g. a variable's value is modified but at the end of a `while` loop. Instead of detecting the endless loop from code, runtime has been restricted to a maximum of two seconds for non-animated programs and thirty seconds for animated programs.

4.2.2 Implemented Views

Since the goal of this product was showing various states of a program in a way that can be explored live, may different views into the classes listed above have been implemented. These views are all available either from `ProcessingProgram` or through `ProcessingSource>>>renderLiveView:`. Note that the convention is that any view has a name of the form `gt...For:`, is categorized as "views" (and of course has a `<gtView>` annotation).

At the level of source code, there's three different views showing the source with syntax highlighting (`gtContentsFor:`), showing the individual source characters with their unicode value (`gtSourceCharsFor:`), and showing the bytes as they would be written to disk, assuming the default UTF-8 encoding also used by the original Processing IDE, with bytes also displayed in hexadecimal and binary notations (`gtSourceBytesFor:`). With these views and suitable sample code, students might be able to deduce some regularities with relation to ASCII character ranges and UTF-8 encoding.

As most of the available views, these views can be combined, so that students can navigate one view and compare the selected character or byte with its position in the source code. Sensible combinations such as `gtSourceBytesPlusSourceFor:` are provided, others can be created as desired on the basis of the provided ones. Using the helper class `ViewComparison`, the same view for multiple programs can also be linked for side-by-side comparison.

For the parsing phase, there's another three views showing either just the tokens after the lexing phase, including line number and indentation (`gtTokensFor:`), showing the abstract syntax tree as a tree list with purely structural tokens visually distinguished (`gtTreeFor:`), and showing the abstract syntax tree layed out horizontally using GT's Mondrian library (`gtTreeMondrianFor:`). All of these views can again adjust live to code changes, allowing students to explore how tokenization and parsing might work by modifying source code and hypothesizing (see figure 4.2).

The view `gtTranspilationFor:` allows on the one hand to see what Processing does implicitly behind the scenes – setting and updating implicit variables such as `width`, `mousePressed`, *etc.*, calling `setup` once and `draw` repeatedly, and running top-level code before entering the animation loop (see figure 4.3); on the other hand, it also allows for a comparison of subsets of the Python and Smalltalk languages.

For the compilation phase, there's views for Smalltalk's intermediary representation without optimizations (`gtIntermediaryRepresentationFor:`) where variables are still named and jump labels sequentially numbered, and for Smalltalk's bytecode (`gtBytecodeFor:`) with bytes being laid out sequentially for an object.[9] At this point, students can see that their original program, which is stored as one set of numbers

[9]The bytecode format used was proposed by Béra and Miranda [18] in 2014 for Pharo from which GT inherited it and diverges somewhat from the original Smalltalk-80 bytecode format [29, p. 596].

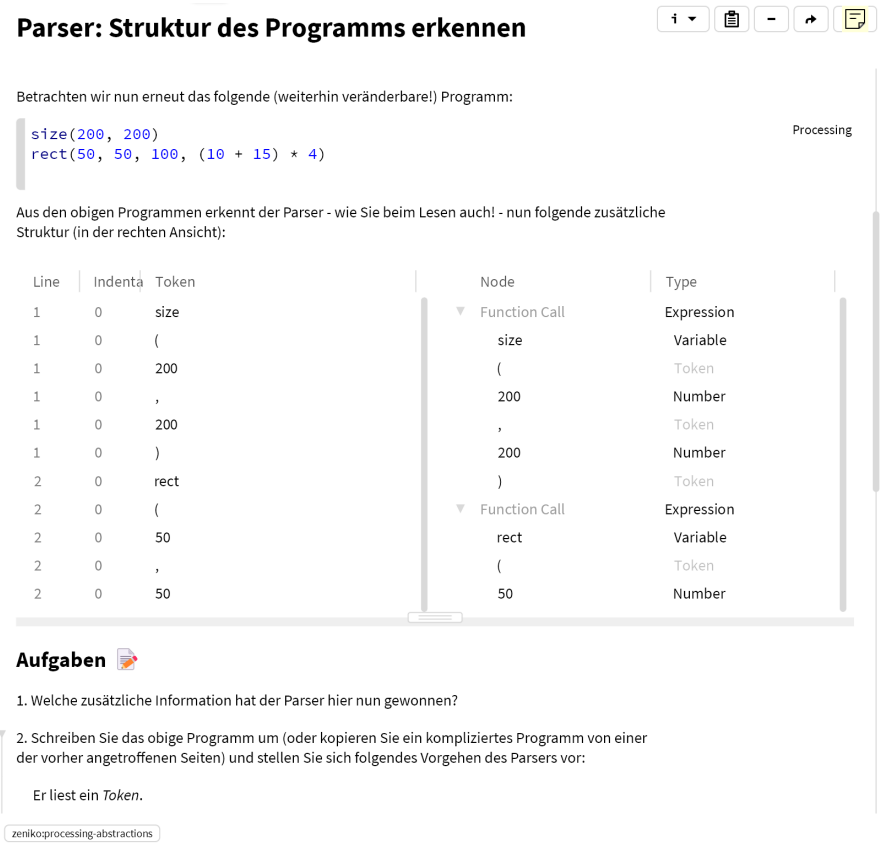


Figure 4.2: Screenshot of a page of student content showing modifyable Processing source with live views for tokenization (left) and abstract syntax tree (right).

```
SubclassOfProcessingCodeBase >> gtRun
   self setup.
   [ gtCanvas frameRate > 0 ] whileTrue: [
      mouseX := gtCanvas mouseX. mouseY := gtCanvas mouseY.
      mousePressed := gtCanvas mousePressed.
      self draw.
      gtCanvas endFrame.
   ].
```

```
ProcessingCanvas >> endFrame [
   presenter updateOutput.
   (1 / frameRate) seconds wait. "The frame rate is adjustable through `frameRate()`"
   frameCount := frameCount + 1.
   transform := #yourself  "Transforms are reset at the end of a draw-cycle"
]
```

Figure 4.3: Implicit animation loop (Transpilation view) and part of the required API (only visible when debugging transpiled code)

(UTF-8 encoded text), has become a different set of numbers which a computer – or in this case the Smalltalk virtual machine – can execute.

