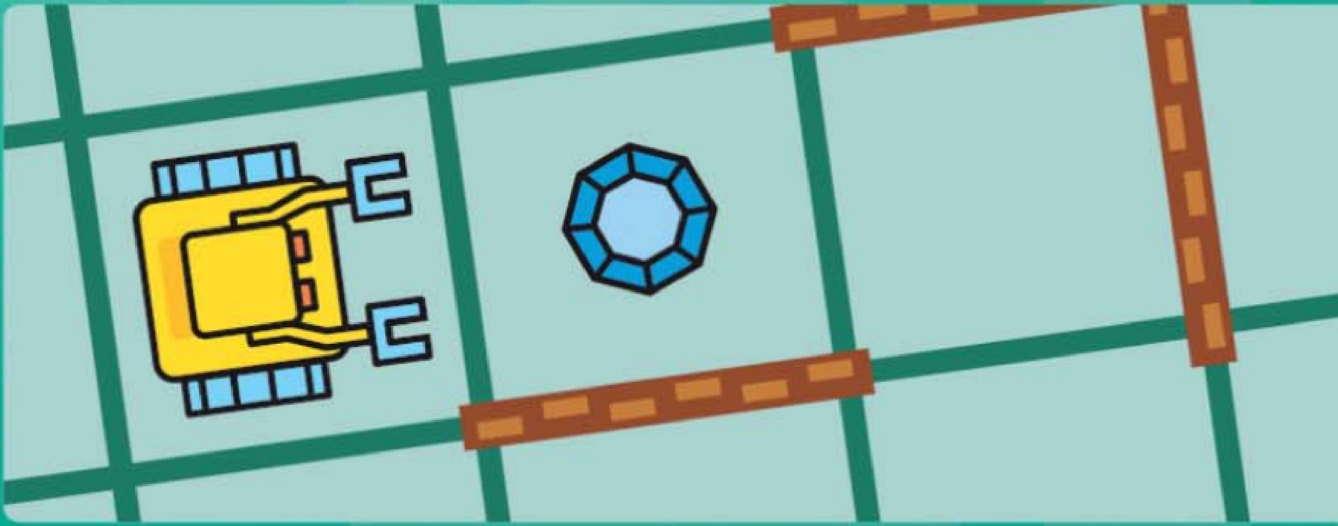
More Than Coding

Learn how to **Think** with Karel the Robot



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About the Author

Dr. Pavel Solin is Professor of Applied and Computational Mathematics at the University of Nevada, Reno. He has been programming computers for 25 years, using computing to solve major projects for U.S. Departments of Energy and Defense, and directing several major open source software projects. He is the author of six monographs and many research articles in international journals. Besides this, Dr. Solin enjoys working with K-12 teachers and students. For more information, visit Dr. Solin's home page `http://nclab.com/pavel/`.

Acknowledgment

We would like to thank many teachers and instructors for providing feedback that is helping us to improve the textbook, the self-paced Karel course, and the Karel language itself.

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Preface

Computer programming is fun. Telling a machine what to do and watch it actually perform the task is amazing. Interacting with the computer will teach you *how to think* and *how to solve problems*. These are the two most important skills in computer programming. Programming is all about breaking complex problems into simpler ones, and solving them, which is very useful in real life as well.

Now, why lose time with an educational programming language if you could learn right away with a real programming language such as C++ or Java? Indeed, these languages are much more powerful than Karel the Robot. But they are not visual, have complicated syntax, and you will end up doing boring math problems in no time. In contrast to that, Karel the Robot is visual, has very simple syntax that allows you to focus on the programming logic that you need to learn in the first place, and it does not contain complicated math (really - there is no arithmetics in Karel since math and programming are two very different things).

Karel the Robot was created at the Stanford University by R.E. Pattis who also wrote the original textbook *Karel the Robot: A Gentle Introduction to the Art of Programming* in the 1980s. His Karel was aimed at university-level students and the syntax was influenced by Pascal, a major programming language of that era. We updated the language while preserving Pattis' original ideas. Our implementation is more oriented towards K-12 students.

The syntax and programming style of our Karel is similar to Python, a major programming language of modern engineering, science, and business applications. After you get used to computational thinking with Karel, learning any new programming language will be much easier for you. NCLab has a follow-up Turtle programming course where you will draw beautiful patterns and even export them for 3D printing. The Turtle has full Python syntax, which you will learn effortlessly in a fun and visual environment. Last, NCLab also has a full Python programming course which exposes you to the reality of problem solving with a powerful programming language. Taking both Karel and Turtle before Python is strongly recommended. For now, have fun with Karel and make sure that you complete at least Karel 1 and Karel 2 (70 game levels).

Have fun and good luck!

Pavel Solin

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1 Earn Black Belt in Computer Programming!

The best way to learn with Karel is to go through the self-paced and self-graded Karel programming course in NCLab, using this textbook as a reference. Karel (shown in Fig. 1) is a determined robot who embarks on a quest to find his missing friend.

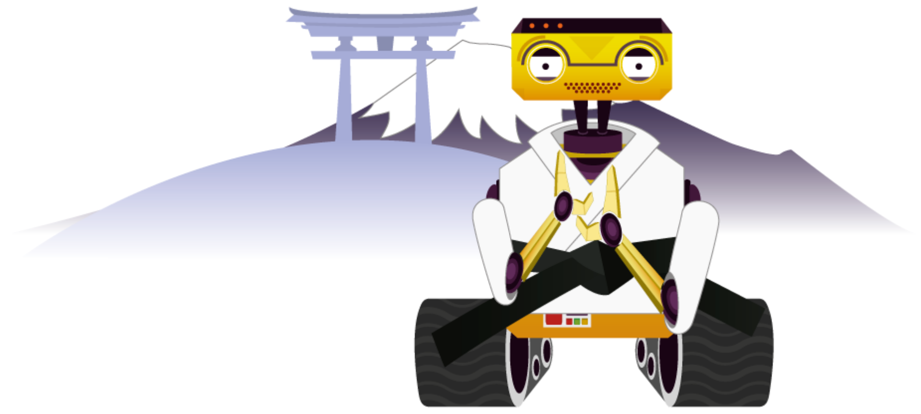


Fig. 1: Karel the Robot.

The course comes with many examples and tutorial videos that ensure that every student can progress at his or her own pace. Lesson plans and student journals are available. The instructor does not have to be an expert in computer programming by any means. The course has over 70 engaging game levels that ensure an exciting and fulfilling learning experience for all students.

Recommended minimum age of students is 10 years because of keyboarding skills, and there is no upper age limit. In fact, many teachers use the Karel course to learn computational thinking skills themselves, and adult learners in general enjoy the course as much as do K-12 students.

A great complementary activity to solving game levels in the self-paced course is creating your own mazes and games, and publishing them on the web for your friends to play. The lesson plans contain more details, and tutorial videos are available on NCLab's home page.

1.1 White Belt

Every student begins his or her journey with solving seven levels in manual mode, earning the White Belt. These levels are designed to make the students familiar with the five basic commands Go, Right, Left, Get, and Put for the robot, with the four directions on the compass, with various game goals and limitations, as well as with the relative right and left (as seen from the point of view of the robot). Fig. 2 shows a sample level *Goldmine* from this section. Here, Karel's task is to collect three gold nuggets and return to his home square, using at most 20 steps. Students guide the robot by clicking on buttons.

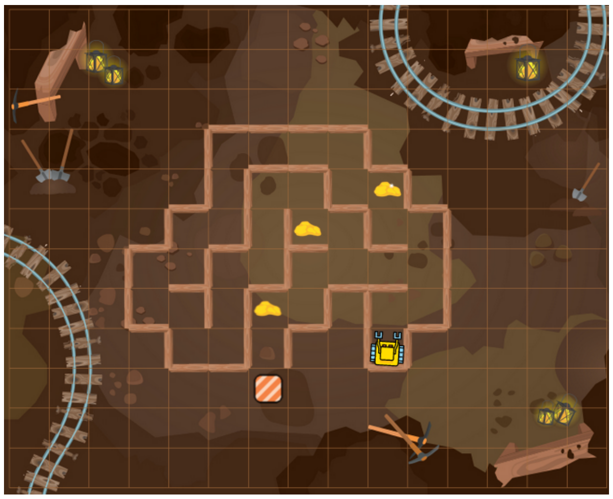


Fig. 2: Sample level *Goldmine* in the White Belt section.

1.2 Yellow Belt

The Yellow Belt section has four Degrees, each one requiring the students to complete seven game levels (28 levels total). In Degree 1, students type elementary commands instead of clicking on buttons. Fig. 3 shows a sample level *Phone* where Karel needs to move the phone on the mark and enter his home square.

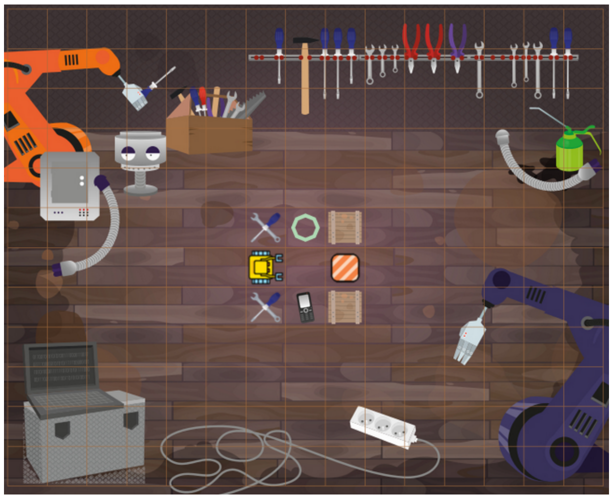


Fig. 3: Sample level *Phone* in Yellow Belt 1.

In Degree 2, students learn how to use the repeat loop. Fig. 4 shows a level *Forgotten* where Karel needs to pick up four books and put them in the bags, using at most 10 lines of code.

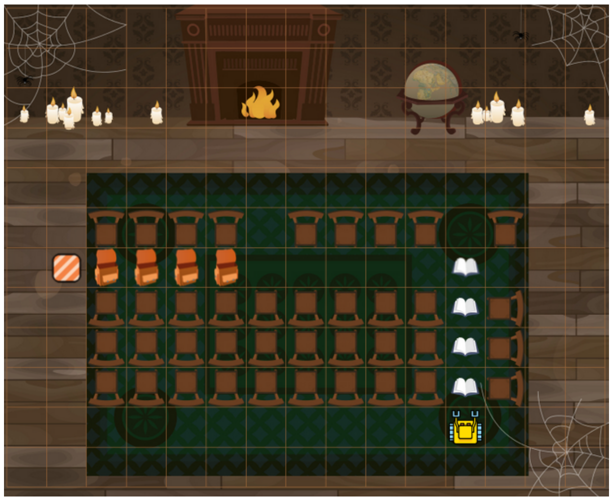


Fig. 4: Sample level *Forgotten* in Yellow Belt 2.

In Degree 3, students learn about if-else conditions. Fig. 5 shows a sample level *Storm* where Karel needs to pick up a medkit, and return home by following a trace of coins and gears.

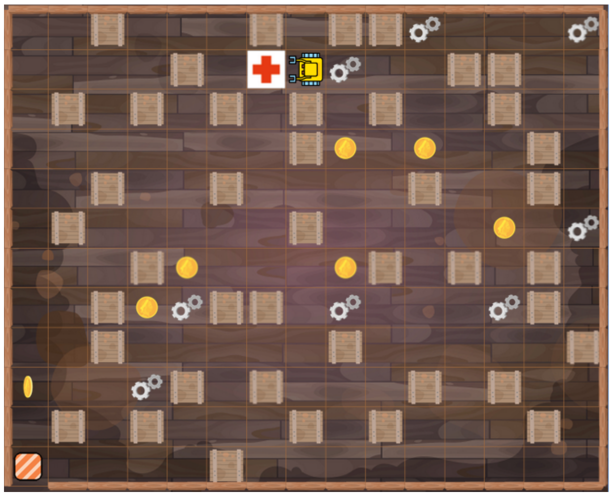


Fig. 5: Sample level *Storm* in Yellow Belt 3.

In the last Degree 4, students learn about the while loop. Fig. 6 shows a sample level *Tunnel* where Karel must collect all keys and reach his home square.

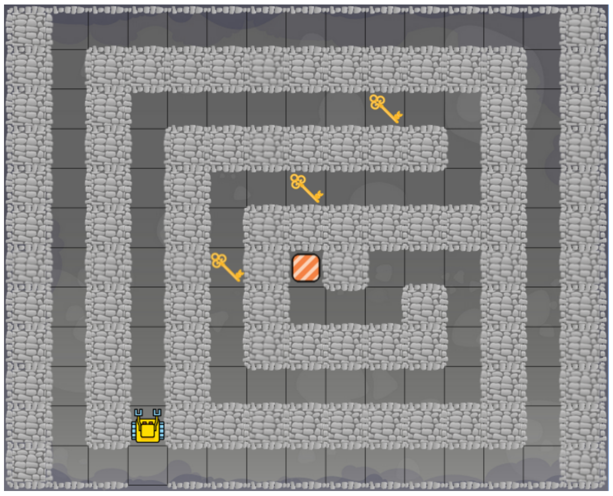


Fig. 6: Sample level *Tunnel* in Yellow Belt 4.

