Construction and Verification of Software

2017 - 2018

MIEI - Integrated Master in Computer Science and Informatics

Consolidation block

Lecture 2 - Specification and Verification

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based on previous editions by **Luís Caires** (lcaires@fct.unl.pt)

Software Correctness

Relevance of Software Correctness

RECAP

- Quality procedures must be enforced at all levels, in particular at the construction phase, where most of the issues are introduced and difficult to circumvent.
- **Questions for you now**:
  - What methods do you currently use to make sure your code is “bullet-proof” ?
  - How can you prove to yourself (and others) that your code is “bullet-proof” ?
  - What arguments do you use to convince yourself and others that your code works as expected and not goes wrong, with respect to functional correctness, security, or concurrency errors?
- You will **know better answers** at the end of this course.

Software Correctness: What and How

RECAP

- **Key engineering concern**:
  Make sure that the software developed and constructed is “correct”.
- What does this mean?
  - Is it crash-free? (“runtime safety”)
  - Gives the right results? (“functional correctness”)
  - Does it operate effectively? (“resource conformance”)
  - Does it violate user privacy? (“security conformance”)
  - …
- several process and methodological approaches to ensure and validate correctness exist (software engineering course)
- In this course, we cover some techniques to rigorously ensure and validate correctness **during software construction**

Correctness is against a specification

RECAP

- Then what does “correct software” mean?
  - Always relative to some given (**our**) specs
- Correct means that software meets **our** specs
  - There is no such thing as the “right specification”
  - In practice, the spec is usually incomplete ...
    - But **the spec must not be wrong** !
    - It should be very easy to check what the spec states
    - The spec **must be simple, much simpler than code**
    - The spec should be **focused** (pick relevant cases)
      - e.g., buffers are not being overrun
      - e.g., never transfer money without logging the source

Checking Specs: Dynamic Verificatio

RECAP

- By “dynamic verification” we mean that verification is **done at runtime**, while the program executes
- Some successful approaches:
  - **unit testing**
  - **coverage testing**
  - **regression testing**
  - **test generation**
  - **runtime monitoring**
- use runtime monitors to (continuously) check that code do not violate correctness properties
- violations causes exceptional behaviour or halt, so errors are detected after something wrong already occurred (think of a car crash, or a securiy leak)

Checking Specs: Dynamic Verificatio

RECAP

- Some shortcomings of dynamic verification
  - always introduces a level of performance overhead
  - may show the existence of some errors, but does not ensure absence of errors (the code passed a test suite today, but may fail with some other clever test)
  - **Challenge**: how do you make sure that you are defining the “right” tests and “enough” tests
  - Will talk about testing methods later on in the course

Checking Specs: Static Verification

- "static verification" means verification at **compile time**
- relies on algorithmic reasoning about what programs do, by analysing the source code, not by running the code
- can ensure absence of all errors of a certain well defined kind, e.g., "no null dereferences"
- can also tackle many complex correctness properties (e.g., functionality, absence of races, security, etc)
- does not introduce in performance overhead at runtime
- success stories:
  - **type checking**, as performed by the compiler
  - **extended checking**, static checking of assertions
  - **abstract interpretation**, simulates execution on a simpler decidable abstract model of runtime data

Checking Specs: Static Verification

- Specifications are the essential tool for abstraction and decomposition.
- For each program we need to know
  - in what conditions it can be used (requires/pre-conditions)
  - what are its effects (effects/ensures/post-conditions)

The post condition assertion can be assumed after the program's execution, provided that the pre-conditions were met at the beginning. That's the only assumptions that can be drawn from the post-condition.

Design by Contract vs Defensive Programming

- Design by contract
  - Eiffel language (Bertrand Meyer)
  - Formal specification of pre-, post-conditions and invariants
  - Assume that all preconditions are met when invoking an operation and that all postconditions will be satisfied after the operation is executed.
- Defensive programming
  - Prepare for all possible inputs and associated responses
- Logic based verification
  - Hoare Logic
  - If all components are verified, all contracts

What may specs look like?

