

# *Formal Methods for C*

*Seminar – Summer Semester 2014*

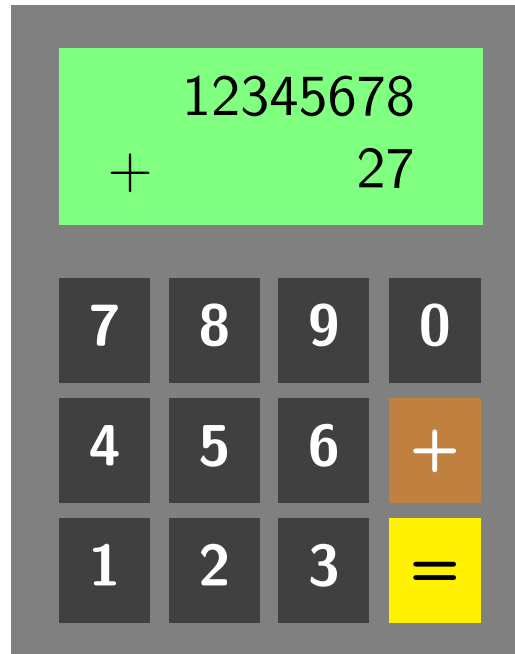
Daniel Dietsch, Sergio Feo Arenis, Marius Greitschus, **Bernd Westphal**

# *Formal Methods*

*Once Upon a Time...*

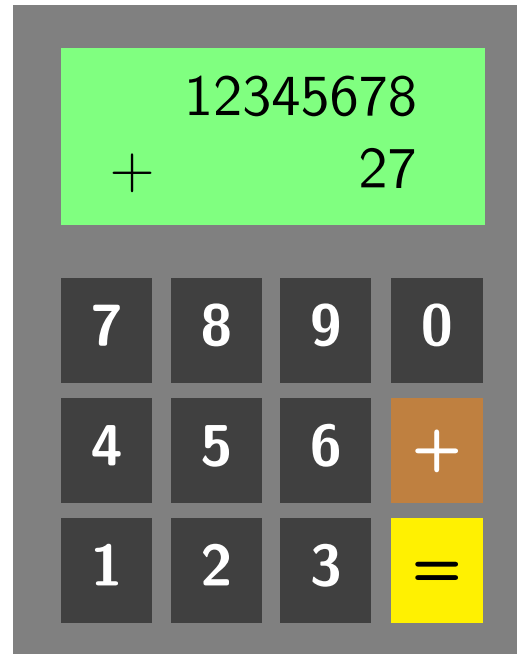
# *Provably Correct vs. Testing: Pocket Calculator*

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# Provably Correct vs. Testing: Pocket Calculator

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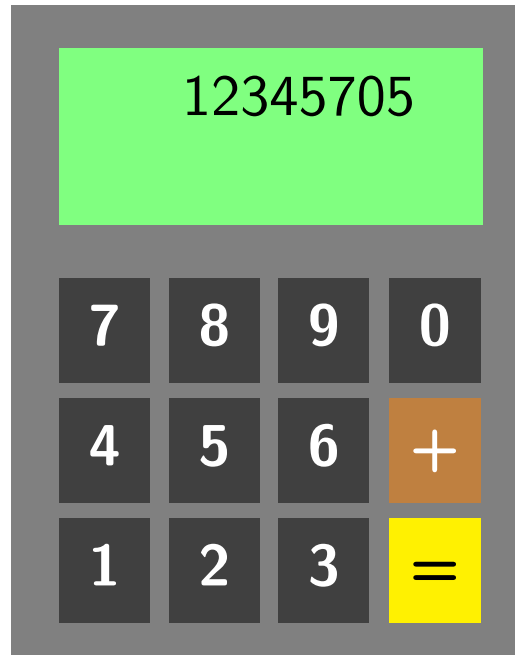


- Requirement:

If  $x$ ,  $+$ , and  $y$  are displayed then after pressing **=**, the sum of  $x$  and  $y$  is displayed if  $x + y$  has at most 8 digits, otherwise “-E-” is displayed.