1.3 Purple Belt

The Purple Belt section has 21 game levels that are split into three Degrees. In Degree 1, students learn about custom commands. Fig. 7 shows a sample level *Water* where Karel must collect all water bottles in order to survive in the desert.

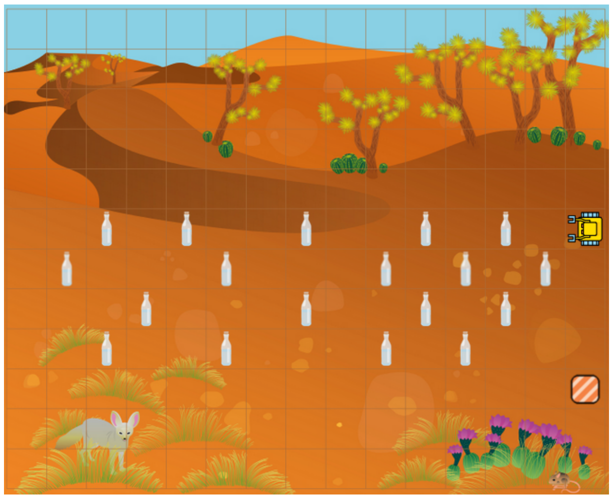


Fig. 7: Sample level *Water* in Purple Belt 1.

In Degree 2 students learn about variables. Fig. 8 shows a sample level *Pipeline* where Karel must count all missing pieces in the pipeline.

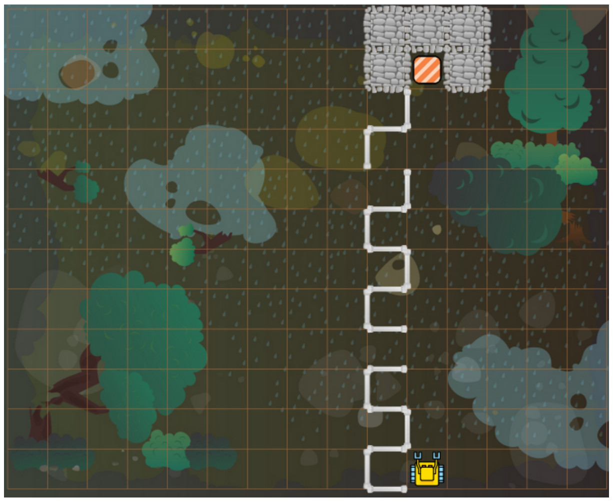


Fig. 8: Sample level *Pipeline* in Purple Belt 2.

In the last Degree 3 students learn about Python lists. Fig. 9 shows a sample level *Rugs* where Karel needs to move all rugs from one house to another, remembering their exact positions.

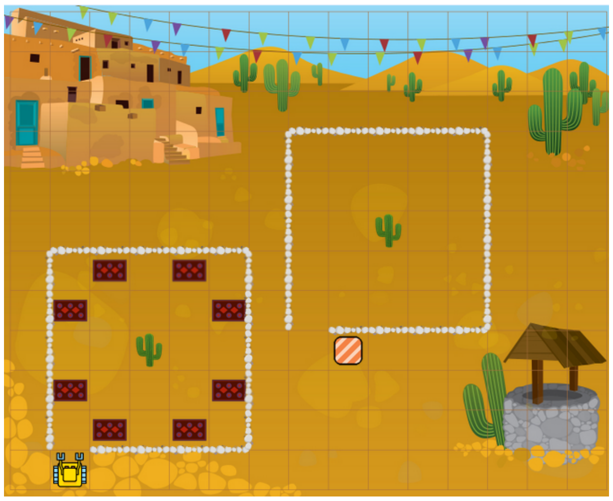


Fig. 9: Sample level *Rugs* in Purple Belt 3.

1.4 Black Belt

The Black Belt has 14 levels that are split into two Degrees. In Degree 1 students learn about recursion. Fig. 10 shows a sample level *Bakery* where Karel needs to eat all pies without using loops.

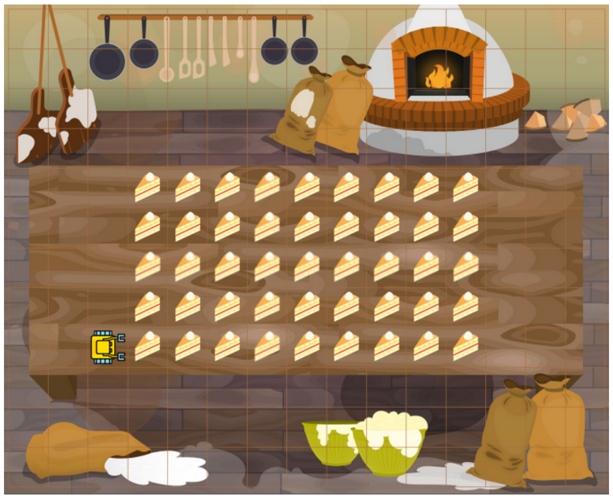


Fig. 10: Sample level *Bakery* in Black Belt 1.

Finally, in Black Belt 2 students apply the techniques and concepts they learned previously, to solve challenging problems. In Fig. 11 Karel needs to clean four oil blots using only 10 lines of code (this leads to three levels of nested loops).

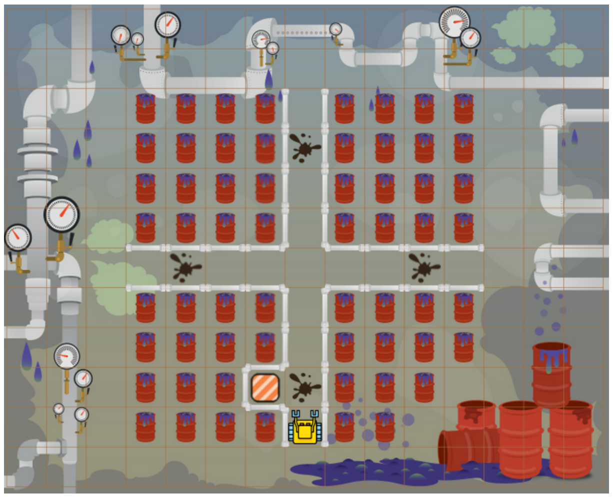


Fig. 11: Sample level *Hazard* in Black Belt 2.

1.5 Extras and Bonuses

For extremely talented students who get way ahead of everyone, there are two more sections with challenging problems where they are guaranteed to find their match. Fig. 12 shows a sample level *Land Surveyor* where Karel must calculate the area of a garden of an arbitrary shape, without actually entering it, just using his GPS coordinates.

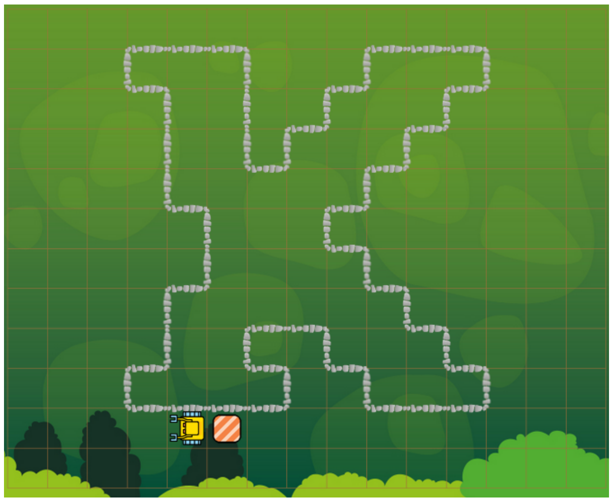


Fig. 12: Sample level *Land Surveyor* in Extras and Bonuses.

2 Introduction

2.1 Objectives

- Learn basic facts about the Karel language and its history.
- Learn how Karel differs from other programming languages.
- Learn what skills this course will give you.

2.2 Brief history

The educational programming language Karel the Robot was introduced by Richard E. Pattis in his book *Karel The Robot: A Gentle Introduction to the Art of Programming* in 1981. Pattis first used the language in his courses at Stanford University, and nowadays Karel is used at countless schools in the world. The language is named after Karel Čapek, a Czech writer who invented the word "robot" in his 1921 science fiction play R.U.R. (Rossum's Universal Robots). Various implementations of the language that can be downloaded from the web are shown in Fig. 13.

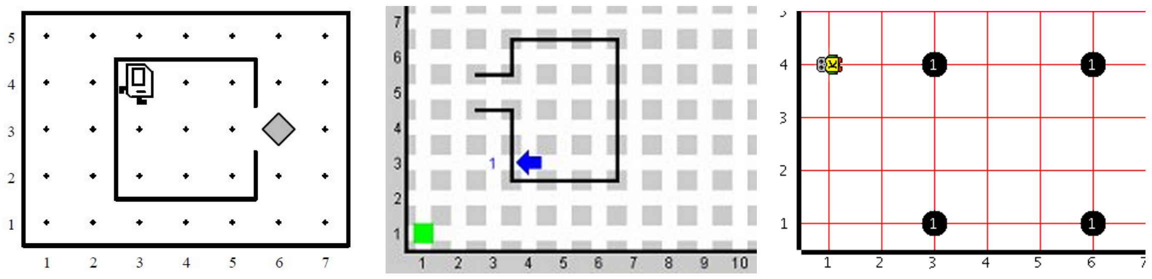


Fig. 13: Various implementations.

The original Karel language was strongly influenced by Pascal, a popular language of the 1980s. Since Pascal is no longer being used today, we refreshed the language and adjusted its syntax to be close to Python, a modern high-level dynamic programming language. Our changes made the language much easier to use. For illustration, compare the original Karel program

```
BEGINNING-OF-PROGRAM

DEFINE turnright AS
BEGIN
    turnleft
    turnleft
    turnleft
END

BEGINNING-OF-EXECUTION
    ITERATE 3 TIMES
    BEGIN
        turnright
        move
    END
    turnoff
END-OF-EXECUTION

END-OF-PROGRAM
```

with its exact NCLab's Karel equivalent

```
def turnright
    repeat 3
        left

repeat 3
    turnright
    go
```

In fact, NCLab's Karel has a built-in command `right` for the right turn, so the above program can be written using just three lines:

```
repeat 3
    right
    go
```

The command `right` was not part of the original Karel language – it was added after a very careful consideration. The main reason for adding it was that it made Karel more pleasant to watch as he moves through the maze. Without this command, any right turn took three left turns, and as a result, Karel resembled a raging tornado. Of course, orthodox Karel fans can still define and use their own `rightturn` command. We made a few additional changes to the language in order to make it more accessible to kids – beepers were replaced with gems, Karel has a `home` in the maze, and there is a new object `tray` that makes it clear where the robot should put gems. Longer commands were replaced with shorter ones, such as `leftturn` with `left`, `move` with `go`, `pickbeeper` with `get`, and `putbeeper` with `put`. Karel's syntax is virtually identical to Python, with the exception of colons in conditions, loops, and new commands – they were left out since our youngest programmers had difficulty typing them.

2.3 Who is Karel?

Karel is a little robot that lives in a maze and loves to collect gems. He was manufactured with only five simple commands in his memory:

- `go` ... make one step forward.
- `get` ... pick up a gem from the ground.
- `left` ... turn left.
- `right` ... turn right.
- `put` ... put a gem on the ground.

He also has six built-in sensors that allow him to check his immediate surroundings:

- `wall` ... helps the robot detect a wall right ahead of him.
- `gem` ... helps the robot detect a gem beneath him.
- `tray` ... helps the robot detect an empty tray beneath him.
- `north` ... helps the robot detect that he is facing North.
- `home` ... helps the robot detect that he is at home.
- `empty` ... helps the robot detect that his bag with gems is empty.

2.4 What will you learn in this course?

Computer programming skills are highly valued today, and they will be even more valued in the future. Karel is the perfect language for beginners. It will teach you how to design algorithms and write working computer programs without struggling with technical complications of mainstream programming languages. Thanks to its simplicity, you should be done with Karel fairly quickly, and in no time you will be ready to move on to other languages. NCLab offers a Python programming course.

2.5 Is Karel a toy language?

Absolutely not! Despite its playful appearance, Karel features all key concepts of modern procedural programming. Technically speaking, it is a complete Turing machine. As a matter of fact, the complexity of algorithms that you will encounter in this textbook ranges from very simple to very hard.