- A classical example is the use of “assertions”
  - You have used assertions before (IP, POO, AED)?
- A simple and fine grained spec is the “Hoare triple”:

$$\{ A \} P \{ B \}$$

- A and B are assertions (conditions on the program state)
- P is the piece of code we want to talk about
- The Hoare triple says:
  - If program P starts in a state satisfying A, then, if it terminates, the resulting state satisfies B.
  - A is called the “pre-condition”
  - B is called the “post-condition”

Interface contracts in ADT specs

- ADT specifications (we will detail this later) involve method contracts, expressed as assertions

```
method P(... parameters ...)
requires pre-condition-assertion      % PRE
ensures post-condition-assertion      % POST
modifies global-state-changed         % MOD
{
   ... method code
}
```

- The method call P(...), whenever started in a state that satisfies PRE, if it terminates, always ends in a state that satisfies POST, and only has effects on MOD

Invariants in ADT specs

- ADT specifications (we will detail this later) may involve representation invariants and abstraction mappings also expressed as assertions

```
class C {
invariant invariant-assertion REPINV
invariant abstraction-map-assertions ABSMAP
{
   ... methods...
}
```

- ADT C implementation relies on a representation type T that satisfies the representation invariant REPINV and maps into the abstract type as specified by ABSMAP

How are Specs verified?

- A logic is used to prove properties of programs
- What kinds of properties are we interested in?
  - safety properties (partial correctness)
  - state that if the program terminates (delivers an outcome), then the final state satisfies some property
  - liveness properties (total correctness)
  - say that the program terminates (at least under certain conditions)
- Hoare logic is the “mother of all program logics”: It provides a foundation for most program logics for imperative programming languages
- Reason of HL success: verification at the level of the programming languages (not of programs, cf. Floyd)

Dafny

"Dafny is an imperative object-based language with built-in specification constructs. The Dafny static program verifier can be used to verify the functional correctness of programs. The specifications include pre- and postconditions, frame specifications (read and write sets), and termination metrics"

Leino, Koenig, 2010

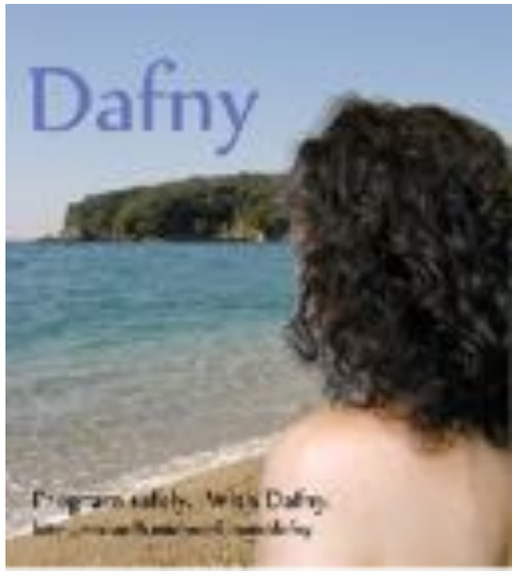
Dafny: An Automatic Program Verifier for Functional Correctness