Finally, there's three views tied to a program's runtime which may be helpful even for a pure introduction to programming: `gtOutptFor:` shows the output of a program which may continuously change, if the program describes an animation, and which may be interacted with[10]; `gtOutputShapesFor:` allows inspecting the individual shapes in the order they've been rendered (this view is disabled for animations); and `gtStepsFor:` shows an overview of all views of `ProcessingRunStep` for every Processing (sub)expression that has been evaluated – including the expression in the source, the transpilation and its bytecode form, current variable values, values on the Smalltalk VM's stack and the current output state. This gives us a debugging view in which a student can step forward and backward through the execution of the program but also shows an excerpt of the different layers involved in program execution.

Any of these views can be integrated on its own into an interactive notebook page for producing student content, they are however also all available to students through the Processing/Python snippet's various execution modes: Either running the program for pure output (▶ or `Ctrl+R`) gives access to the most common views by inspecting the object behind the output (▶`i` in the upper right corner); or running the program for details (▶`a` or `Ctrl+D`) yields all the views through `i` at the top center. For manageability, both of these options can be ignored at the start, as the default views should provide sufficient informations and the remaining ones can be continually introduced during class.

4.3 Usage

With this, high school teachers get a toolkit for teaching programming and systems at various levels:

At the start of a course, the environment can be used as an introduction to programming (see the suggested lessons in 5.1). When the limitations of the environment are reached, the move over to the official Processing IDE should be seamless: code copied over and run (with the same icon and shortcut) yields the same output and can then be further modified with the full Processing API, once students are ready.

When teaching computer architecture, the environment can be used for either exploring the various abstraction levels involved or even again as a full course embedded in notebook pages (see 5.2). In case of both usages, this better ties together programming and system architecture. And if programming has happened in Processing, students can investigate their own programs instead of mainly relying on those given by the teacher.

In an indepth course for students specializing in computer science, this environment can further be used to teach the inner workings of a compiler from lexer to optimizer (see 5.3).

Finally, this environment could also be used as a stepping stone for introducing Smalltalk as a different programming language and GT as the moldable environment it is, leading students to molding the provided materials further by e. g. extending the Processing API, developing new views or starting to work on a language of their own (see 5.4).

In all cases, GT can also be used as a digital notebook by students, where they solve tasks directly in the page, add their own notes and keep their modified examples.

While this environment is mainly targetted at high school students, it could also be used in middle school. For middle schoolers, the exposed user interface would however have to be reduced as far as possible to keep it manageable. It could however work at least in a smaller group with interested and motivated students wanting to step beyond block based programming languages. For university students, there's currently not enough depth available.

[10] For now only using the mouse which changes the implicit variables `mouseX`, `mouseY` and `mousePressed` and calls the callbacks `mousePressed`, `mouseReleased`, `mouseClicked` and `mouseMoved` if any of them has been defined by the user.

5 Implementation: Lesson Plans

In its current form, the "Processing Abstractions" environment as presented in chapter 4 is mainly targetted at the obligatory introduction to computer sciences at high school level.

Before going into empirical results from using this environment in two courses, three lesson plans will be presented for which it has been developed: a *Sichtenwechsel* in computer architecture (section 5.2); an introduction into the inner workings of a compiler (section 5.3); and first a plan for a general introduction to programming (section 5.1). Some ideas for how to expand it for other school levels will be presented in section 5.4.

For all the lessons, students will need a local environment of "Processing Abstractions" installed on a computer available to them. See appendix A for how to set it up. Additionally, for non-German speaking students the contents will have to be translated to the teaching language.

5.1 Introduction to Programming

While the "Processing Abstractions" environment has been developed for linking programming and computer architecture, it can also be used for an introduction to programming. This does even help linking programming and computer architecture for students, since they can start at the same point and reuse the experience already gained.

5.1.1 Educational objective

After the introduction, students should be able to ...

- work within GT.
- read, write and understand programs with a limited command set, including working with the implicit animation loop.
- learn from their mistakes, correct themselves and not be afraid of breaking things.

In the end, students should have a solid foundation for taking on the task of writing a basic but still interesting app or game.[1]

5.1.2 Prerequisites

Students need experience in using their own computer, including ...

- downloading and extracting archives, and
- dealing with their virus scanner.[2]

Additionally, the teacher must prepare their contents in GT e. g. as described in A and distribute them. Ensure that the first lesson page will be displayed on first startup.

5.1.3 Introduction to Glamorous Toolkit

Since Glamorous Toolkit will be a new environment altogether for all students, some basics on its usage have to be introduced first within ten minutes:

→ Ask students to download and extract your GT distribution as homework for the first lesson. Under Windows, they might run into a first issue with their virus scanner blocking the download, so remind them about what to do in that case.[3]

→ Tell students to start GT and open the notebook page about working with Glamorous Toolkit ("Arbeiten mit Glamorous Toolkit" in the included teaching materials). Also ask them to help their neighbours, if they see them struggling. Use the time while students are reading and doing the first tasks for ensuring that everyone has managed to get GT running.

→ Introduce GT as an interactive notebook similar to what students already know from class.[4] One main difference will be that additional views will open to the side, hiding the table of contents. So show them, how to get back by selecting the left-most view (through the blue dots at the center top) and expand it (through the ✪ at the top left).

→ If you want students to be able to take notes of their own inside GT notebooks, show them how to move a page to their local knowledge base (where it can be backed up individually) and how to create and structure new paragraphs (`Ctrl+Enter`, `Alt+Shift+Arrow`). Markdown syntax for formatting does not have to be introduced explicitly, that can be replicated by students by inspecting your content.

→ Finally, keep in mind GT's ability to be inspected at every level and point more advanced students towards using these (e. g. by `Ctrl+Shift+Alt+Click` anywhere, by double-clicking on list items, or by going through the different views of an object).

[1] Possible ideas, which all have been implemented by students, include: "Flappy Bird", "Geometry Dash", "Pong", "Doodle Jump", "Snake", a quiz, a labyrinth, *etc.*. For most of these, "Processing Abstractions" provides sufficent support, the main deficit being the lack of keyboard input.

[2] At least under Windows, many scanners flag GT as untrustworthy due to its executable lacking a valid signature. Some virus scanners even block the entire download, if the archive is distributed over a network.