2.6 How does Karel differ from other programming languages?

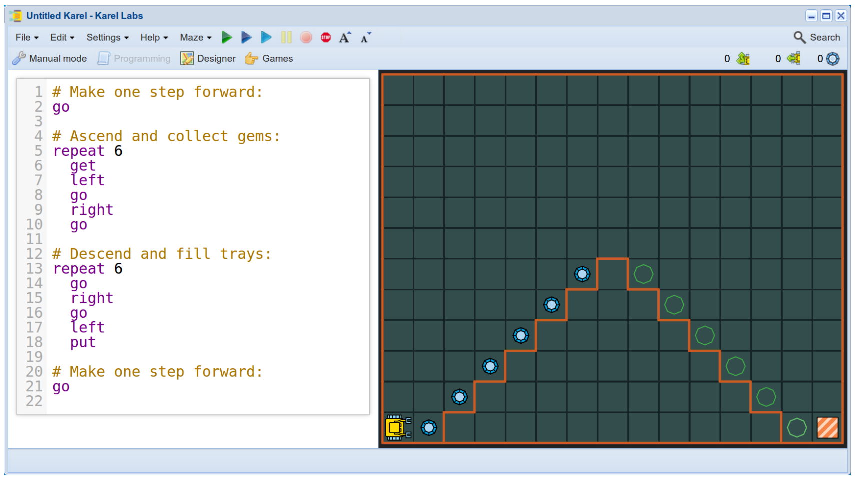
The biggest conceptual difference between Karel and mainstream procedural programming languages such as Python, C, C++, Java or Fortran is that *the robot does not know math*. This is because Math is not needed to understand how to design great algorithms and to translate them into efficient computer programs.

3 Launching Karel

3.1 Objectives

– Learn to launch Karel and work with the graphical application.
– Learn that Karel has several modes and how they differ.

The simplest way to launch Karel is to double click on the Programming icon on Desktop and select Karel in the menu. This will launch the module in Programming Mode with a demo program, as shown in Fig. 14.



```
# Make one step forward:
go

# Ascend and collect gems:
repeat 6
  get
  left
  go
  right
  go

# Descend and fill trays:
repeat 6
  go
  right
  go
  left
  put

# Make one step forward:
go
```

Fig. 14: The Karel module launches with a demo program.

From Programming Mode, one can switch to First Steps, Designer, and Games. These modes will be discussed in more detail in Paragraph 3.3.

3.2 Main menu

The application window contains the main menu on top, work area on the left, maze on the right, and status bar on the bottom. The menus are fairly intuitive, so let us explain just a few selected functions. In the *File* menu:

– Under *Learning materials* you will find this textbook, interactive exercises, and instructors have access to solution programs.
– *New* will create a new Karel file.
– *Open* will open an existing Karel file.

– *Save in NCLab* will save your file in your NCLab account.
– *Publish to the web* will create a static HTML link for your project.

The *Maze* menu facilitates operation with mazes, including creating a new random one, duplicating an existing maze, restoring maze to its saved version, and save and remove maze. The *Edit* menu enables operation with code cells and HTML cells (to be discussed in Section 7). In *Settings* one can change Karel's speed, adjust sound preferences, etc.

The green and red buttons are used to run and stop programs, respectively, and the two buttons next to them on the right can be used to increase and decrease font size. The triplet of icons on far right are the operations counter, step counter, and gem counter.

3.3 Karel modes

The module operates in four modes:

– In *First Steps*, Karel is controlled using the mouse. Watch out and do not crash!
– In *Programming Mode*, the robot is controlled using written commands.
– *Designer* allows users to create custom mazes.
– *Game Mode* allows users to create and share games.

4 First Steps

4.1 Objectives

- Review directions on the compass.
- Learn to guide the robot by clicking on buttons.
- Learn about error messages.
- Learn to work with *left* and *right* from the robot's point of view.
- Learn to plan your actions ahead of time.

4.2 Compass

Fig. 15 shows the four directions on the compass: North, South, West, and East.

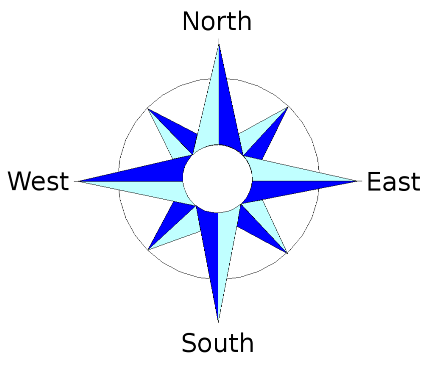


Fig. 15: Four directions on the compass.

4.3 Control buttons

After launching Karel, switch to First Steps. The following five buttons will appear in the left panel:

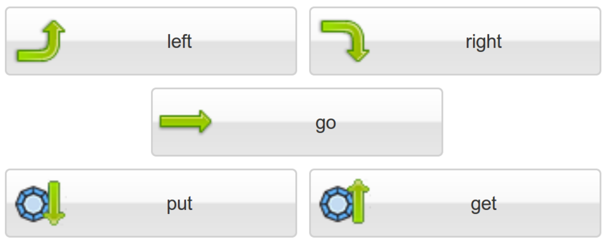


Fig. 16: Karel's buttons in First Steps (robot facing East).

Pressing `left` will turn the robot 90 degrees to the left, pressing `right` will turn him 90 degrees to the right. These two buttons never can cause an error, but the others can.

4.4 Error messages

Pressing `go` will advance the robot one step forward. If he crashes into a wall, he will throw an error message:

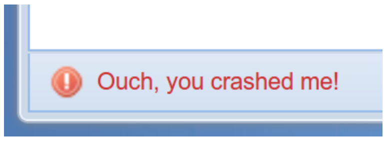

Ouch, you crashed me!

Fig. 17: Error messages appear in the bottom-left corner.

Upon pressing `put`, the robot will reach into his bag and put a gem on the ground. If his bag is empty, he will throw an error message as well. An indicator showing how many gems are in the bag can be found in the upper right corner of the window. Last, pressing `get` makes the robot pick up a gem from the ground. If there is no gem to collect, he will throw an error message.

4.5 Robot's view

When the robot turns, the arrows on the buttons adjust automatically to reflect his view of things. This is illustrated in Fig. 18.

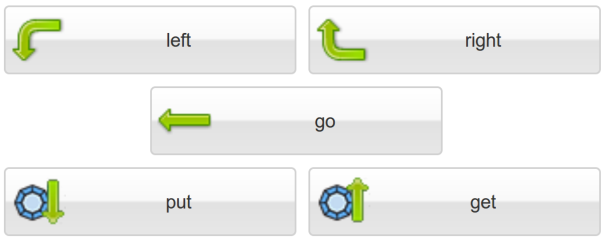


Fig. 18: Karel's buttons in First Steps (robot facing West).

5 Programming

5.1 Objectives

- Write your first computer program.
- Learn the difference between *algorithm* and *program*.
- Learn the difference between *logical* and *syntax* errors.
- Learn that *debugging* is an indivisible part of computer programming.

5.2 Typing commands

Commands are entered into a *code cell* that is located in the left panel. In Programming Mode, we can use the commands `left`, `right`, `go`, `get`, `put`, `repeat`, and many more. One or more commands form a *computer program* or *computer code*. There are two simple rules to remember:

1. Always type one command per line.
2. Indentation matters - every command starts at the beginning of line.

Following these rules will make your code clean and well readable.

5.3 Algorithm

Karel always follows your commands *exactly*. No exceptions. If the robot does something wrong, such as crashing into a wall, then most likely it was not his mistake but yours. Your *algorithm* was wrong.

Algorithm is a sequence of logical steps that leads to the solution of the given task.

Algorithms are written using common human language. Consider a maze shown in Fig. 19. Karel's task is to pick up the gem and return to his home square.

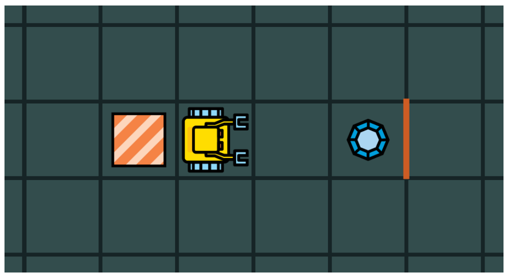


Fig. 19: Collect the gem and get home!

This task can be solved using the following algorithm:

```
Make two steps forward
Collect the gem
Turn around
Make three steps forward
```

In the next paragraph, we will convert this algorithm into a *computer program*.

5.4 Program

Translating an algorithm to a particular programming language yields a *computer program*.

In our case this is the Karel language of course. One possible program corresponding to the above algoritm is:

```
go
go
get
left
left
go
go
go
```

Often there is more than one way to translate an algorithm to a computer program. For example, the above algorithm can be also translated to

```
go
go
right
get
right
go
go
go
```

5.5 Logical and syntax errors

Mistakes in algorithms are called *logical errors*.

Let's return to the setting shown in Fig. 19 and consider the algorithm

```
Make three steps forward
Collect the gem
Turn around
Make three steps forward
```

This makes the robot crash! We made a mistake in the planning – a *logical error*.

Mistakes in programs, such as misspelling a command, writing "1O" instead of "10", or forgetting indentation are called *syntax errors*.

Find three syntax errors in the following program!

```
go
go
got
r1ght
night
go
go
go
```

Mistakes or either kind are called *bugs* and the procedure of eliminating them is called *debugging*. Depending on how careful we were while preparing our algorithm and writing the program, debugging takes either a short time or a long time. It does not happen often that a program works correctly right away.

Of logical and syntax errors, the former are harder to find. Therefore, always make sure to design a good algorithm and to think it through, before you start coding.

When our program contains a syntax error, the robot outputs an *error message* and does nothing. When the algorithm contains a logical error, then various things may happen: The robot may execute the program without fulfilling the goals. Or, he may do something that will trigger and error message and stop program execution.

6 Counting Loop

6.1 Objectives

- Learn to make the robot repeat something a given number of times.
- Learn what *body of loop* means and that indentation matters.

Counting loops are present in all procedural programming languages and they allow us to repeat some command, or a sequence of commands, a given number of times.

In Karel, counting loops are written using the command `repeat`. Some other languages use different commands, but the idea is always the same.

6.2 Elegant way to walk

Look at the following maze where Karel needs to collect a gem and return to his home square.

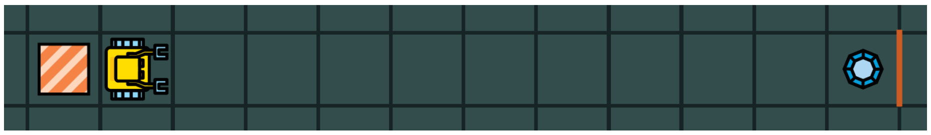


Fig. 20: Repeating an action a given number of times.

Of course we could type

```
go
go
go
go
go
go
go
go
go
go
get
left
left
```

```
go
go
go
go
go
go
go
go
go
go
go
```

But such program would not get you hired as a computer programmer! Namely, the same goal can be accomplished much more elegantly, by telling Karel to `repeat` the `go` command `10` times, get the gem, turn back, and `repeat` the `go` command another `11` times:

```
repeat 10
    go
get
repeat 2
    left
repeat 11
    go
```

That's it! Are you wondering why some commands are indented? We will explain this right now.

6.3 Body of loop

Commands to be repeated are called the *body of the loop*. In Karel, the body of the loop is defined by indentation. This is the same as in Python. Some other languages use other ways, for example C/C++ use curly braces.

In the above program, each loop's body is formed by a single command, but if there were more of them, all of them would be indented. In Karel, you can choose between a 2-indent and a 4-indent. The former yields more compact code with not-so-long lines, but the latter is easier to read.

6.4 Mistakes in indentation

A mistake in indentation can change the body of a loop, and consequently the entire program may end up doing something unexpected. For illustration, assume the maze shown in Fig. 21. Karel's task is to walk around the block and stop in the upper left corner, facing South.

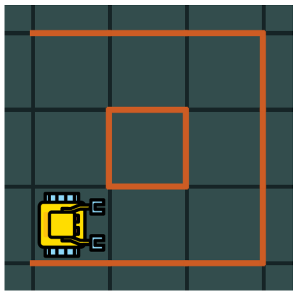


Fig. 21: Karel walks around the block.

This can be done using the following four lines of code:

```
repeat 3
    go
    go
    left
```

The robot's position after executing the program is shown in Fig. 22.

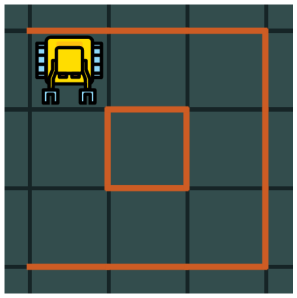


Fig. 22: Karel's position after executing the program.

Now let's unindent the last command as if by mistake:

```
repeat 3
    go
    go
left
```

Now the robot is told to make six steps forward and then turn to the left – which makes him crash right into the wall!