# Provably Correct vs. Testing: Pocket Calculator

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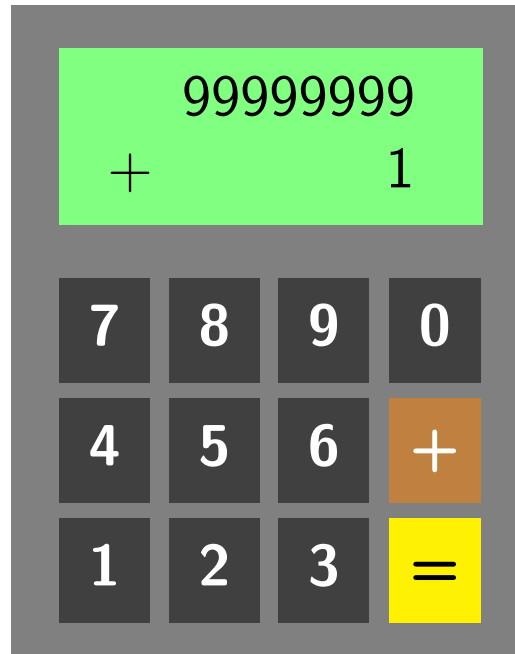


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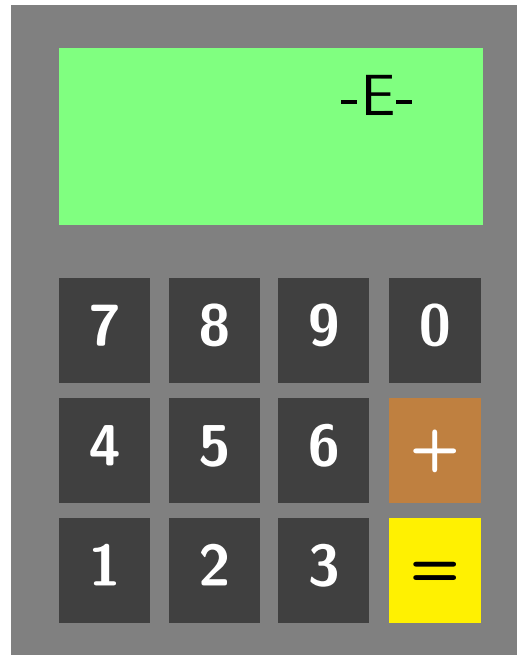


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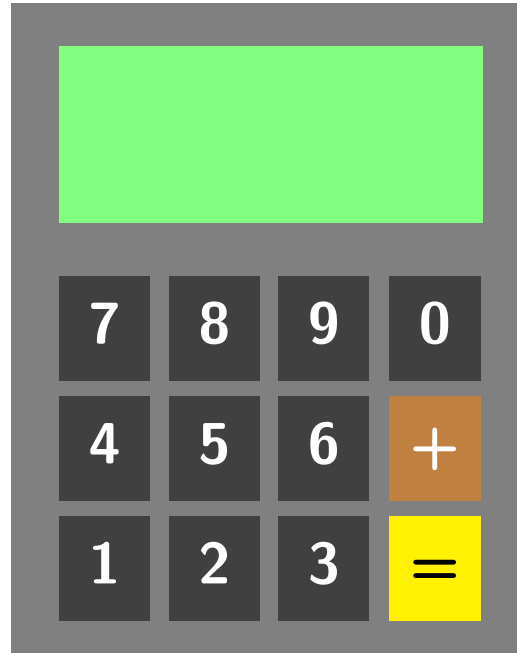
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# Testing the Pocket Calculator

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Test some representatives of “equivalence classes”:

- $n + 1$ ,  $n$  small,
- $n + m$ ,  $n$  small,  $m$  small (for non error),
- $n + m$ ,  $n$  big,  $m$  big (for non error),
- $n + m$ ,  $n$  huge,  $m$  small (for error),
- ...