[3] In most virus scanner settings, the warning can be overruled by the user; else they might have to *temporarily* disable scanning for this one download.

[4] Many schools have standardized on working with the Microsoft 365 Office Suite which includes OneNote.

Please note that as described in 3.3, GT is bleeding edge technology and might not always behave the way you and your students have become used to: Since notebook pages are rendered progressively, scrolling won't always work smoothly (and will scroll inner content, if the mouse cursor isn't positioned at a page's border); occasionally unexpected error messages trigger the debugger to pop up which has to be closed again; and sometimes the keyboard modifiers may get stuck, resulting in shortcuts no longer working (which is resolved by switching to a different app and back).

5.1.4 Lesson Plan

Since this isn't the focus of this thesis, we won't go into much detail about introducing programming, but just summarize what might work within the provided environment:

Start top down as suggested in 2.1.5 from either abstract art or games[5] and start dissecting how this concrete entity might be described, first in natural language and then in formalized language.

Then follow Reas and Fry [44] and introduce the Processing language (see 3.1), by starting with a sequence of statements with few commands (e. g. `size`, `rect`, `ellipse` and `fill`), and then sequentially introducing comments, colors, variables and arithmetic, the animation loop, conditions and interactivity.

Every concept can be described on a notebook page with given examples for first exploring the effects of a command and its arguments[6] and then later using the concept for solving problems by starting from a skeleton program (see figure 5.1 for an example of both).

At the beginning, debugging will only consist in modifying values and observing live changes until the desired output is reached. At later stages, the step-by-step execution views will be useful, where executed expression, variable values and visual output are displayed side-by-side and execution can be played forward and also in reverse.

Quicker and more proficient students could also already at this point start to delve deeper: The third and fourth execution icons will lead them to discover by themselves what lies under the hood.

Sample content for this is included in the *Unterrichtsmaterialien* of "Processing Abstractions" as "*Programmieren mit Processing*".

5.2 Lesson on Computer Architecture

The main objective of this thesis was to demonstrate, how understanding of what happens when executing a program could be improved by having students perform a *Sichtenwechsel*. The same goes for the other way around, where computer architecture is explained in more concrete form by tying it to previous programming experience.

Introductions to computer science which extend beyond a pure programming course often contain lessons on computer architecture. E. g. the curriculum [13, p. 145] asks for students to "know how computers and networks are structured and work".

We again propose to approach this task top down (see 2.1.5) and move along the path specified in figure 2.1. This will be outlined here with validation of part of this approach following in 6.1.

With respect to manageability (see 2.1.3), it is proposed to mostly skip the inner workings of a compiler and treat that in a separate sequence (maybe only for students specializing in computer science).

[5] Most one-tap games should work, e. g. `https://www.lessmilk.com/almost-pong/` has reasonably simple gameplay with minimalist visuals.

[6] Students may either describe the expected behavior and then verify that their expectation matches the outcome, or less taxingly try given or random values and then describe their observations. Variations consist e. g. in a student describing desired behavior and then (another student) trying to achieve this.

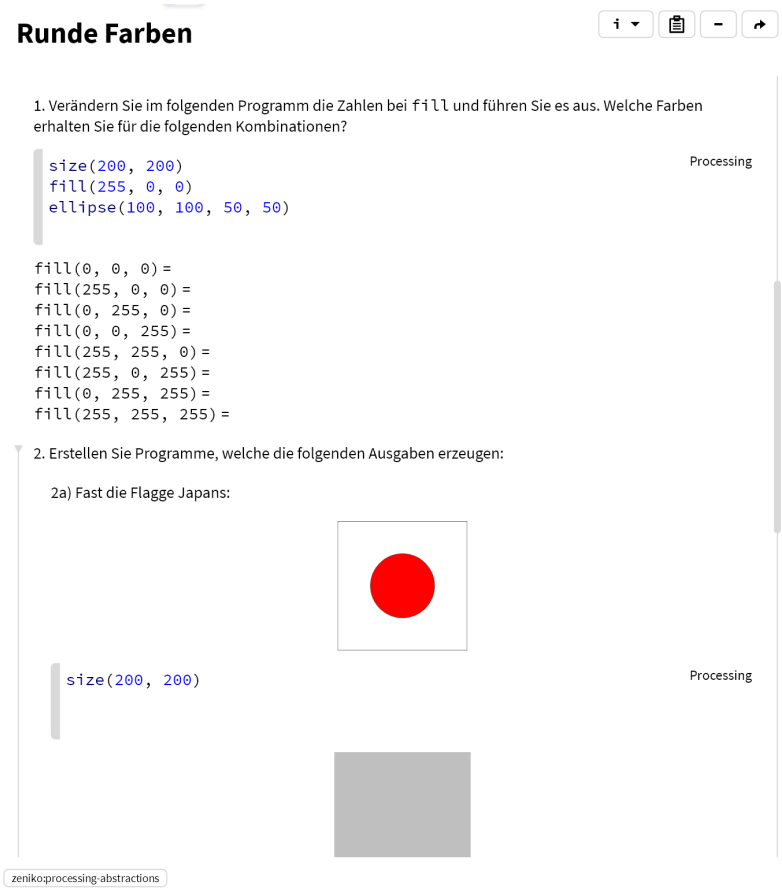


Figure 5.1: Excerpt from an interactive notebook page with exploratory and live programming tasks.

5.2.1 Educational objective

After these lessons, students should be able to ...

- explain the concepts of (virtual) machine, memory, stack, machine language, and program counter (with relation to a von Neumann model).
- elaborate why machine language must be different from a high-level language such as Processing.
- explain why some commands are slower than others.
- connect their knowledge about encodings with how values and machine code are stored.
- consequently understand how one of their programs might be run on actual hardware and document their understanding with correct terms.

5.2.2 Prerequisites

Students must already have basic programming skills in a high level language. In particular, they must know about variables and loops. If they don't know Processing or at least Python yet, a brief introduction (maybe along the ideas proposed in 5.1 above) is required.