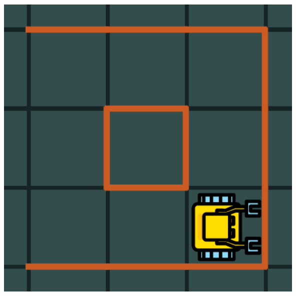


Fig. 23: Mistake in indentation causes the robot to crash.

There is an error message telling where in the code the problem occurred:

```
Ouch, you crashed me!
Line 2: go
```

6.5 Nested loops

In the last two programs, the `go` command was written on two consecutive lines. This is OK since with the `repeat` command we would also need two lines. But consider the situation shown in Fig. 24 and imagine that Karel has to walk around the block now, returning to his original position.

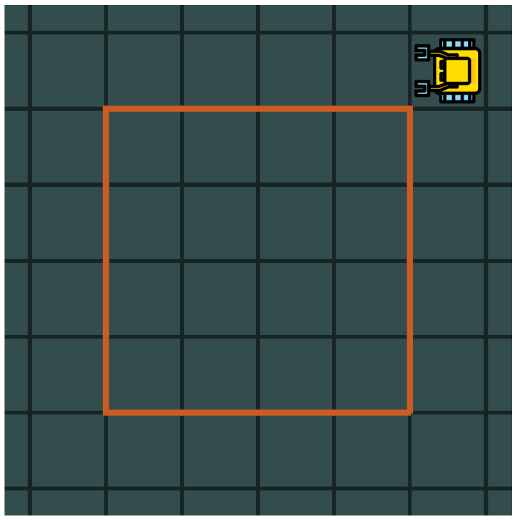


Fig. 24: Walk around a larger block.

Writing the `go` command inside the `repeat` loop on five consecutive lines would not be OK – the code would be much longer than necessary. The following code does the job elegantly:

```
repeat 4
    repeat 5
        go
    left
```

When a loop is used within another loop's body, we say that the loops are *nested*. Notice that the same indentation scheme applies to each of the two loops.

6.6 Walking around four blocks

Let's look at one last example: Karel stands at the intersection of two streets that separate four blocks, as shown in Fig. 25. His task is to walk around the first block until he reaches the intersection, walk around the second block until he reaches the intersection, and so on, until he is finished with all four blocks.

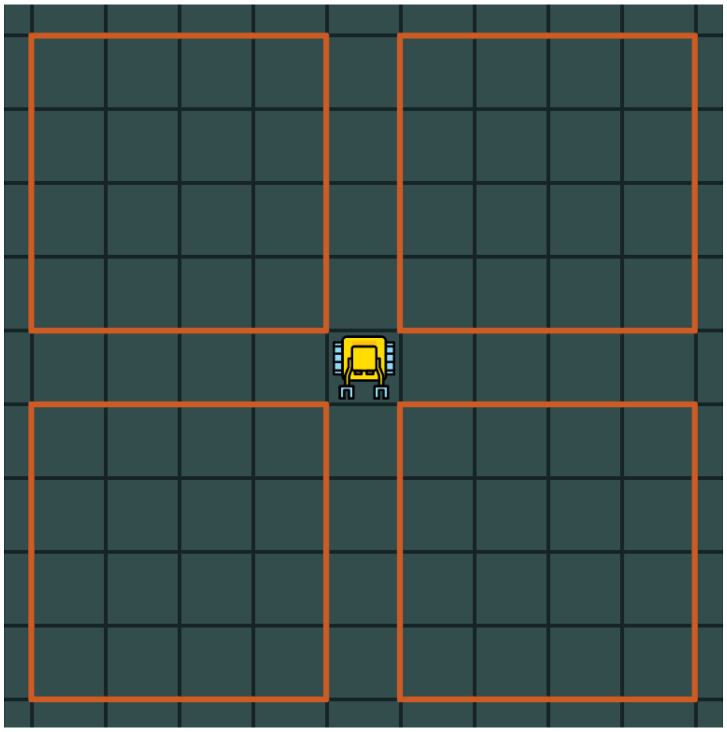


Fig. 25: Standing on an intersection.

This can be done using the following program:

```
repeat 4
    repeat 4
        repeat 5
            go
        left
    right
```

Take your time to build this maze and run the program, it is worth the time!

7 Working with Code and HTML Cells

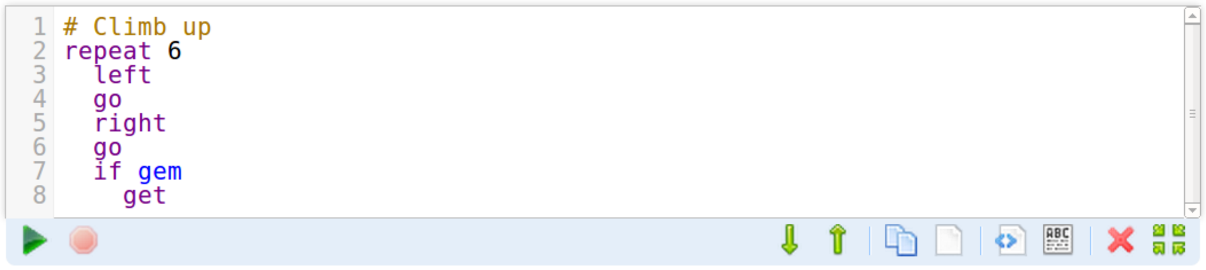
7.1 Objectives

- Learn how to add and use new code cells and HTML cells.
- Learn how to change the order of cells.
- Learn how to run all code cells at once, and how to run them individually.
- Learn how to clear, collapse, remove and merge cells.

7.2 Code cells

So far we have worked with a single code cell, but having multiple code cells can be useful when we want to run different parts of our program separately. While the green arrow button in the main menu runs all code cells (one after another), each code cell also has its own green arrow button beneath it, that runs just that cell and nothing else.

It is also possible to insert descriptive HTML cells between code cells. Fig. 26 shows a sample code cell including its bottom menubar.



```
# Climb up
repeat 6
  left
  go
  right
  go
  if gem
    get
```

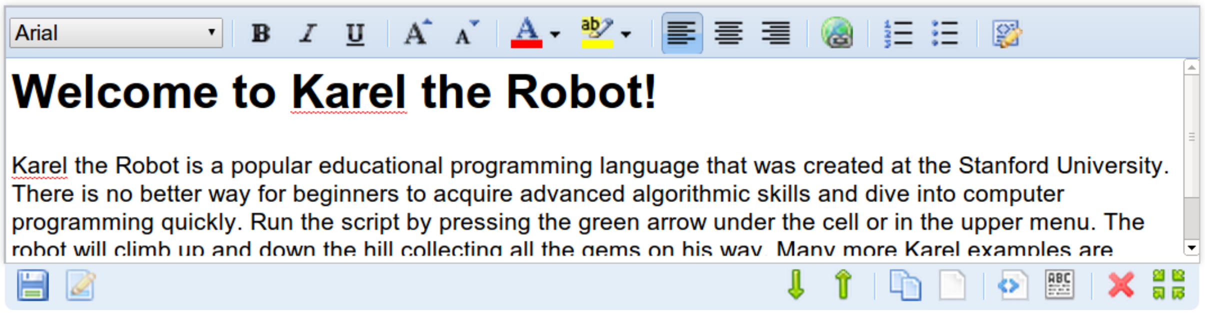
Fig. 26: Sample code cell.

Left to right, the icons under the code cell have the following meaning:

- Run the program in this particular code cell.
- Stop the code cell (this icon becomes active when the program is running).
- Move the cell under the one below it (changes the order of cells in the worksheet).
- Move the cell above the one above it (changes the order of cells in the worksheet).
- Duplicate the cell (new code cell with the same contents is created).
- Clear the cell (erase all contents).
- Add empty code cell under the cell.
- Add empty HTML cell under the cell.
- Remove the cell.
- Collapse the cell.

7.3 HTML cells

HTML cells use a WYSIWYG text and HTML editor to add descriptions and illustrations to the worksheet. Fig. 27 shows a sample HTML cell.



Welcome to Karel the Robot!

Karel the Robot is a popular educational programming language that was created at the Stanford University. There is no better way for beginners to acquire advanced algorithmic skills and dive into computer programming quickly. Run the script by pressing the green arrow under the cell or in the upper menu. The robot will climb up and down the hill collecting all the gems on his way. Many more Karel examples are

Fig. 27: Sample HTML cell.

This cell has two menus. The top one is related to text editing and inclusion of images, the bottom one is analogous to the menu of code cells. Let us begin with the top menu: Left to right, the buttons and icons have the following meaning:

- Select text font.
- Make selected text boldface.
- Make selected text italics.
- Underline selected text.
- Increase font size for selected text.
- Decrease font size for selected text.
- Choose foreground text color
- Choose background text color
- Align text left
- Center text
- Align text right
- Add a hyperlink.
- Create enumerated list.
- Create bullet list.
- Edit source HTML code. This is also how images can be added via external links.

The bottom menu, left to right:

- Save the HTML cell.

- Edit the HTML cell.
- Move the cell under the one below it (changes the order of cells in the worksheet).
- Move the cell above the one above it (changes the order of cells in the worksheet).
- Duplicate the cell (new HTML cell with the same contents is created).
- Clear the cell (erase all contents).
- Add empty code cell under the cell.
- Add empty HTML cell under the cell.
- Remove the cell.
- Collapse the cell.

Additional operations with cells such as their merging can be done via the Edit menu.

8 Conditions

8.1 Objectives

- Understand the role of conditions in programming.
- Learn to use Karel's sensors in conjunction with conditions to help the robot check his surroundings and react accordingly.

Conditions are present in every programming language. Their purpose is to make decisions while the program is running, and handle various unexpected situations. In Karel's case, conditions will usually be related to checking his surroundings via the sensors `wall`, `gem`, `tray`, `empty`, `north` and `home`.

8.2 The `wall` sensor

The `wall` sensor helps the robot determine whether or not there is a wall right in front of him. The usage of this sensor can be illustrated using a simple program "Careful step": If there is wall in front of you, turn back, else make one step forward. Note the user comment following the hash symbol `#`. Comments are not part of the program - in other words, the program below has five lines:

```
# Program "Careful step".
if wall
    repeat 2
        left
else
    go
```

Imagine that Karel stands in front of a gem as shown in Fig. 28.

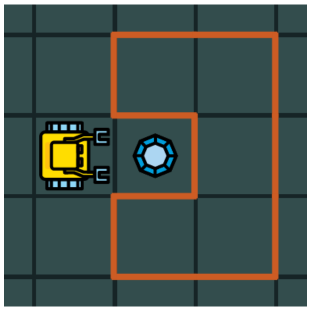


Fig. 28: Karel's initial position.

Now let us run the program three times by clicking three times on the green arrow button. Here is a sequence of Karel's positions after each evaluation:

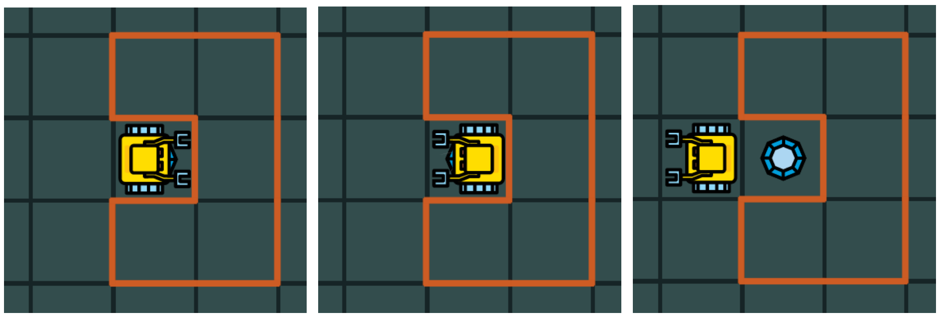


Fig. 29: Left to right – Karel's positions after executing the program "Careful step" one, two, and three times.

8.3 The keyword not

Karel can utilize the keyword not (negation) in conditions. For illustration, the last program can be rewritten as follows, without changing its function:

```
# Program "Careful step".
if not wall
    go
else
    repeat 2
        left
```

8.4 The gem sensor

The gem sensor allows Karel to detect a gem on the ground beneath him. The gem must lie in the same square – the robot cannot see what is one or more steps ahead. Consider the situation shown in Fig. 28 again:

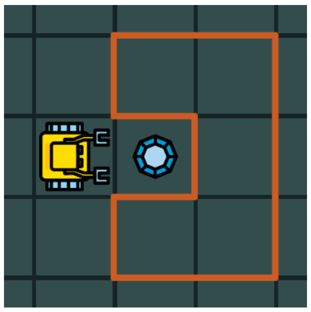


Fig. 30: Karel's initial position, same as before.

Let's extend the program "Careful step" in such a way that Karel picks up the gem on the way:

```
# Program "Careful step II".
if gem
    get
if wall
    repeat 2
        left
else
    go
```

The sequence of Karel's positions after each evaluation is shown in Fig. 31.