e.g.  $27 + 1$

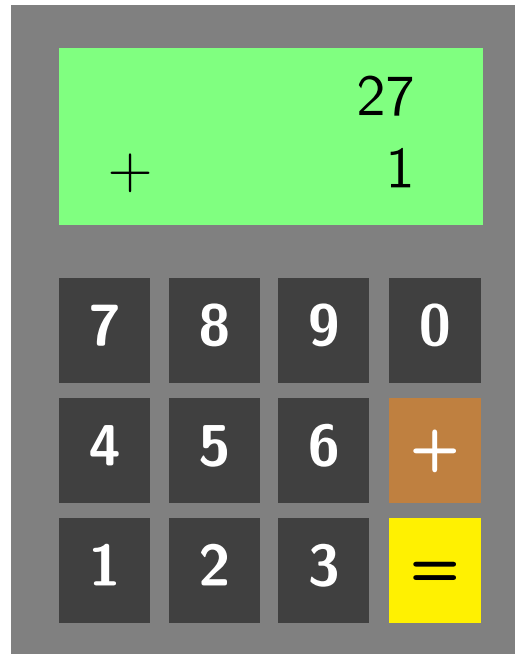
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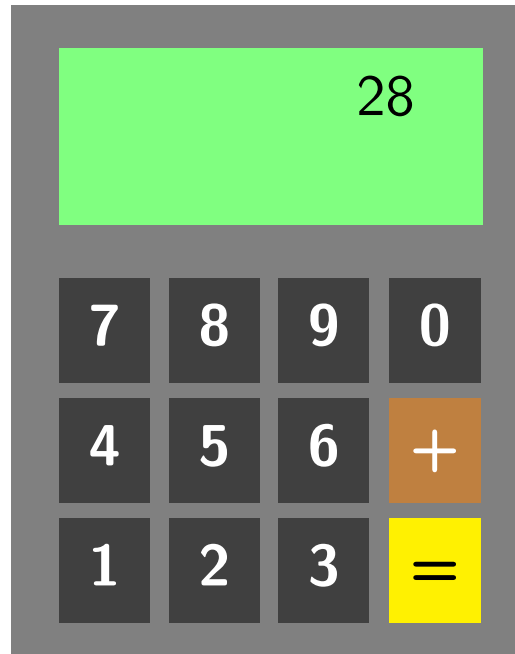
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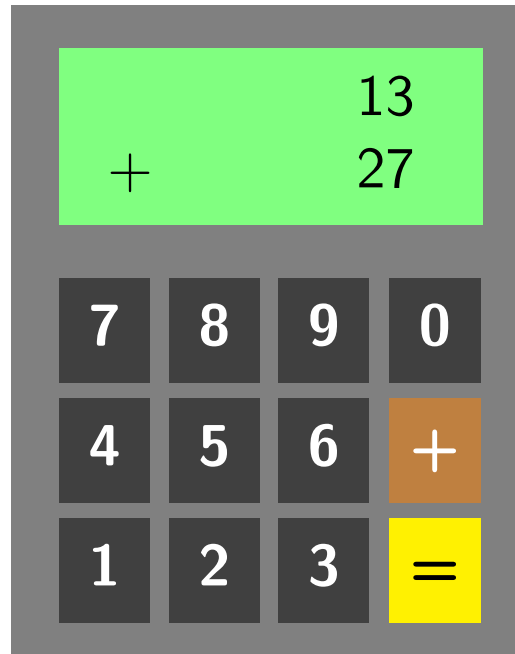
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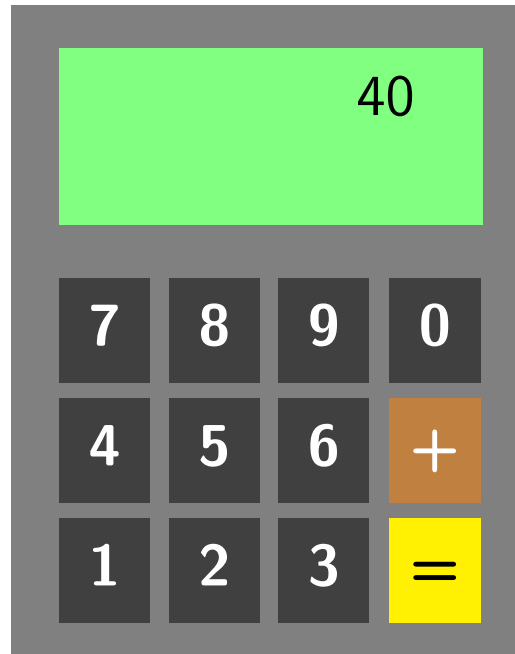
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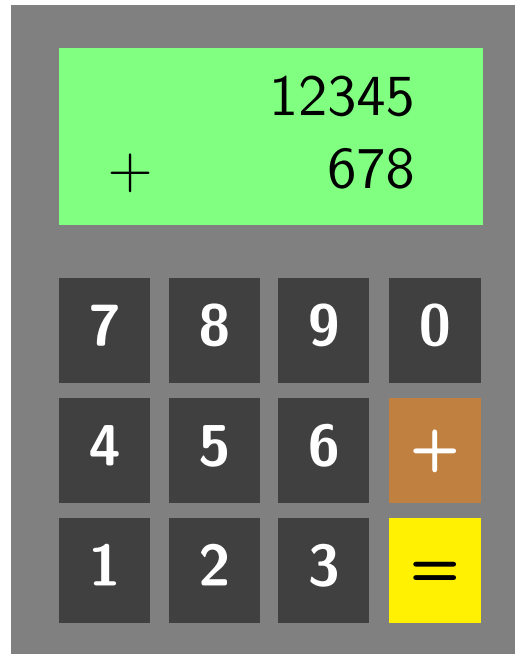