5.2.3 Lesson Plan

Whereas Nisan and Schocken [42] introduce their bottom up course with a top down overview, we propose doing the same in reverse for this top down approach:

→ Start with a brief repetition on programming by giving students a few quickly solved tasks (including one about the animation loop, where at least the skeleton structure is given). If this is the student's first encounter with Glamorous Toolkit, use this opportunity to introduce it (see 5.1.3).

→ Show students the innards of a computer and ask where their programs reside in there. Use this for discussing hard drives and volatile memory, and a repetition about encodings and how everything boils down to `1`s and `0`s (or current and no current respectively).

→ Briefly start at the desired lowest abstraction layer, e. g. (light) switches, and explain how they're used for creating processors.

→ Ask students about games they play and have them describe possible player *actions* and compare them with actual player *input*.[7]. This repeats top down abstraction decomposition as maybe already encountered in the introduction to programming lessons and allows to bring the foundational idea of multitier architectures back to students minds.[8]

→ Have students go back to a sample or one of their own Processing progams and let it (again) be displayed in machine code. Provide them several examples, e. g. with variable assignment, with conditionals and loops, and let them assemble the required machine code mnemonics and byte values.[9] Suggest variations for the example, so that even with less programming experience they may find regularities.

[7] Alternatively, if starting from art instead of games, decompose drawing e. g. a house into individual brush strokes
[8] Multitier architectures might already have been discussed as part of networking lessons.
[9] Ideally, distribute the examples over small student groups, two groups per example.

→ Collect their findings and group their arguments: pushing to the stack/accumulator (machine codes 0–83), returning (88–94), binary arithmetic and comparison operations (96–111), common commands (112–127), message sending/function calls (128–175), jumps (176–199), storing results (200–216), combined multi-byte instructions (first byte: 224–255) [18, p. 12].[10]

→ Take a step back: What is relevant for running a program? This should yield memory, (arithmetic) operations, input and output and control flow. Let students go back to their examples and see if Processing code doing for one or multiple of these core concepts map to the found machine codes.

→ Introduce von Neumann architecture (see figure 5.2) as an abstraction of the encountered concepts. What physical parts of a computer belong to the idealized concepts?

→ Discuss virtual machines in comparison to physical machines[11] and the difference of stack and register machines, VMs tending to the former and physical machines to the latter.

→ Go back to Processing and inspect a combined execution view (see figure 5.3). By stepping forward and backward, students should be able to observe the role of the stack and the program counter. Let them explore execution flow and write down what role the program counter has and what the calling convention for Processing API calls seems to be.

→ As a break or maybe as homework, let students play "Human Resource Machine"[12] [4], which introduces students to a different architecture. The first 6 levels should be doable for everybody, with quicker students finding sufficient challenges later on.[13]

→ Compare the two instruction architectures with relation to expressitivity and register vs. stack based design.

→ Finally, treat circuits, logic gates, transistors and maybe down to silicon outside of GT to the desired depth.

5.3 Lesson on Compilers

Once students have an approximate understanding of into what a program must be transformed in order to be run on actual hardware or inside a VM, the question remains as to how the transformation from source code to machine code happens.

While this is usually not in the focus of a general introduction into computer science beyond the superficial treatment occurring during the lessons on computer architecture, this is quite relevant for students specializing in computer science.

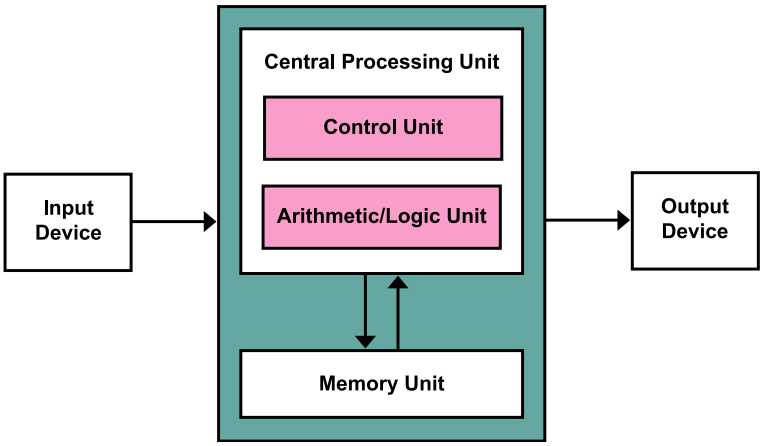
However, using the environment presented here, this topic could just as well be used either for all students or for quicker students to work on mostly by themselves. Part of the lesson presented here has indeed been validated under these circumstances (cf. 6.2).

[10] Students should at this point be able to explain where these seemingly odd number ranges stem from.

[11] VMs being used for portability reasons such as the Smalltalk VM, the Java VM, Microsoft's dotNet VM or any browser's VM for WASM.

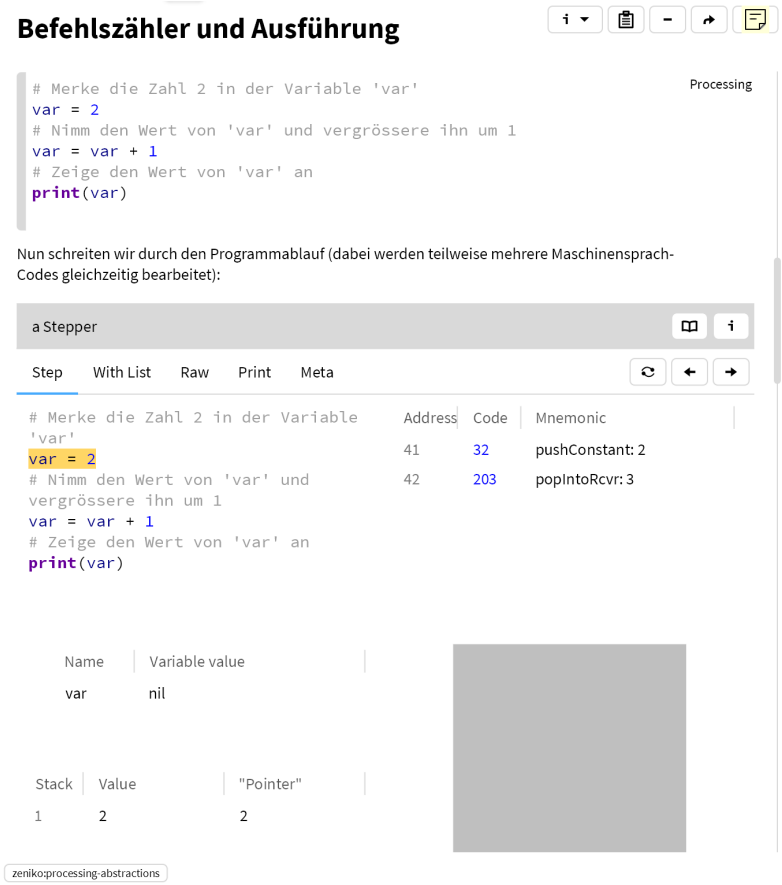
[12] The "Hour of Code Edition" is free to download for notebooks.