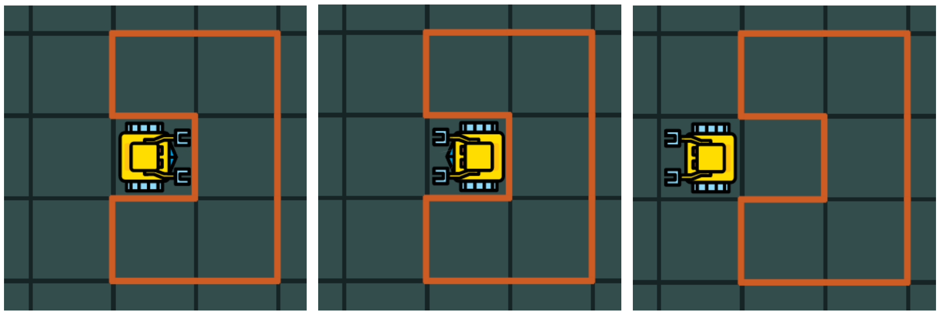


Fig. 31: Left to right – Karel's positions after executing the program "Careful step II" one, two, and three times.

8.5 The `tray` sensor

The `tray` sensor allows Karel to detect an *empty* tray beneath him. A tray that is filled with a gem will not be detected. As with gems, there may be more than one tray in a square. Let's consider the situation shown in Fig. 32 where the home square is 10 steps ahead of Karel. The positions of the gem and of the tray are random but Karel knows that the gem comes first. It is his task to find the gem, move it on the tray, and enter the home square.

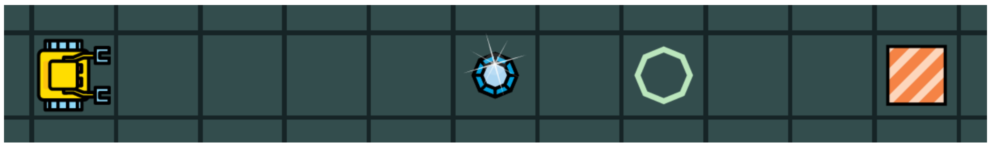


Fig. 32: Karel's task is to find the gem, and move it on the tray.

The program looks as follows:

```
repeat 10
    go
    if gem
        get
    if tray
        put
```

8.6 Repairing pavement

The `empty` sensor allows the robot to check whether his bag is empty, or, in the combination with the keyword `not`, whether his bag contains at least one gem. Imagine that Karel's block has four houses with pavements around them, as shown in Fig. 33. After the winter the pavements are damaged and some tiles (gems) are missing. Karel has an unknown number of tiles in his bag. Write a program for him to repair the pavements. Your program should not throw an error if Karel runs out of gems!

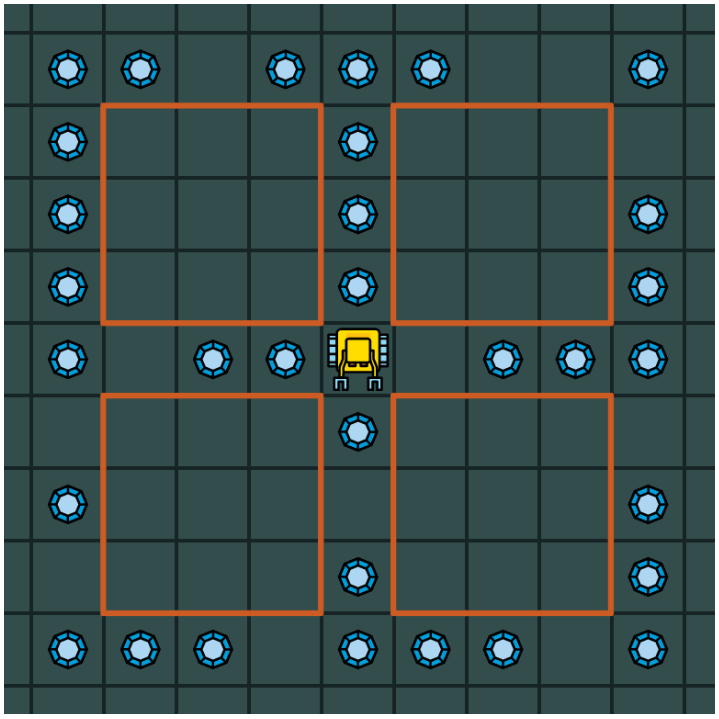


Fig. 33: Karel is repairing pavement.

We can use the program from Subsection 6.6 as the basis for our new program. First let's adjust the numbers of repetitions in the loops to match the current layout of the maze. In fact just the deepest one needs to be changed from five to four since the new blocks are only three units long. The other two loops remain unchanged since each square has still four edges and there are four squares as before. So the new program is:

```
repeat 4
    repeat 4
        repeat 4
            go
        left
    right
```

This will work, but Karel will not be doing any repairs, just walk all pavements and return to his initial position. To repair the pavement, we need to insert an additional condition in front of each `go` command:

```
repeat 4
    repeat 4
        repeat 4
            if not gem
                put
            go
        left
    right
```

Is this program OK? Not yet! If the number of gems in Karel's bag is less than the number of missing tiles in the pavement, the program will stop with an error message. So, we need to check the `empty` sensor before each `put` command. The final program has the form:

```
repeat 4
    repeat 4
        repeat 4
            if not gem
                if not empty
                    put
            go
        left
    right
```

Good job! Fig. 34 shows the pavement after the program is execured. Before running the program, we inserted 15 gems into Karel's bag in Designer.

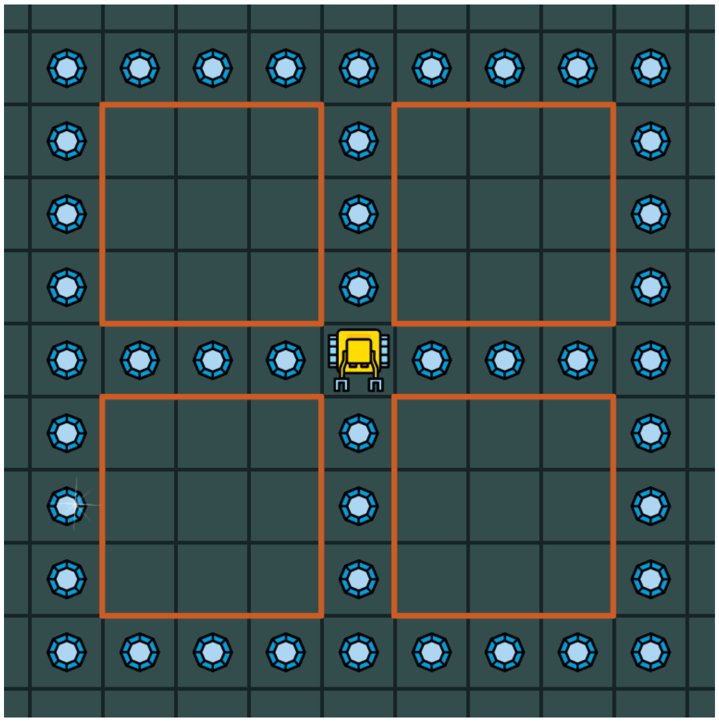


Fig. 34: After running the program, the pavement is repaired!

Try to return to the maze from Fig. 33 and run this program with just 10 gems in the robot's bag! What is supposed to happen?

8.7 Making the robot face any direction

This sensor can be used not only to check if the robot faces North, but also to make him face any given direction. For this, we always must make him face North first, because this is the only direction he can verify. Let's write a program that makes the robot face South no matter which direction he is currently facing!

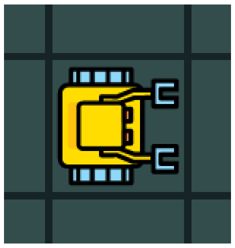


Fig. 35: Karel faces a random direction.

The program uses the fact that in any situation, at most three left turns are enough to make the robot face North:

```
# First turn North:
repeat 3
   if not north
       left
# Then turn South:
repeat 2
   left
```

9 Conditional Loop

9.1 Objectives

– Learn to repeat a command or a sequence of commands until some goal is achieved, not knowing in advance how many repetitions will be needed.

The *conditional loop* (`while` loop) is present in all procedural programming languages. It allows us to repeat some action without knowing in advance how many repetitions will be needed. This can be the case, for example, when Karel needs to walk straight to the nearest wall. He cannot measure the distance to a wall that is farther ahead, so this task cannot be accomplished using the `repeat` loop.

9.2 Finding a lost gem

To demonstrate the usage of the `while` loop, consider the situation shown in Fig. 36 where Karel stands at a random position in a maze without walls. Last time he walked the perimeter of the maze, Karel lost a gem somewhere. He does not know where the gem is - he only knows that it lies somewhere at the outer wall. Let us write a program for the robot to find and collect his lost gem!

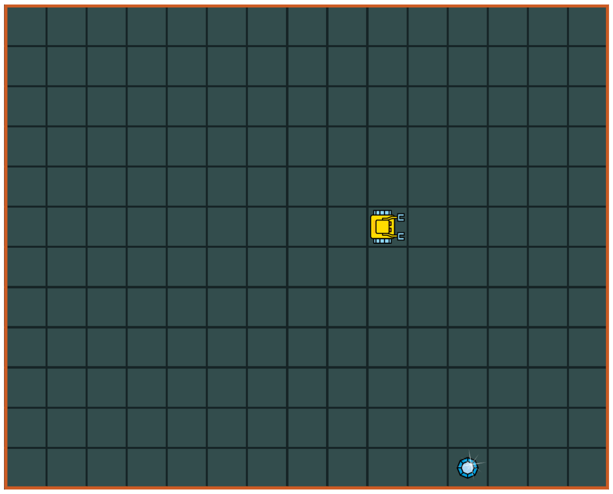


Fig. 36: There is only one gem, located somewhere at the exterior wall.

This can be done using five lines of code:

```
while not gem
    while not wall
        go
    left
get
```

9.3 Writing programs in steps

Is it difficult to write a program like the one above? Not at all! But it is important to build it in several steps, rather than trying to write it all at once. That's how even the most experienced computer programmers do it. As Step 1, write a loop that brings the robot to the outer wall. Clearly, this needs to be done as that's where the gem is. And, we also turn the robot left (could be right), because facing the wall would not get us anywhere:

```
while not wall
    go
left
```

Looking at this loop, we realize that it also can be used to bring the robot to the next corner, where he will turn left again. This is great, because he can just repeat this loop until he finds the gem! Hence as Step 2, we include an outer loop:

```
while not gem
    while not wall
        go
    left
```

As the last Step 3, Karel needs to collect the gem that he found. Hence we arrive at the original program from above:

```
while not gem
    while not wall
        go
    left
get
```

9.4 Rock climbing

This time Karel stands in front of a high cliff:

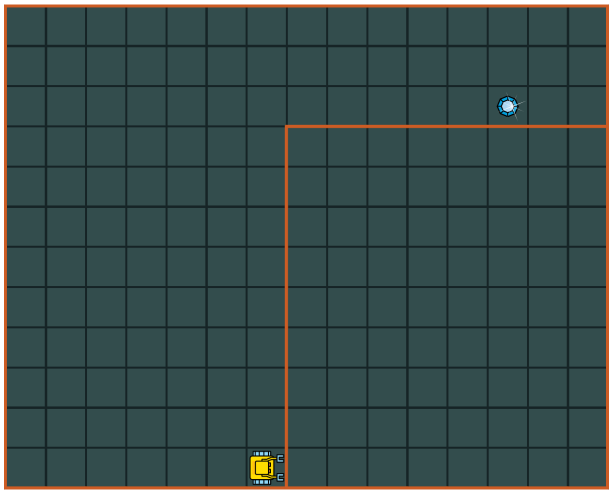


Fig. 37: Karel is climbing rocks.

He knows that there is a gem up there, and wants it, but he does not know how high the cliff is, or the exact position of the gem. Let's help the robot climb the cliff and collect the gem!

This can be done using seven lines of code:

```
while wall
    left
    go
    right

while not gem
    go
get
```

As an exercises, extend this program by a second part where Karel gets back down to his initial position!

10 Custom Commands

10.1 Objectives

– Learn to split complex tasks into smaller ones.
– Learn to use custom commands as it makes programs simpler.

When writing a new program, it is a good idea to check whether it contains simpler tasks that can be solved first. If so, solve them, and create a custom commands (*subprograms*) for them. Then, suddenly, the original task does not appear that difficult anymore! We will give an example after showing how new commands are defined:

10.2 Defining new commands

New commands are defined using the reserved word `def`. For example, in a program where the robot needs to turn back in various situations, it is a good idea to define a new command `turnback`:

```
def turnback
    repeat 2
        left
```

Note that the body of a new command needs to be indented analogously to the body of loops and conditions.
In another program, the robot may need to frequently collect all gems that lie on the ground beneath him. For that we can define a new command `getall`:

```
def getall
    while gem
        get
```

The newly defined commands can be used as any other commands in our programs.