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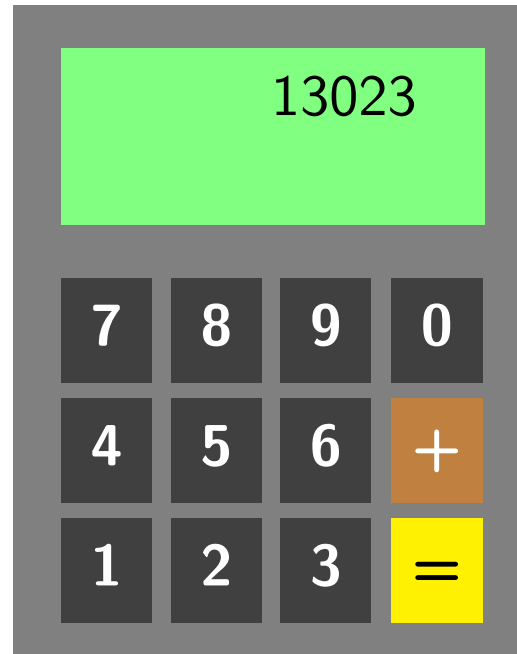
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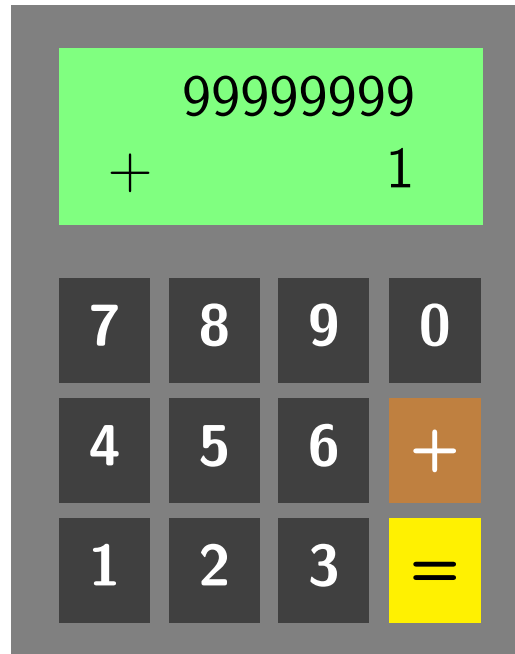
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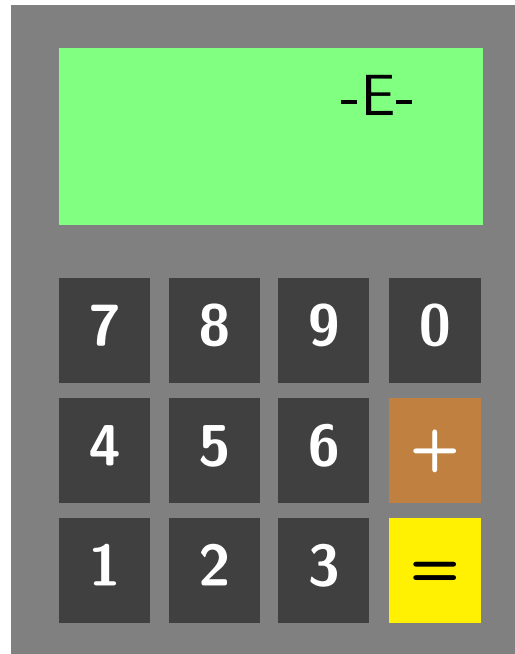
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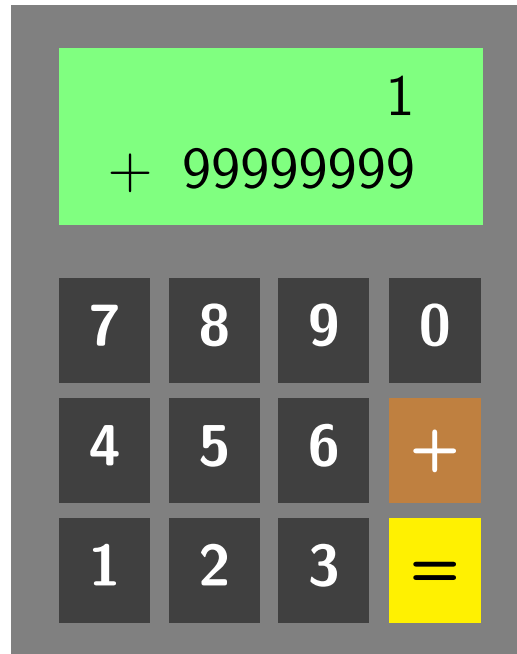
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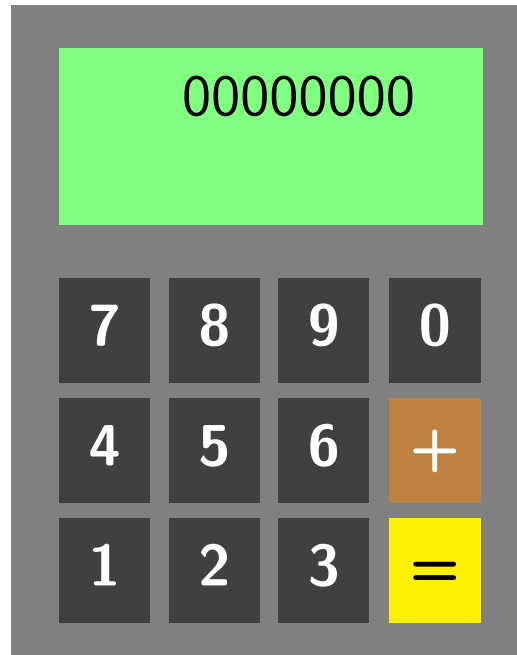
# Testing the Pocket Calculator: One More Try