[13] You can also come back during compiler lessons, as "Human Resource Machine" has implementing various optimizations as additional challenges.



☰ replace or properly attribute: Kapooht, 2013, CC BY-SA 3.0

Figure 5.2: Von Neumann architecture.



☰ Decide which screenshots belong into the appendix instead.

Figure 5.3: Excerpt from an interactive notebook page on program execution in a VM.

5.3.1 Educational objective

After these lessons, students should be able to ...

- explain the difference between high and low level languages.
- enumerate the steps required during compilation, using proper terminology (lexer, parser, transpiler, compiler, optimizer).
- connect this knowledge with their knowledge on computer architecture and programming.

5.3.2 Prerequisites

Students must have experience in programming and computer architecture, e. g. from the lessons described above (cf. **??** and 5.2). It helps, if their programming experience is based on Processing or at least Python. Additionally, the need to have GT installed and introduced (see 5.1.3).

5.3.3 Lesson Plan

The natural way to progress on understanding a compiler is top down, which is the same as chronological order:

→ Before starting to fill in the content missing from the previous lesson on computer architecture, begin with a repetition on how a program is run in a VM (see figure 5.3), letting students run again a given or one of their own program and seeing into what commands their code was translated.

→ As an analogy, analyse with students how they would go about translating an unknown language using just a dictionary: splitting the text into words where punctuation yields some structure; then looking words up (where again several words might belong together for the sake of translation[14]); writing the translation down; and finally rewriting it so that it sounds more akin to how you'd write it in the target language. This analogy yields a fitting overview over the different steps involved.

→ Now let students work through discovering the individual concepts encountered:

- Have them compare a program and the resulting lexed tokens: What modifications to a program result in different tokens, what modifications don't cause changes? What does this correspond to in the analogy about translating a natural language?
- Have them compare the abstract syntax trees resulting from their program(s). Are they able to explain how the parser structures the tokens together? How would they go about if all they saw were just two tokens? (For this, use a view of tokens showing just two lines.)
- Discuss how a recursive descent parser works through tokens. Since Python and thus Processing based on Python uses indentation for command grouping, also highlight the need for tracking indentation at least per statement.
- Optionally have students compare given Processing source code with the resulting AST and transpiled Smalltalk: How literal is the translation? What is different between Processing and Smalltalk? Have them try to invent a syntax of their own which is easier to map to the AST (and later discuss Lisp and Forth syntaxes as examples for alternative, easier to parse syntaxes[15]).

[14] Compare e. g. the meanings of "see", "see to", "see through" and "see out".
[15] Views for variants of both are available.

- Since usually, an intermediary representation is directly produced from an AST, collect common statement types (variable assignment, function calls, loops, ...) and have them translated live to intermediary representation. Let students work out common patterns to see what translation might take place.
- Have views for intermediary representation and actual Smalltalk bytecode side-by-side for students to figure out, what transformations remain and why these might be required (comparing with their knowledge from computer architecture lessons).
- Should students have prior experience with "Human Resource Machine" [4], have them translate Processing to a program in that game's simplified language and translate code for a level of that game back to Processing (and from that Smalltalk bytecode with the environment's help).
- For the final step, offer some simple code examples which can obviously be simplified.[16]. What optimizations are present in the intermediary representation and which in bytecode? What patterns could be optimized? Also discuss the difference of optimizing for size, for speed and for quick compilation.[17]

→ What can't be shown inside GT are the equivalent of optimizations within a processor (or already the x86, IA64, *etc.* code produced by the Just in Time compiler). Students should at this point however have sufficient understanding of the various transformations, that they might be able to understand what happened e. g. with the Spectre attack [36] and why understanding of machine code might be relevant for timing attacks.

5.4 Further Lesson Ideas

Whereas the environment presented here is mainly targeted at introductionary high school classes, it might also be employed in a specialization course. Since this isn't this thesis' focus, we'll just list a few ideas:

- Smalltalk is a rather elegant language and has aged quite well. It can still be used to introduce students into pure object oriented programming with a for them somewhat unusual syntax. And such an introduction could use transpilations from "Processing Abstractions" as a stepping stone, if students have already used it.
- Since the here provided code is run dynamically in Glamorous Toolkit, it can also be molded further, e. g. to implement as of yet missing support for object oriented programming.
- The provided code might also be used as a template for students to implement their own programming language or see if they manage to write an interpreter for one of the two provided prefix and postfix mini-languages.[18]

[16] E. g. `print(1+1+1+1+1)` or `for i in rnage(10): pass`, both of which should be trivially optimizeable

[17] For players of "Human Resource Machine", the first two are the bonus challenges for all later levels.

[18] This might already have been discussed in the compiler lessons above. Very briefly, a program such as `a = 42; print(a)` is translated to `(= a 42) (print a)` and `$a 42 = a print` respectively which both should be simple enough to parse.

6 Validation

The contents produced for this thesis have been used with two courses. Evaluation of the feedback provided by students show that they did like working with the provided environment and that their understanding of the abstractions involved in programming have increased somewhat. Due to limitations in the study setting, however further analysis will be required in order to generalize these findings.

Both courses were held with classes at Gymnasium Neufeld which we have been teaching ourselves for one and two years respectively. These classes consist of Swiss high school students at ninth and tenth grade (of twelve grades) respectively.

6.1 First Round

6.1.1 Setting

The first evaluation round took place in a computer science class consisting of 17 tenth grad students. This class had at this point encountered most of the base curriculum of computer science as required in the Canton of Berne [13, p. 145–146] with only the introduction to systems architecture missing.