10.3 Arcade game

This time Karel needs to go through several floors of an arcade game shown in Fig. 38, collect all gems, and enter his home square which is located at the East end of the top floor. There is only one opening between each two floors. Initially, the robot stands somewhere in the first floor. This example is available under Examples in Learning resources for Karel.

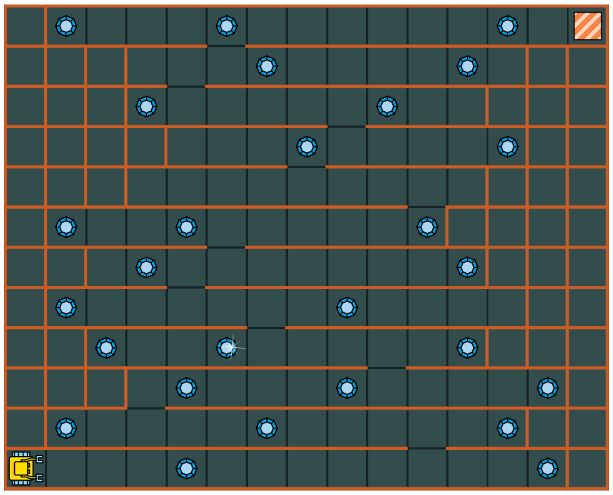


Fig. 38: Karel is playing an arcade game.

Clearly, this problem is more complex than anything we solved before. So, let us first look for smaller tasks that the robot will be doing in each floor. For sure, he will need to turn around from time to time, so let's start with introducing the `turnback` command:

```
# New command to turn back:
def turnback
    repeat 2
        left
```

Since the robot does not know the exact positions of gems, he will always need to sweep the entire floor. Let's introduce a new command for this. We will assume that the robot stands at the West end of the floor, facing East:

```
# Sweep one floor from left to right.
# Assumes that robot stands at the
# West end, facing East:
def sweep
    while not wall
        while gem
            get
        go
        # Do not forget gems in the last square:
        while gem
            get
```

Next we need a new command that will move the robot to the West end of the floor and make him face East, as required by the command `sweep`. Let us call this new command `gowest`

```
# Reach West end of the current floor
# and turn around to face East:
def gowest
    # Turn West:
    while not north
        left
    left
    # Go to West end:
    while not wall
        go
    # Turn around:
    turnback
```

Almost there! The last new command we need is to get to the next floor. Let us call it `moveup`:

```
# Find the opening and move one
# floor up. Assumes that robot is
# at the East end of a floor,
# facing East:
def moveup
    if not home
    # Face North:
    left
    # Find opening:
    while wall
        left
        go
        right
    # Pass through opening:
    go
```

In the last step we put together the previously defined commands `gowest`, `sweep` and `moveup` to define a new command `arcade`:

```
# Main procedure:
def arcade
    while not home
        gowest
        sweep
        moveup
```

The main program includes just the command `arcade`:

```
# Main program:
arcade
```

Fig. 39 shows the arcade after the program has finished:

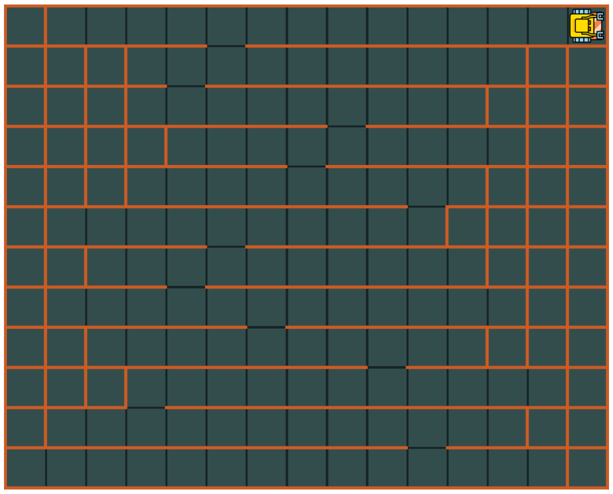


Fig. 39: Arcade after our program has finished.

11 Variables

11.1 Objectives

- Learn the purpose of variables in computer programming.
- Learn to work with numerical and logical variables and text strings.
- Learn to define and use functions that return values.
- Learn the difference between global and local variables.

11.2 Karel grows up

Karel grew up and left the home of his parents to experience life on his own. Therefore, the robot's home square usually will not be present in the maze. There are additional changes that reflect Karel's growing up – there is a GPS device that he can use to determine his position in the maze, he can print messages, work with variables and lists, employ functions that return values, use complex logical operations, make random decisions, and more. A compact overview of all programming functionality can be found in Section 16.

11.3 Purpose of variables

In programming, variables are used to store useful information for later use. To give a few examples, this information can be a number, word, sentence, or a logical value (`True` or `False`). Variables can be rather complex - we will encounter *lists* where multiple values can be stored, such as the robot's path, positions of gems in the maze, etc.

11.4 Types of variables

All of us use variables in our lives. One of the first ones is our own name.

Text strings

Say that your name is "Melissa". When you were about two years old, you saved your own name in your memory. Using computer language, you defined a new variable `my_name` as follows:

```
my_name = "Melissa"
```

The variable `my_name` stores a *text string* (string of characters).

Numbers

Later in life we learn about various important numbers such as

```
seconds_per_minute = 60
```

or `minutes_per_hour` whose value is 60 as well, `hours_per_day` whose value is 24, and so on. But we also use variables whose values change, such as `days_per_year`, `number_of_my_pets`, etc. In Karel, we will only use integers (not general real numbers) as the purpose of the language is not to do math.

Logical variables

Logical variables can only store two possible values, either `True` or `False`. We use many of them in our lives:

```
I_have_a_dog = True
I_own_a_car = False
```

Of course, for someone else these variables will have different values. Logical variables and operations will be discussed in more detail in Section 13.

11.5 Using the GPS device and the `print` command

Karel can retrieve his coordinates at any time via the commands `gpsx` and `gpsy`. He also has a new ability to output text messages via the `print` command. The usage of these commands can be illustrated using a short program where Karel determines his coordinates in the maze and prints them:

```
print "Horizontal position:", gpsx
print "Vertical position:", gpsy
```

For the maze shown below,
the above program will have the following output:

```
Horizontal position: 0
Vertical position: 0
```

The maze width (in west-east direction) is 15 tiles, and its height (in south-north direction) is 12 tiles. If Karel stands in the north-east corner as shown in Fig. 41,

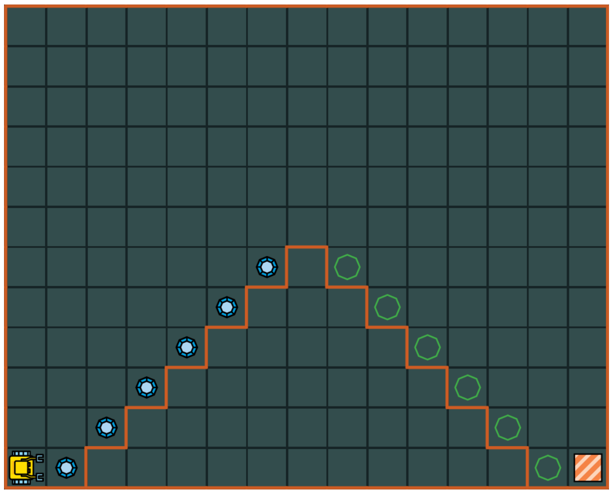


Fig. 40: South-west corner of the maze has GPS coordinates [0, 0].

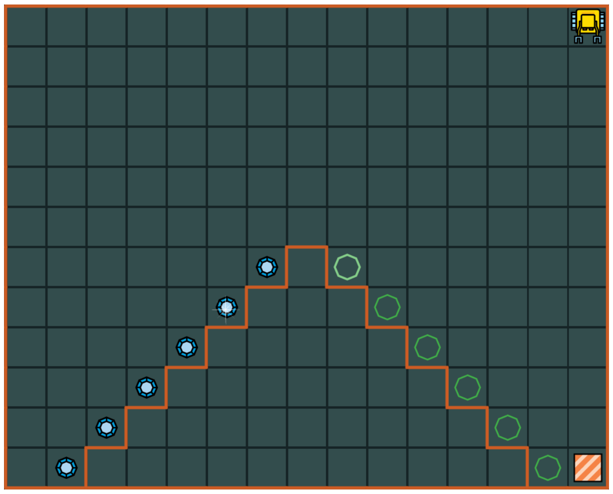


Fig. 41: North-east corner of the maze has GPS coordinates [14, 11].

then the output of the program is

```
Horizontal position: 14
Vertical position: 11
```

Move Karel to other parts of the maze and run the program again, to make yourself familiar with how the GPS device works!

The `print` command can be used to display more complicated sentences where text and variables are separated by commas:

```
print "My GPS coordinates are", gpsx, "and", gpsy
```

Which, for the above maze, produces the output:

```
My GPS coordinates are 14 and 11
```

11.6 Defining custom functions

We can use the keyword `return` in the body of a command to return a value. Such commands are called *functions*. They are also defined using the keyword `def`. For example, with the following function `countsteps` the robot will walk straight towards the closest wall and return the number of steps he needed to reach it:

```
def countsteps
    n = 0
    while not wall
        go
        inc(n)
    return n
```

Notice couple of things here:

- The variable `n` was created and initialized by `0` using `n = 0`. In Karel, we do not have to state the type of a variable in advance – the interpreter will figure it out from the type of value that is first assigned to it.
- The `inc()` function increases the value of an integer variable by one. There is also a function `dec()`, not used in the above program, that decreases the value of an integer variable by one. More about these two functions will be said in Paragraph 11.10.

The function can then be used as follows:

```
num = countsteps
print "I reached wall in", num, "steps!"
```

Here, we create a new variable `num` and initialize it using the integer value that is returned by the function `countsteps`. The result is then printed. For the situation shown in Fig. 41, the output is

```
I reached wall in 11 steps!
```

11.7 Measuring the length of a wall

Here, Karel's task is to measure and print the length of an arbitrary wall. The wall has a beginning and an end, does not contain loops, the robot faces the first wall segment, and the wall continues to the robot's left as shown in Fig. 42:

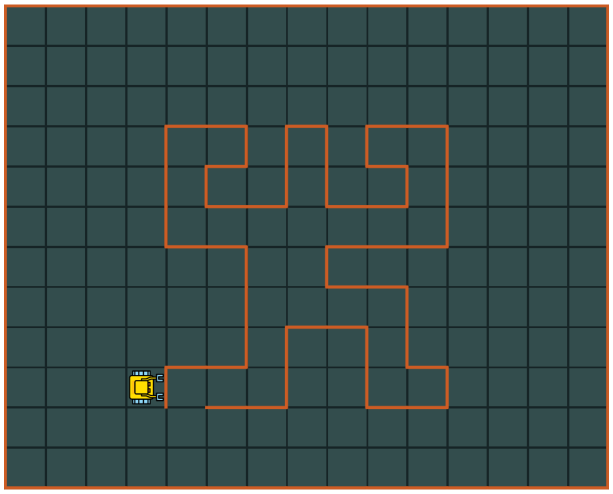


Fig. 42: Measuring the length of an arbitrary wall.

This task can be solved using the following function `measurewall` that has 13 lines:

```
# Function to measure the length
# of an arbitrary wall:
def measurewall
  l = 0
  while wall
    inc(l)
    left
    if not wall
      go
      right
      if not wall
        go
        right
        if not wall
            return l

# Call the function:
print "Length of wall is", measurewall
```

Running the program with the maze from Fig. 42, we obtain:

```
Length of wall is: 53
```

This example is available in Learning resources to the Karel module. Change the wall and see if the program still works correctly!

11.8 Creating and initializing numerical variables

In Karel, numerical variables can be created and initialized in several different ways:

1. By setting them to an integer number. For example, a new variable `a` is created and set to zero as follows:

   ```
   a = 0
   ```

2. By setting them to `gpsx`. New variable `posx` is created and set to `gpsx` by typing

   ```
   posx = gpsx
   ```

3. By setting them to `gpsy`. New variable `posy` is created and set to `gpsy` via

   ```
   posy = gpsy
   ```

4. Initialize them with an existing value. If there already is an integer variable `var1`, then a new variable `var2` can be created as follows:

   ```
   var2 = var1
   ```

5. Initialize them with value returned by an existing function. Using the function `countsteps` from the previous paragraph, we can type:

   ```
   num = countsteps
   ```

11.9 Changing values of numerical variables

The value of a numerical variable can be updated at any time by redefining it via one of the five options described in the previous paragraph.