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# Testing the Pocket Calculator: One More Try

---



- Oops...

# *Behind the Scenes: Test 999999999 + 1 Failed...*

---

```
1  int add( int x, int y )
2  {
3      if (y == 1) // be fast
4          return ++x;
5      else
6          return x+y;
7  }
```

# *Behind the Scenes: Test 999999999 + 1 Failed...*

---

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- **Tester:** “Hey, you’ve got to care for the 8-digit constraint in line 6!”

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- **Programmer:** “Eh, piece of cake. \*tippedittipp\* Here you are!”

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```
1  int add( int x, int y )
2  {
3      if (y == 1) // be fast
4          return ++x;
5
6      int r = x + y;
7
8      if (r > 999999999)
9          r = -1;
10
11     return r;
12 }
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- **Tester:** “Hey, you’ve got to care for the 8-digit constraint in line 6!”
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- **Programmer:** “Eh, piece of cake. \*tippedittipp\* Here you are!”
- **Tester:** “Fine, all tests passed!”



# The Tests Revisited

---

With our test cases

- $27 + 1$ ,
- $13 + 27$ ,
- $12345 + 678$ ,
- $999999999 + 1$

we have

```
1  int add( int x, int y )
2  {
3      if (y == 1) // be fast
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5
6      int r = x + y;
7
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# The Tests Revisited

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With our test cases

- $27 + 1$ ,
- $13 + 27$ ,
- $12345 + 678$ ,
- $99999999 + 1$

we have

- 100% statement coverage,

```
1  int add( int x, int y )
2  {
3      if (y == 1) // be fast
4          return ++x;
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# The Tests Revisited

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With our test cases

- $27 + 1$ ,
- $13 + 27$ ,
- $12345 + 678$ ,
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we have

- 100% statement coverage,
- 100% branch coverage,

```
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- 100% branch coverage,
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# The Tests Revisited

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With our test cases

- $27 + 1$ ,
- $13 + 27$ ,
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we have

- 100% statement coverage,
- 100% branch coverage,
- 100% condition coverage,
- ...

and still didn't spot the bug.