Specifically, the introduction to programming had happened using Processing with Python syntax inside the Processing IDE, so students had already the desired prior experience in programming with Processing. Additionally, the class had written their last partial exam five weeks prior which had among others contained a repetition sequence on binary numbers and encodings.

Contrary to the suggestions in 5.2, the introduction to computer architecture was happening bottom up, loosely following Nisan and Schocken's ideas [42] in a significantly abbreviated course of only 6 instead of 12 weeks.[1]

At the point where the environment developed for this thesis was introduced, students had already encountered some of the foundational building blocks of a modern microchip: transistors built out of semiconductors, logic gates and circuits up to an adder circuit as the basis of an ALU.

The plan was thus to connect the already encountered foundation with their knowledge about programming by revealing and discussing several of the involved abstraction layers. Due to time constraints, only

[1] The reason for this was originally the same as Nisan and Schocken's, i. e. building concepts on a solid foundation.

an excerpt of the sequence proposed in 5.2 could be realized.

At the day of the lessons, 14 of the 17 students were present. At the start of the first lesson, "Glamorous Toolkit" was distributed through the school's OneDrive infrastructure. The GT environment was then introduced similar to 5.1.3 but, as was the rest of the lessons, mostly in a self-guided way with instructions being provided in GT notebook pages.[2]

During the lessons, students were supported where needed but left to work at their own individual pace which the reduced number of students allowed for. Afterwards, a questionnaire was distributed to students for receiving their own feedback in addition to the collected observations.

At least one of the students missing the lessons was successfully able to work on the provided contents on her own.

6.1.2 Observations

During the time available, students have been able to work on their own for large amounts of time with only few common issues occurring. The interactive notebook pages seemed to allow for creating an effective teaching environment.

Additionally, many students have been observed to actively tinker with the interactive elements, as was desired and was to be expected from providing an environment for live programming and exploration. Except for a few hickups where the GT notebook pages stopped updating (for which the usual cure of "reloading" helped), the interactivity worked reliably – up to the point, where students found it so engaging that they got sidetracked by writing and modifying programs for their effect instead of the changes to the views for different layers.

Nonetheless, the more active students have been able to work through the subject matter on their own, whereas less interested students had to be motivated from time to time to continue reading and interacting. With students being able to work on their own, we had ample time for supporting these students with instructions, hints and some motivating background information.

Despite their prior Processing knowledge, students were sometimes out of their depth when changes to a Processing program were asked for. In a next round, this sequence would have to be placed closer to a programming sequence with Processing or at least a brief repetition of just using Processing would be helpful.

What caused most issues was the way GT opened notebook pages from content links in a new page adjacent to the previous one, hiding the table of contents in the process, instead of opening them in place of the previous page as students were used to from webbrowsers. This caused students to lose track of on what pages they were supposed to be working, to the point of occasionally skipping part of the assigned content. This happened despite the brief introduction into working with GT where closing additional pages and getting the table of contents back was an explicit introductionary task.

The overall impression of the lessons was that students had been working productively, mostly autonomously and at their own pace with the provided teaching materials.

6.1.3 Student Feedback

In order to verify our own observations, students were provided with a questionnaire for providing feedback. Of the 17 students, however only 11 returned feedback despite frequent reminding. The following yields thus at best qualitative results.[3]

[2] The exact state of the materials is available on GitHub [48] in commit `71047704f7f70c13d3d01ac520618e15d569274f` of May 12th.

[3] Questionnaire data in anonymized for is available at `https://github.com/zeniko/gyminf-thesis/blob/main/data/data_6_1.csv`.

Additionally, three weeks later, the students have written another partial exam with individual tasks referring back to the lessons with GT.

Student feedback shows the following: Students quite liked working with the provided environment (grading it in mostly 4/5) and reported that it worked reasonably well but not yet perfect (most students grading it either 3/5 or 4/5). This is consistent with our own observations.

Part of the reason for their liking working this way might be due to their noting programming (and one game programming project one year ago) as what they liked most about their computer science class with half the students naming this their "highlight".

When asked explicitly about the usefulness of the various abstraction views provided, students noted that they were very useful (mostly grading it either 4/5 or 5/5). Also, a majority of students indicated repeatedly actively interacting with the program samples.

What they liked the most was being able to work at their own speed (and optionally being able to decide for themselves whether to work together or alone) which is due to guidance from the environment which allows to introduce interactive tasks in place which students may explore autonomously in order to understand. One student explicitly noted that being able to see changes reflected instantly was gratifying.

Their main concern was two of the more engaged students noting that some explanations were not yet as clear as they could be, requiring them to ask instead of being able to work for themselves. Additionally, the quickest working student would have preferred fewer links within notebook pages, reducing the annoyance of losing the table of contents from webbrowser habits.

Students gave their feedback between one day and one week after the lesson. When asked to reword the learned content in their own words, most of them failed to describe what they'd learned entirely correctly. Would there answers have been graded, all but one students would have only been awarded at most half the points. Also, the desired connection with the previously taught contents about transistors and logic gates remained unclear with this time all students getting at most half the points.

Finally, the partial exam resulted in students answering questions related to these lessons only about 46% correctly. The result does however weakly correlate with students' general commitment (measured by their final grade, yielding a rang correlation of 0.48).

6.1.4 Learnings

The desired effects of having students better understand abstraction layers seems to not yet have been achieved. While the environment was engaging and led students to explore on their own, explanations will have to be expanded and made clearer for students to be able to fully understand what they're shown.

Part of the issue is however that time was too short and the implementation not fully fledged out, so these findings might also be due to both of these. So further analysis will be required and the environment will have to be tested at a larger scale with the other classes with better integration in the curriculum (as suggested by the author in 5.2).

At least some of the technical issues observed have since been remedied, although mostly by more explicitly telling students what to do when issues arise.

Also, since GT runs purely on the student's own computers, their progress can't be observed other than by monitoring their screens. For this, either a separate progress tracker (such as `https://learningview.org/`) would have to be used or a sequence of short tests, not only checking for progress of reading but also of comprehension.