11.10 Using functions `inc()` and `dec()`

Karel does not know mathematical symbols '+' and '-'. But for counting purposes, he can increase and decrease the value of an integer variable by one using the functions `inc()` and `dec()`, respectively. He can also increase and decrease the value of a variable by more than one via `inc(n, num)` and `dec(n, num)`, where `n` is the name of the variable and `num` is an integer number.

11.11 Comparison operations

Integer numbers and numerical variables can be compared using the standard operators `>, <, >=, <=, ==, !=, <>`. In this order, they read "greater than", "less than", "greater than or equal to", "less than or equal to", "equal to", "not equal to" and "not equal to" (the last two operations have the same meaning). The result of each such operation is a logical value `True` or `False`, and it can be either used in a condition or conditional loop, or assigned to a variable. For example,

```
a = 1
b = 5
print a < b
```

yields the output

```
True
```

The code

```
a = 1
b = 5
c = a > b
print c
```

yields

```
False
```

The code

```
a = 0
while a <= 5
  print a
  inc(a)
```

yields

```
0
1
2
3
4
5
```

11.12 Text strings

Text string variables are created and initialized analogously to the numerical ones:

```
robots_name = "Karel"
```

They can be printed as usual. The code

```
print "Robot's name is", robots_name
```

yields

```
Robot's name is Karel
```

A text string variable can be used to initialize a new one. Let's say that someone wants to rename the robot to "Carlos" (which is the Spanish version of "Karel"), and store his original name in the variable `robots_name_orig`. This is done as follows:

```
robots_name_orig = robots_name
robots_name = "Carlos"
```

11.13 Local and global variables

A variable that is created within a function is *local to that function*, meaning that it can be used in the function only. If we attempt to use it outside of that function, an error is thrown. The following code creates a local variable `a` within a function called `myfunction`:

```
def myfunction
  a = 1
  return

myfunction
print a
```

When run, the code throws an error message:

```
Unknown variable/procedure "a"
```

On the other hand, variables created within the main program are *global*. Global variables can be used in functions. For illustration, let us adjust the above program to:

```
def myfunction
  print "b =", b
  return

b = 5

myfunction
```

The output of this program is:

```
b = 5
```

One should use local variables whenever possible, as this keeps the code safe and well organized. Use of global variables should be kept at a minimum.

12 Lists

12.1 Objectives

– Understand the concept of a list.
– Learn basic operations with lists.
– Learn to work with indices.

Lists are useful data structures that can be used to store multiple integer values, GPS coordinates, logical values, and/or text strings at the same time. Values of different types can be combined and lists can even contain other lists. For example, a list can store the robot's path, positions of all gems in the maze, positions and shapes of obstacles that the robot encounters, and much more. Objects in a list are ordered and they can be added to the end of a list, accessed by their index, and deleted from any position of the list.

12.2 Compatibility with Python

Karel lists are a "subset" of lists in the Python programming language. In other words, everything that you learn here will work in Python, but Python provides additional functionality for lists which is not present in Karel.

12.3 Creating a list

We use square brackets when creating lists. An empty list `U` is created as follows:

```
U = []
```

Lists can be also created non-empty:

```
V = [1, 2, 3, 4, 5]
```

We can use variables when creating a list:

```
c = 100
W = [0, 50, c]
print W
```

The output of this code is

```
[0, 50, 100]
```

Integer numbers can be combined with text strings:

```
X = [1, "Hello", 2]
```

Lists can contain other lists as their elements:

```
Y = [1, "Hello", 2, [1, 2, 3]]
```

We can print a list:

```
print "This is the list Y:", Y
```

The output of this code is:

```
This is the list Y: [1, "Hello", 2, [1, 2, 3]]
```

12.4 Accessing list items by their indices

List items can be accessed and either printed, assigned to other variables, or used in some other way, via their indices. Indices always start from zero. In other words, `L[0]` is the first item in the list `L`, `L[1]` is the second item, etc. Working with indices can be illustrated using the following simple code

```
L = [8, 12, 16, 20]
print "First item:", L[0]
print "Second item:", L[1]
print "Third item:", L[2]
print "Fourth item:", L[3]
```

whose output is

```
First item: 8
Second item: 12
Third item: 16
Fourth item: 20
```

12.5 Appending items to a list

An arbitrary object `obj` (integer, text string, logical value, another list, etc.) can be appended to the end of an existing list using the `append()` function. For a list `L` this would be

```
L.append(obj)
```

For illustration, the code

```
K = [1, 11]
K.append(21)
print K
```

has the output

```
[1, 11, 21]
```

12.6 Removing items via the `pop()` function

The `i`th item (where indices start from zero) can be deleted from a list `L` and assigned to a variable `x` via

```
x = L.pop(i)
```

For illustration, let us create a list `X` containing three text strings "Monday", "Tuesday" and "Wednesday", and then delete the second item:

```
X = ["Monday", "Tuesday", "Wednesday"]
day = X.pop(1)
print day
print X
```

The output of this code is

```
Tuesday
['Monday', 'Wednesday']
```

If the `pop()` function is used without an index, it removes and returns the last object of the list:

```
day = X.pop()
print day
print X
```

Output:

```
Wednesday
['Monday']
```

12.7 Deleting items via the `del` command

The purpose of the `del` command is similar to the `pop()` function except that the deleted object is destroyed (it cannot be assigned to a variable). The `i`th item can be deleted from a list `L` via

```
del L[i]
```

For illustration, the output of the code

```
L = ["Monday", "Tuesday", "Wednesday"]
del L[0]
print L
del L[0]
print L
```

is

```
['Tuesday', 'Wednesday']
['Wednesday']
```

12.8 Length of a list

The function `len(X)` returns the length of the list `X`. For illustration, the code

```
M = ["John", "Josh", "Jim", "Jane"]
n = len(M)
print "Length of the list is", n
```

has the output

```
Length of the list is 4
```

12.9 Parsing lists

In Karel, lists can be parsed via the `for` command that is the same as the corresponding command in Python. For illustration, the following code defines a list `M` consisting of four numbers `1, 2, 3, 4` and prints each of them, increased by two:

```
M = [1, 3, 5, 7]
for n in M
    print inc(n, 2)
```

The output is:

```
3
5
7
9
```

12.10 Recording robot's path

Let us take the function `measurewall` from Subsection 11.7 and adjust it in such a way that the robot's path is recorded in a list and returned. The new function will be called `recordpath`:

```
# Function to record robot's path:
def recordpath
  L = [[gpsx, gpsy]]
  while wall
    left
    if not wall
      go
      L.append([gpsx, gpsy])
      right
      if not wall
        go
        L.append([gpsx, gpsy])
        right
        if not wall
            return L

# Record the path and print it:
print recordpath
```

This time we will use a shorter wall so that the resulting list is not too long:

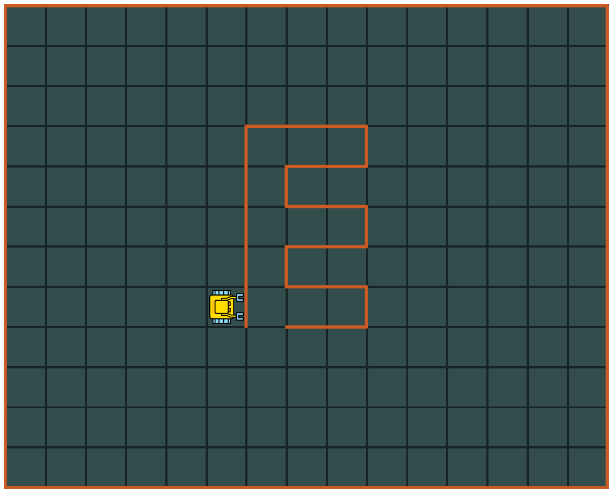


Fig. 43: Recording robot's path.

Running the program with the maze from Fig. 43 yields:

```
[[5, 4], [5, 5], [5, 6], [5, 7], [5, 8], [5, 9], [6, 9],
[7, 9], [8, 9], [9, 9], [9, 8], [9, 7], [8, 7], [7, 7],
[8, 7], [9, 7], [9, 6], [9, 5], [8, 5], [7, 5], [8, 5],
[9, 5], [9, 4], [9, 3], [8, 3], [7, 3], [6, 3], [6, 4]]
```

This is just as it should be – recall that the coordinates start with `[0, 0]` which is the bottom-left corner square.

12.11 Replaying robot's path from a list

Now we will teach Karel to move according to a path that is stored as a list of GPS coordinates. More precisely, the path will be given in terms of `[gpsx, gpsy]` pairs stored in a list `L`. As a first step, we need to implement four functions that will turn the robot to face North, East, South and West. We also implement a procedure `gotoposition` that moves the robot from any initial position to a position `NEWX, NEWY`:

```
# Turn North:
def turnnorth
    while not north
        left

# Turn East:
def turneast
    turnnorth
    right

# Turn South:
def turnsouth
    turneast
    right

# Turn West:
def turnwest
    turnnorth
    left
```

```
# Move from the current position to
# a new position [NEWX, NEWY]:
def gotoposition
    # Horizontal direction first:
    posx = gpsx
    if posx < NEWX
        turneast
        repeat dec(NEWX, posx)
            go
    else
        turnwest
        repeat dec(posx, NEWX)
            go
    # Vertical direction:
    posy = gpsy
    if posy < NEWY
        turnnorth
        repeat dec(NEWY, posy)
            go
    else
        turnsouth
        repeat dec(posy, NEWY)
            go
```

As you can see, we are not assuming that the new position is adjacent to the current one – this makes the procedure `gotoposition` more generally usable. The last step is easy, we just need to parse the list `L`, and make the robot go to every new position:

```
# Parse list L, always go to the
# next position:
def playlist
    n = len(L)
    i = 0
    repeat n
        newpair = L[i]
        NEWX = newpair[0]
        NEWY = newpair[1]
        gotoposition
        inc(i)
```

The variable `newpair` is there because Karel does not allow double indices. What remains to be done now is to just run the program with a sample list `L`:

```
# Sample list L:
L = [[3, 10], [5, 5], [10, 10], [1, 1]]
# We need these two global variables:
NEWX = gpsx
NEWY = gpsy
# Go!
playlist
```

The reader can notice usage of global variables `NEWX`, `NEWY` and `L` here. This is not the best programming practice but the Karel language does not allow functions to accept parameters, so it needs to be done this way for the moment. We plan to implement passing parameters into functions soon.

12.12 Recording positions of gems

Gems are distributed randomly along the maze perimeter. The squares may contain more than one gem. The robot should walk the maze perimeter and record the positions and counts of all gems into a list. Each list entry should have the form `[gpsx, gpsy, number]`. At the end, the robot should print the list.

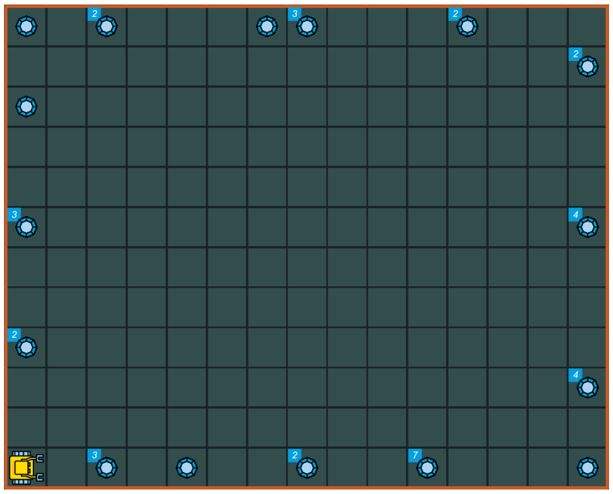


Fig. 44: Gems are distributed randomly along maze perimeter.

One possible program to do this looks as follows. First we write a function `countgems` that will count the number of gems in a square and return their number:

```
def countgems
  num = 0
  # Collect all gems:
  while gem
    get
    inc(num)
  # Put the gems back:
  repeat num
    put
  return num
```

Then we can use this function to obtain the desired list:

```
# Locate all gems:
def locategems
  repeat 4
    while not wall
      go
      if gem
        L.append([gpsx, gpsy, countgems])
    left
  return L

# Call the main function:
L = []
listofgems = locategems
print "Here is the report:"
print listofgems
```

For the maze shown in Fig. 44, the output of the program is

```
Here is the report:
[[2, 0, 3], [4, 0, 1], [7, 0, 2], [10, 0, 7], [14, 0, 1],
[14, 2, 4], [14, 6, 4], [14, 10, 2], [11, 11, 2], [7, 11, 3],
[6, 11, 1], [2, 11, 2], [0, 11, 1], [0, 9, 1], [0, 6, 3],
[0, 3, 2]]
```

12.13 Lists contained in other lists

In some of the latest programs we encountered lists that were contained in other lists. In other programming languages, items of embedded lists are accessed via multiple indices. This is not allowed in Karel, but it can be done without multiple indices as well. Look, for example, at the following code that goes through the list `L` from the last program, and creates another list `L2` that only contains the counts of gems (their coordinates are left out):

```
L2 = []
for x in L
  L2.append(x[2])
print "Skipping the coordinates:"
print L2
```

13 Tour of Logic

13.1 Objectives

– Review elementary logic.
– Practice working with logical expressions.
– Learn about truth tables.