```
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11     return r;
12 }
```

To be sure, we'd need to test all (how many?) combinations – **impractical!**

# What If We Need to Be Sure?

---

```
1  #define DIGIT_8_MAX 99999999
2
3  int add( int x, int y )
4  {
5
6
7
8
9
10     int r;
11
12     if (y == 1) // be fast
13         r = ++x;
14     else {
15         r = x + y;
16
17         if (r > DIGIT_8_MAX)
18             r = -1;
19     }
20
21
22     return r;
23 }
```

# What If We Need to Be Sure?

(i) A precise (formal) specification:

- $x$  and  $y$  are non-negative 8-digit numbers:  
 $0 \leq x < 10^8$   
 $0 \leq y < 10^8$
- all non-negative returned numbers are 8-digit:  
 $r < 10^8$

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(ii) A representation of the specification understood by a verification tool.

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- all non-negative returned numbers are 8-digit:

$$r < 10^8$$

(ii) A representation of the specification understood by a verification tool.

```
1  #define DIGIT_8_MAX 99999999
2
3  int add( int x, int y )
4  {
5      assert (x >= 0);
6      assert (x <= DIGIT_8_MAX);
7      assert (y >= 0);
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10     int r;
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12     if (y == 1) // be fast
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$$r < 10^8$$

(ii) A representation of the specification understood by a verification tool.

(iii) A verification tool:

```
% check add.c
line 19: assertion violated
%
```

```
1  #define DIGIT_8_MAX 99999999
2
3  int add( int x, int y )
4  {
5      assert( x >= 0 );
6      assert( x <= DIGIT_8_MAX );
7      assert( y >= 0 );
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19     }
20
21     assert( r <= DIGIT_8_MAX );
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```

# What If We Need to Be Sure?

- Fix and check the fixed version:

```
% check add.c
verification succeeded
%
```

```
1  #define DIGIT_8_MAX 99999999
2
3  int add( int x, int y )
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```
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- **How is this possible?**
- **Subject of the seminar!**

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# What If We Need to Be Sure?

- Fix and check the fixed version:

```
% check add.c
verification succeeded
%
```

- **How is this possible?**
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- Alternative outcome:

```
% check add.c
out of memory
%
```