☰ consider removing page linking in "Unterrichtseinheiten"

6.2 Second Round

6.2.1 Setting

The second evaluation round took place in a computer science class consisting of 23 ninth grade students. This class had at that point passed about half the required contents of the base curriculum to computer science [13, p. 145–146], including application usage, various encodings, algorithms and an introduction to programming using Processing eight weeks prior.[4]

Two lessons at the end of the school year could be set aside for an introduction to compilers as part of this thesis. These would usually have to be placed later in the curriculum, either together with the introduction to computer architecture or beyond.

The plan was to implement an excerpt of the course from 5.3. As a quick overview, "Human Resource Machine" was used for introducing students to the limitations of machine language and motivating the need for compiling programs before executing them on actual hardware. Afterwards, GT was introduced with additional stress on using the table of contents for navigation. Finally, students were asked to work through the provided contents at their own speed. Towards the end of the lessons, students were given time to fill out a questionnaire.

One unplanned limitation of these lessons were summer being early with high temperatures. As a consequence, only 15 of the 23 students were present for the introduction and the introduction had to be moved to a different, cooler location.

6.2.2 Observations

In general, the students worked reliably with the provided contents. In particular, this group seemed to quite naturally take notes within the GT notebook pages, making the content their own.

Working speed again was heterogenous, but some smaller groups formed which supported each other. One student in particular volunteered repeatedly to help his peers.

Despite programming with Processing being rather fresh, fewer students seemed to interact with the sample programs provided, despite tasks asking them to do so explicitly. About half the students seemed content to observe views as static content.

This group had more problems getting GT even to run. Even though these students had already successfully downloaded and used apps on their own, somehow despite a separate GT launcher in the top level folder being provided, many failed to start GT on their own.

Part of these issues might however relate to temperatures making it more difficult for students to focus.

6.2.3 Student Feedback

Of the 15 students present, 14 managed to hand in the questionnaire (with the last student's computer running out of battery). With this small number of answers, again no reasonable quantitative evaluation is possible.

The students answers show that many of them (12/15) have worked slower than expected, only learning about lexer and parser in the hour provided. Also, disappointingly only two of the 15 were at least somewhat confident that they would be able to explain the learned content to their peers.

This is consistent with students failing to answer basic questions about the need for compilation (half of them not answering or answering entirely wrong) but slightly better about the roles of lexer and parser (one third answering correctly and one third getting at least half of their answer correct).

[4] For timing reasons, unfortunately the programming project had to be postponed.

It is difficult to judge how much of this is due to the environment not meeting expectations and how much is due to summer, as when asked directly about their thoughts of the provided environment, students wrongly referred ot the latter than the former.

The only general remark where students agreed on was that they had enjoyed programming (11/15) which however in contrast to the other class (see 6.1) did not result in as much tinkering (with only 4/15 students reportedly playing around and exploring).

6.2.4 Learnings

Unfortunately, not much was to be learned from this test, mostly due to environmental factors. A repetition of this setting will thus be required at a later time.

At least the content that students actually got to seems to have been sufficiently clear for them to somewhat understand.

7 Conclusion

7.1 Future Work

- Lack of first class functions (beyond code blocks): transpiling only known functions
- No type checking (Python and Smalltalk are both strictly but dynamically typed)
- Option to translate bytecode or intermediary code to other assembly syntaxes (Intel x86, LMA, WASM, ...)

A

Installing and Using Processing Abstractions

In order to set up Processing Abstractions, first download Glamorous Toolkit from https://gtoolkit.com/download/ for your platform and extract the archive's entire content.

Before running it, create a new text file called startup.st in GT's top-level folder besides GlamorousToolkit.image with the following content (access it through figure A.1):

```
Metacello new
   repository: 'github://zeniko/gt-exploration:thesis/src';
   baseline: 'GtExploration';
   load.

Metacello new
   repository: 'github://zeniko/processing-abstractions:thesis/src';
   baseline: 'ProcessingAbstractions';
   load.

"Hide the 'Implementation and Tests' section."
GtExplorationHomeSection studentMode: true.

"Make indenting keyboard shortcuts available to non-US-English keyboard layouts
(cf. https://github.com/feenkcom/gtoolkit/issues/3002)."
LeSnippetElement keyboardShortcuts
   at: #IndentSnippet
      put: BlKeyCombinationBuilder new alt shift arrowRight build;
   at: #UnindentSnippet
      put: BlKeyCombinationBuilder new alt shift arrowLeft build.

"Make the zoom in keyboard shortcut available to de-CH keyboard layouts
(cf. https://github.com/feenkcom/gtoolkit/issues/4624)."
TLeWithFontSize compile:
   ((TLeWithFontSize methodNamed: #initializeFontSizeShortcuts) sourceCode
      copyReplaceAll: 'equal' with: 'shift minus').

"Patch unneeded addressbar out of YouTube snippet
(cf. https://github.com/feenkcom/gtoolkit/issues/4560)."
```

Figure A.1: QR-link to the code for `startup.st` for convenience

```
LeYoutubeReferenceElement compile:
   ((LeYoutubeReferenceElement methodNamed: #updatePicture) sourceCode
      copyReplaceAll: '</iframe>'' ' with: '</iframe>''; removeChildAt: 1 ').
```

Finally run the `GlamorousToolkit` executable (under Windows and Linux it's located in the `bin` subfolder). The content of `Processing Abstractions` are now available behind the "Unterrichtseinheiten" home tile.

Verify that everything works as desired and then close and save the changes to the image. Now, the above `startup.st` can be removed, since all its changes have been persisted in GT's `.image` file.

Warning: If you've already used GT before, the contents of your local knowledge database will also be included in GT's image. Therefore rename that folder (usually `lepiter/default` in your documents folder) before starting the GT meant for distribution.

Also, since the executable `GlamorousToolkit.exe` is located in a subdirectory under Windows and Linux, adding a top-level link can help students. See `https://github.com/zeniko/gtRunner` for a ready-to-use drop-in.

B GT Processing API

This appendix lists the available API calls implemented in Processing Abstraction's Processing. This has been auto-generated from GT page "Processing API":

B.1 Rendering

B.1.1 Setup

`background(r, g, b)`
Clears the canvas and changes its color (see `fill(r, g, b)`). Default is light gray (192, 192, 192).