13.2 Simple logical expressions

As we already know, logical expressions are expressions that are either `True` or `False`. We say that `True` or `False` is their *value*. Here are some real-life examples, try to answer them with `True` or `False`:

– "I am 12 years old."
– "My dad is a teacher."
– "My school is a STEM Academy."

And here are some Karel examples:

– `wall` ... `True` if the robot is facing a wall, `False` otherwise.
– `gem` ... `True` if a gem is beneath the robot, `False` otherwise.
– `tray` ... `True` if a tray is beneath the robot, `False` otherwise.
– `north` ... `True` if the robot is facing North, `False` otherwise.
– `home` ... `True` if the robot is home, `False` otherwise.
– `empty` ... `True` if the robot's bag is empty, `False` otherwise.

13.3 Complex logical expressions

In programming as well as in real life we often deal with logical expressions that are more complex. Often we use two or more simple logical expressions in one sentence, and moreover we combine them with logical operations `and`, `or` or `not`.

For example, the sentence "I will go skiing on Saturday if weather is good and if Michael joins me." includes three simple logical expressions. Let's call them for brevity

`A` = "I will go skiing on Saturday."
`B` = "The weather is good."
`C` = "Michael joins me."

There is a logical operation `and` between the expressions `B`, `C`. The original sentence can be written briefly as if `B and C` then `A`

We love this kind of brevity in programming because it makes the code short. Let's say that we can predict the future and we know that the weather will be good and that Michael will go as well. Then we can translate the above condition into computer code. We also print the resulting value of `A` at the end:

```
# Let's say that weather will be good
# and Michael will join you:
B = True
C = True
# This is how you decide:
if B and C
    A = True
else
    A = False
# Print the result:
if A
    print "I will go ski on Sunday."
else
    print "I will not go ski on Sunday."
```

Output:

```
I will go ski on Sunday.
```

13.4 Truth tables

Each of these three logical operations comes with its own *truth table* that summarizes its results for different values of operands. The truth table for the logical `and` is:

A	B	A and B
True	True	True
True	False	False
False	True	False
False	False	False

The truth table for logical `or` is:

A	B	A or B
True	True	True
True	False	True
False	True	True
False	False	False

The truth table for logical `not` is:

A	not A
True	False
False	True

And finally, the truth table for *if A then B* is:

A	B	if A then B
True	True	True
True	False	False
False	True	True
False	False	True

Some people have difficulty wrapping their head around the last table. They ask: How can the expression *if A then B* be true when A is false? But it is the case. Consider the following example: "If Earth is flat, then Moon is flat as well.". This expression is true, there is nothing wrong with it. Since Earth is not flat, the rest is irrelevant.

14 Randomness

14.1 Objectives

- Learn how to make random decisions using the `rand` command.
- Learn to simulate random processes.

Karel can make random decisions via the command `rand` that returns with equal probability either `True` or `False`. Typical usage of this command is

```
if rand
    do_something
else
    do_something_else
```

14.2 Using random moves to search entire maze

As a first example, here is a nice short program that makes Karel walk randomly through the maze and look for gems:

```
# This is a simple way to
# create an infinite loop:
while True
    # Make a random number of steps forward:
    while rand
        if not wall
            go
        if gem
            get
    # Turn either right or left:
    if rand
        right
    else
        left
```

After some time (it may take a while) the robot reaches all reachable gems and collects them! The program is in fact an infinite loop, so you will have to eventually stop it via the red button.

15 Recursion

15.1 Objectives

– Understand what recursion is and when it can be useful.
– Learn to write good recursive algorithms.

By a *recursive* algorithm we mean an algorithm that makes a call to itself. How does it sound? In our life we use recursion all the time. For example, when we descend a staircase, our algorithm is:

```
Descend_staircase
    Descend_one_step
    If this_was_not_the_last_step
        Descend_staircase
```

Recursion is not applicable to all types of problems, but it can be very helpful, especially when:

– The problem can be reduced to the same one, just smaller in size.
– The same algorithm can be applied to solve the smaller problem.

In the program, this means that some command calls itself, either directly or through other commands.

15.2 How it works

Consider the following program:

```
def reach_wall
    if not wall
        go
        reach_wall

reach_wall
```

Initial position of the robot is shown in Fig. 45:
When the command `reach_wall` is first called, the robot stands three steps away from the wall and thus the `if not wall` condition passes. Then the command `go` follows and the robot's position changes as shown in Fig. 46.
Next the robot executes the `reach_wall` command that follows the `go` command. A good way to understand what happens is to imagine that the command is replaced

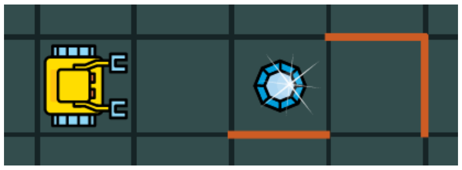


Fig. 45: Robot's initial position.

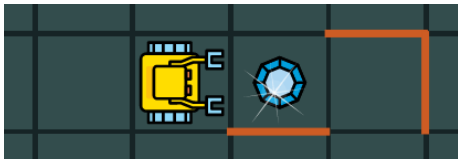


Fig. 46: Robot's position after making the first step forward.

with its own body. So the corresponding code would look as follows:

```
if not wall
    go
    if not wall
        go
        reach_wall
```

Since the robot is two steps away from the wall, the second `if not wall` condition passes and he makes a second step forward. His new position is shown in Fig. 47.

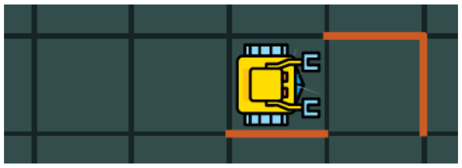


Fig. 47: Robot's position after making the second step forward.

Next the robot executes the third `reach_wall` command. Again we can imagine that the command is replaced with its own body. The corresponding code would look as follows:

```
if not wall
    go
    if not wall
        go
        if not wall
            go
            reach_wall
```

Since the robot is one step away from the wall, the third `if not wall` condition passes and he makes a third step forward. His new position is shown in Fig. 48.

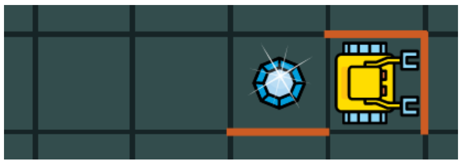


Fig. 48: Robot's position after making the third step forward.

Now the robot stands in front of the wall. The `reach_wall` command is executed one more time, so we can imagine that its body is pasted into the code one last time:

```
if not wall
    go
    if not wall
        go
        if not wall
            go
            if not wall
                go
                reach_wall
```

However, now the `if not wall` condition does not pass, which means that the program is finished.

Of course, in this example it would have been much easier to use a `while` loop but that was not the point. We will encounter situations where recursive algorithms are much easier to write than non-recursive ones.

15.3 The base case

In the last example, to prevent infinite recursion, we used an `if` statement. The `else` statement can be omitted which means "else do nothing". In recursive algorithms, we always need an `if` or `if-else` statement of some sort, where one branch makes a recursive call while the other one does not. The branch without a recursive call is called the *base case*. A bad example of a recursive command without a base case would be

```
def turn_forever
    left
    turn_forever

turn_forever
```

This program is an infinite recursion that needs to be stopped using the red stop button.

15.4 Diamond staircase revisited

Recall the Staircase example from Section 10:

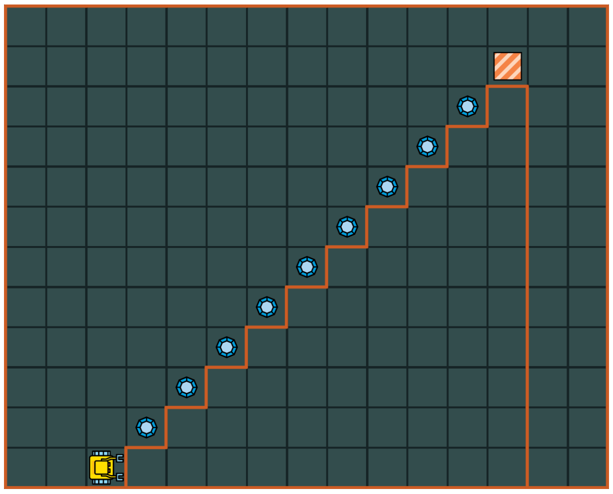


Fig. 49: The Staircase problem.

The goal is to climb the stairs, collect all gems, and enter the home square. Here is a recursive program to do this:

```
def climb_stairs
    if not home
        left
        go
        right
        go
        if gem
            get
        climb_stairs

climb_stairs
```

If an algorithm comes in both a recursive and a non-recursive version, then the following should be taken into account:

- The recursive version will be slightly slower than a non-recursive one. The reason is the overhead related to creating a new instance of the recursive command and calling it.
- The recursive version will also require more memory – when a recursive command is called 1000 times, then it actually exists in 1000 copies in the memory. Hence, recursion is not recommended with very large numbers of repetitions.

Recursive algorithms are used mainly where non-recursive ones are cumbersome to design. For example, much code written for traversing tree-like data structures is recursive. Also certain sorting algorithms are more naturally written in recursive form. We will discuss these subjects in more detail later.

15.5 Mutually recursive commands

Recursion can have interesting forms. For example, there can be a pair of commands that call themselves mutually, such as the commands `odd` and `even` in the following example (that also solves the Staircase problem). Note the presence of base case in both recursive commands:

```
def climb_step
    left
    go
    right
    go
    get

def odd
    if not home
        climb_step
        even

def even
    if not home
        climb_step
        odd

odd
```

16 Appendix - Overview of Functionality by Mode

16.1 First Steps (Section 4)

In First Steps, Karel can be guided by clicking on buttons:

– `go` ... make one step forward.
– `left` ... turn left.
– `right` ... turn right.
– `put` ... put a gem on the ground.
– `get` ... pick up a gem from the ground.

16.2 Programming Mode (Sections 5 – 15)

In Programming Mode, Karel has the following functionality:

– `go` ... make one step forward.
– `left` ... turn left.
– `right` ... turn right.
– `put` ... put a gem on the ground.
– `get` ... pick up a gem from the ground.
– `repeat` ... counting loop (repeat an action a given number of times).
– `if - else` ... condition.
– `while` ... conditional loop (repeat an action while a condition is satisfied).
– `def` ... define a new command.
– `wall` ... sensor that checks if the robot faces a wall.
– `gem` ... sensor that checks if there is a gem beneath the robot.
– `tray` ... sensor that checks if there is a tray beneath the robot.
– `empty` ... sensor that checks if the robot's bag with gems is empty.
– `home` ... sensor that checks if the robot is in the home square.
– `north` ... sensor that checks if the robot faces North.
– `print` ... print strings and variables.
– `gpsx` ... GPS coordinate in the horizontal direction.
– `gpsy` ... GPS coordinate in the vertical direction.
– `a = 0` ... create a new variable `a` and initialize it with zero.
For additional ways to initialize variables see Subsection 11.8.
– `inc(a)` ... increases the value of variable `a` by one.
– `inc(a, value)` ... increases the value of variable `a` by `value`.
– `dec(a)` ... decreases the value of variable `a` by one.
– `dec(a, value)` ... decreases the value of variable `a` by `value`.
– `rand` ... random command (returns randomly `True` or `False`).

- `return` ... returns a value, to be used in functions.
- `and` ... binary logical *and*.
- `or` ... binary logical *or*.
- `not` ... unary logical *not*.
- `L[]` ... create an empty list `L`.
- `len(L)` ... length of list `L`.
- `L[i]` ... object at position `i` in list `L`. Note: `L[0]` is the first item in the list.
- `L.append(x)` ... appends `x` to the end of list `L`.
- `x = L.pop()` ... removes the last item of list `L` and assigns it to `x`.
- `del L[i]` ... removes from list `L` object at position `i`.
- `for x in L` ... Python way to parse lists.
- Numerical and logical (Boolean) variables.
- Complex logical expressions.
- Functions that return values.
- Lists.
- Recursion.

17 What next?

Congratulations, you made it through Karel the Robot! We hope that you enjoyed the course. If you can think of any way to improve the application Karel the Robot or this textbook, we would like to hear from you. If you have an interesting new game or exercise for Karel, please let us know as well.

You are now ready to learn a next programming language! We would recommend Python which is a modern dynamic programming language that is used in many applications in business, science, engineering, and other areas. NCLab provides a Python course.

In any case, our team wishes you good luck, and keep us in your favorite bookmarks!

Your Authors