- None the wiser...

```
1 #define DIGIT_8_MAX 99999999
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# *Bottom Line: Formal Methods for C*

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A working definition for “formal methods for C”:

- (i) A precise, formal, mathematical **requirements specification**.
- (ii) An algorithm which is able to **prove or disprove** for a given piece of C code whether it satisfies the specification.
- (iii) At best: an implementation of that algorithm.

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- The requirements specification may upfront be wrong.
- The tool output may be interpreted in a wrong way.
- The tool may have bugs or run on buggy hardware.
- ...
- For production, the program may be compiled with a buggy compiler.
- ...

# *(Anticipated) Benefits*

---

- **Increased confidence.**
- Sometimes **reduced overall costs**: “find errors early”, despite **additional costs** for formalisation.

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## **Possible motivations:**

- **Loss of lives**: aerospace, railway, automotive, fire alarm, ...
- **Loss of health**: medical devices, ...
- **Loss of privacy**: encryption protocols, ...
- **Loss of money**: satellites, factory automation, ...
- ...

# *(Anticipated) Benefits*

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- **Increased confidence.**
- Sometimes **reduced overall costs**: “find errors early”, despite **additional costs** for formalisation.

## **Possible motivations:**

- **Loss of lives**: aerospace, railway, automotive, fire alarm, ...
- **Loss of health**: medical devices, ...
- **Loss of privacy**: encryption protocols, ...
- **Loss of money**: satellites, factory automation, ...
- ...

Errors sometimes already avoided by formalising requirements – e.g. “Heartbleed” could possibly have been avoided if RFC 6520 stated

*A heartbeat protocol message is **valid** if and only if*

*...  $\wedge$  M.payload\_length = length(M.payload)  $\wedge$  ...*

*Not **valid** messages **MUST** be discarded.*

# *The Seminar*

*Seminar...?*



# *The Task*

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- **Attend** the 2-3 introductory lectures on C and formal methods basics.

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- **Choose** a verification tool from the list (or propose your own).

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- **Thread 1**: Literature research, what's the theory behind the tool?

# The Task

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- **Attend** the 2-3 introductory lectures on C and formal methods basics.
- **Choose** a verification tool from the list (or propose your own).
- **Thread 1:** Literature research, what's the theory behind the tool?
- **Thread 2:** Get your hands dirty.
  - get acquainted with the tool on the VM (“Hi tool, nice to meet you!”)
  - reproduce and understand the tool provider's favourite example(s)
  - show one more property in that example,  
find one more bug in that (possibly reasonably modified) example
  - see how the tool does on these three examples:
    - `scan_ushort()`
    - low battery monitor – programming task
    - a big example

# *The Task*

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- **Attend** the 2-3 introductory lectures on C and formal methods basics.
- **Choose** a verification tool from the list (or propose your own).
- **Thread 1:** Literature research, what's the theory behind the tool?
- **Thread 2:** Get your hands dirty.

# *The Task*

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- **Attend** the 2-3 introductory lectures on C and formal methods basics.
- **Choose** a verification tool from the list (or propose your own).
- **Thread 1:** Literature research, what's the theory behind the tool?
- **Thread 2:** Get your hands dirty.
- **Present:** Block-Seminar, 30 min. (?) presentation with
  - tool name, brief history, etc.
  - what are the tool's capabilities?
  - what's the theory behind the tool?
  - how did the tool perform on the examples?
  - conclusionand participation in discussion after talk.

# Formalia

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**Grade:**  $r \cdot b \cdot (0.3 \cdot S + 0.7 \cdot T)$

- $r \in \{0, 1\}$ : repeatability package\* (RP) for favourite example
- $b \in \{0, 1\}$ : low battery monitor, not obviously broken
- $S \in \{1.0, \dots, 4.0, 6.0\}$ : talk structure
- $T \in \{1.0, \dots, 4.0, 6.0\}$ : presentation (incl. RP for three examples)

## Deadlines:

- 30.6.2014: “theory behind the tool” part of the talk
- 14.7.2014: talk structure
- **tba**: presentation

\*: shell script, Makefile, etc. which produces the results reported on in the talk by running the chosen verification tool on the examples with necessary parameters etc.

# *Talk Structure*

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- Formal Methods for C Kickoff
  - Introduction, ca. 10 Slides
  - Formal Methods, ca. 3 Slides
  - Formalia, ca. 3 Slides



# *Talk Structure*

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- Formal Methods for C Kickoff
  - Introduction, ca. 10 Slides
  - Formal Methods, ca. 3 Slides
  - Formalia, ca. 3 Slides

No.

# Talk Structure Example

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- Formal Methods for C Kickoff

**Goal:** give sufficient information for semester planning regarding workload, i.e. sketch goals and content, fix requirements, discuss grading, agree on common language

- Introduction (ca. 10 Slides)

**Goal:** point out difference between testing and verification

- little story on pocket calculator: show a bug which happens to be missed by tests
- give example for a proper formal requirement on pocket calculator, say how verification would be used given the C code

- Formal Methods (ca. 3 Slides)

**Goal:** agree on common understanding of “formal methods”, give outlook on motivation for their use and their limitations

- working definition: formal requirements, prove/disprove algorithm, tool
- limitations: e.g. bugs in checking tool
- benefits: increased confidence, maybe lower overall cost
- motivation: safety critical domain (transport, health, ...)

- Formalia (ca. 3 Slides)

**Goal:** agree on expected work, propose schedule and deadlines

- firstly the C seminar, then choose a tool
- then literature research and hands-on experience (two threads)
- hands-on experience: tool's favourite example and three given ones
- finally, block seminar; sketch expected content of talk
- clarify “structure” using bad/good example

# *Plan Proposal*

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- check the VM and the homepage for the offered tools/topics
- decide until next week: favourite (and second best) topic
- now: decide for meeting time(s) for introductory lecture
- next meeting: assign topics (and supervisor)

# *References*

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[ISO, 1999] ISO (1999). Programming languages – C. Technical Report ISO/IEC 9899:1999, ISO. Second edition, 1999-12-01.