`background(gray)`
Clears the canvas and changes its color (see `fill(gray)`). Default is light gray (192).

`size(width, height)`
Prepares an output canvas of the given dimensions. This command must always be called first (for animations: first command in `def setup`).

B.1.2 Shapes

`circle(x, y, d)`
Draws a circle with the given diameter and its center at `(x; y)`. Short for `ellipse(x, y, d, d)`.

`ellipse(x, y, dx, dy)`
Draws an ellipse with the given diameters and its center at `(x; y)`.

`image(image, x, y),image(image, x, y, width, height)`
Renders the image loaded with `loadImage(...)` at the given coordinates (and scales it to fit the given size). Arguments following after the first are identical to `rect`'s. If `width` and `height` are not given, the image's native dimensions are used.

`line(x1, y1, x2, y2)`
Draws a line from `(x1; y1)` to `(x2; y2)`.

`loadImage(pathOrUrl)`
Loads the image from the given URL or path. The returned value is to be used with `image(...)`. Paths can be absolute or relative to either `FileLocator class>>gtResource` or:

```
Element
GtInspector newOn: FileLocator documents / 'lepiter'
```

`rect(x, y, width, height)`
Draws a rectangle of the given width and height, parallel to the coordinate axes with its top left corner at `(x; y)`.

`square(x, y, side)`
Draws a square with the given side length, parallel to the coordinate axes with its top left corner at `(x; y)`. Short for `rect(x, y, side, side)`.

`text(string, x, y)`
Renders the given `string` with its baseline starting at `(x; y)`.

`textSize(size)`
Sets the size for rendering text in pixels. Default is 12px.

`triangle(x1, y1, x2, y2, x3, y3)`
Draws a triangle with its vertices at the points `(x1; y1)`, `(x2; y2)` and `(x3; y3)`.

B.1.3 Colors

`color(r, g, b)`
Generates a color object which can be stored in a variable also be used with `fill(...)`, `stroke(...)` and `background(...)`.

`fill(r, g, b)`
Selects the color to use for filling rendered shapes. The color is given as three values in the range of 0 to 255 (red, green and blue respectively). Default is white (255, 255, 255).

`fill(gray)`
Selects the gray scale value to use for filling rendered shapes. The color is given as a single value in the range of 0 to 255 (black/dark to white/light). Default is white (255).

`noStroke()`
Disables borders for future shapes. Equivalent to `strokeWeight(0)`.

`stroke(r, g, b)`
Selects the color to use for the borders of rendered shapes (see `fill(r, g, b)`). Default is black (0, 0, 0).

`stroke(gray)`
Selects the gray scale value to use for the borders of rendered shapes (see `fill(gray)`). Default is black (0).

`strokeWeight(weight)`
Determines the size of drawn borders in pixels. Default is 0.5px.

B.1.4 Transforms

`rotate(angle)`
Rotates all future shapes by the given angle (in `radians`!) clockwise around the origin.

`scale(factor)`
Linearly scales all future shapes by the given factor from the origin.

`translate(x, y)`
Moves the origin `(0; 0)` for all future shapes (defaults to the upper left corner).

B.2 Events

`def draw():`
is called repeatedly (up to `frameRate` times per second) for drawing the output.

`def mouseClicked():`
is called whenever a mouse button has been clicked *and* released.

`def mouseMoved():`
is called whenever the mouse has been moved. Alternatively query `mouseX` and `mouseY` in `draw()`.

`def mousePressed():`
is called whenever a mouse button has been pressed. Alternatively query `mousePressed` in `draw()`.

`def mouseReleased():`
is called whenever a mouse button has been released.

`def setup():`
is called once as the program starts.

B.3 Mathematics

`cos(angle)`
Returns the cosine value for the given angle (measured in radians).

`int(value)`
Rounds the value to an integer.

`PI`
The value of the mathematical constant p.

`max(a, b)`
Returns the larger of the two values (`max(a)` returns the largest value contained in the list `a`).

`min(a, b)`
Returns the smaller of the two values (`min(a)` returns the smallest value contained in the list `a`).

`radians(angle)`
Converts the given angle (measured in degrees) into radians.

`random(limit)`
Returns a random floating point number between 0 and limit (inclusive).

randomSeed(seed)
Reinitializes the random generator with the given `seed` number. Using the same number will result in the exact same sequence of pseudo-randomly generated numbers.

sin(angle)
Returns the sine value for the given angle (measured in radians).

sq(value)
Returns the squared value. Equivalent to `value ** 2`

sqrt(value)
Returns the square root of the given value.

tan(angle)
Returns the tangent value for the given angle (measured in radians).

B.4 Lists

append(list, value)
Appends the value to the end of the list and returns *a new* list (equivalent to `list + [value]`).

concat(list, otherList)
Combines the two lists to a single *new* list (equivalent to `list + otherList`).

reversed(list), reverse(list)
Returns a *new* list with its content reversed. (Note: `list[::-1]` is *not yet* supported.)

shorten(list)
Returns a *new* list without the last argument (equivalent to `list[:-1]`).

sorted(list), sort(list)
Returns *new* list with its content sorted.

B.5 Miscellanea

delay(ms)
Waits `ms` milliseconds before continuing (mainly needed for demonstration purposes).

frameRate(fps)
Limits the frame rate of animations to a maximum of `fps` frames per second. Default is 30.

height
Contains the canvas height as set by `size()`.

millis()
Returns the number of milliseconds that have passed since the program has started.

mouseX, mouseY, mousePressed
Contains the `x`- and `y`-coordinates of the mouse cursor and whether the mouse has been pressed at the start of a `draw`-phase (undefined outside of `draw`).

print(value), println(value)
Prints the given value into an output console (mainly for debugging and for graphic-less program).

`str(value)`
Turns the value into a string, e. g. for concatenating several values for use with `text(...)`.

`width`
Contains the canvas width as set by `size()`.

☰ Synchronize with `https://github.com/zeniko/gt-exploration/blob/thesis/lepiter/68t44r92c7d0lr4e4ggiqmsq8.lepiter` and `https://github.com/zeniko/processing-abstractions/blob/thesis/lepiter/310yy5nuue5px1i3go4w0bjqo.lepiter`

C

Technical Implementation of “Processing Abstractions”

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