K. Rustan M. Leino
Microsoft Research
leino@microsoft.com

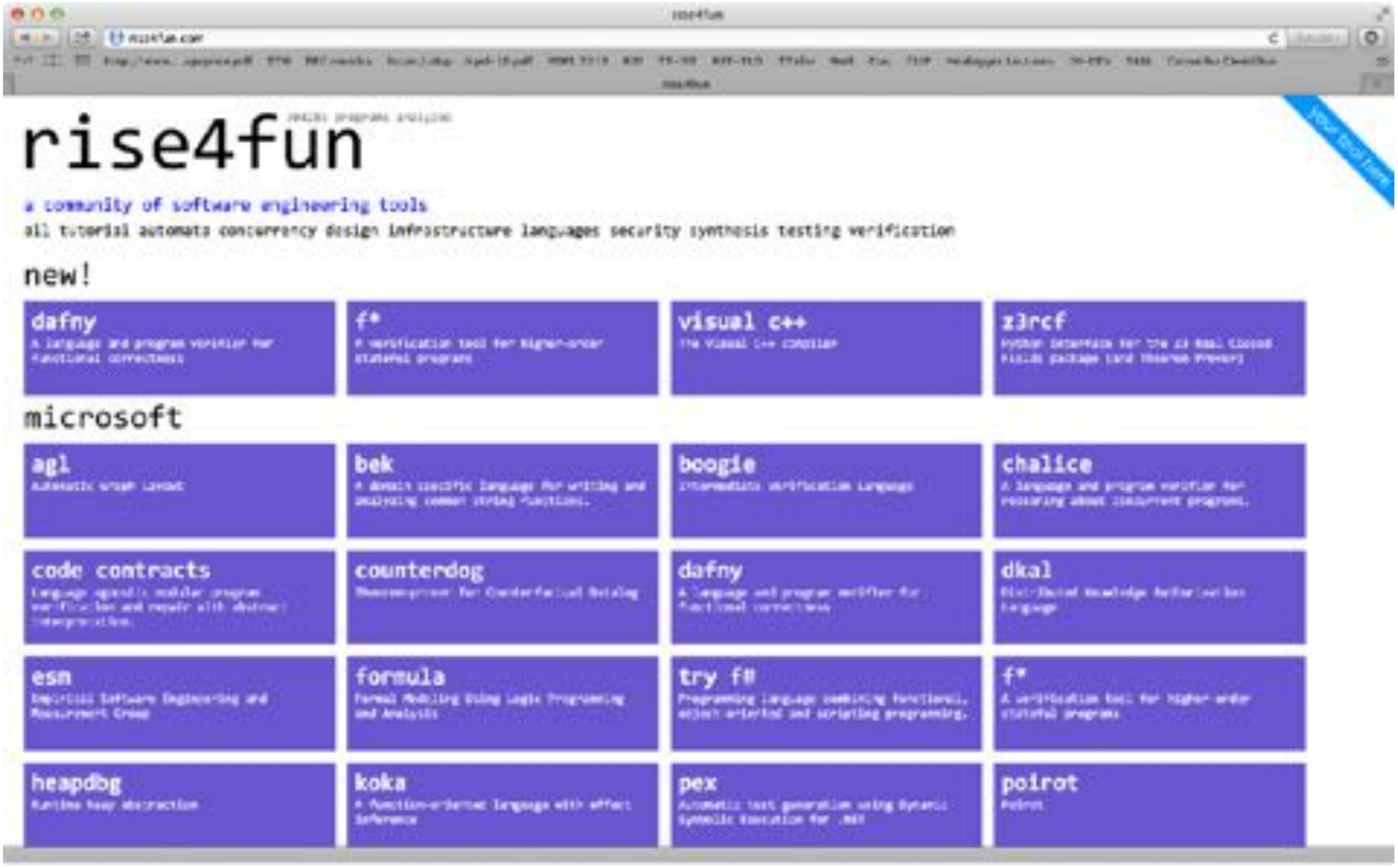
Abstract

Traditionally, the full verification of a program's functional correctness has been obtained with pen and paper or with interactive proof assistants, whereas only reduced verification tasks, such as extended static checking, have enjoyed the automation offered by satisfiability-modulo-theories (SMT) solvers. More recently, powerful SMT solvers and well-designed program verifiers are starting to break that tradition, thus reducing the effort involved in doing full verification.

This paper gives a tour of the language and verifier Dafny, which has been used to verify the functional correctness of a number of challenging pointer-based programs. The paper describes the features incorporated in Dafny, illustrating their use by small examples and giving a sense of how they are coded for an SMT solver. As a larger case study, the paper shows the full functional specification of the Schorr-Waite algorithm in Dafny.



rise4fun @ Microsoft Research (MSR)



A glimpse of Dafny programming

dafny Research

Is this program correct?

```
1  class PSet
2  {
3    var s: set<int>;
4    var n: int;
5
6    function SetInv(): bool
7    reads this;
8    {
9      (forall x::x in s ==> x >= 0) && |s| == n
10   }
11
12 method initBag()
13 ensures SetInv();
14 modifies this;
15 {
16   s := {};
17   n := 0;
18 }
19
20 method add(x:int)
21   requires SetInv() && x >= 0;
22   modifies this;
```

▶ tutorial

home video permalink

'←' shortcut: Alt+B

Basic Program Specs (Hoare Logic)

A.M. TURING AWARD

C. A. R. HOARE
United Kingdom – **1980**

For his fundamental contributions to the definition and design of programming languages.

Hoare Logic (1969)

An Axiomatic Basis for Computer Programming

C. A. R. Hoare
The Queen's University of Belfast, Northern Ireland*

In this paper an attempt is made to explore the logical foundations of computer programming by use of techniques which were first applied in the study of geometry and have later been extended to other branches of mathematics. This involves the elucidation of sets of axioms and rules of inference which can be used in proofs of the properties of computer programs. Examples are given of such axioms and rules, and a formal proof of a simple theorem is displayed. Finally, it is argued that important advantages, both theoretical and practical, may follow from a pursuance of these topics.

KEY WORDS AND PHRASES: axiomatic method, theory of programming, proofs of programs, formal language definition, programming language design, machine-independent programming, program documentation
CR CATEGORY: 4.0, 4.21, 4.22, 5.20, 5.21, 5.23, 5.24

of axioms it is possible to deduce such simple theorems as:

$$x = x + y \times 0$$

$$y \leqslant r \supset r + y \times q = (r - y) + y \times (1 + q)$$

The proof of the second of these is:

A5 $(r - y) + y \times (1 + q)$

$= (r - y) + (y \times 1 + y \times q)$

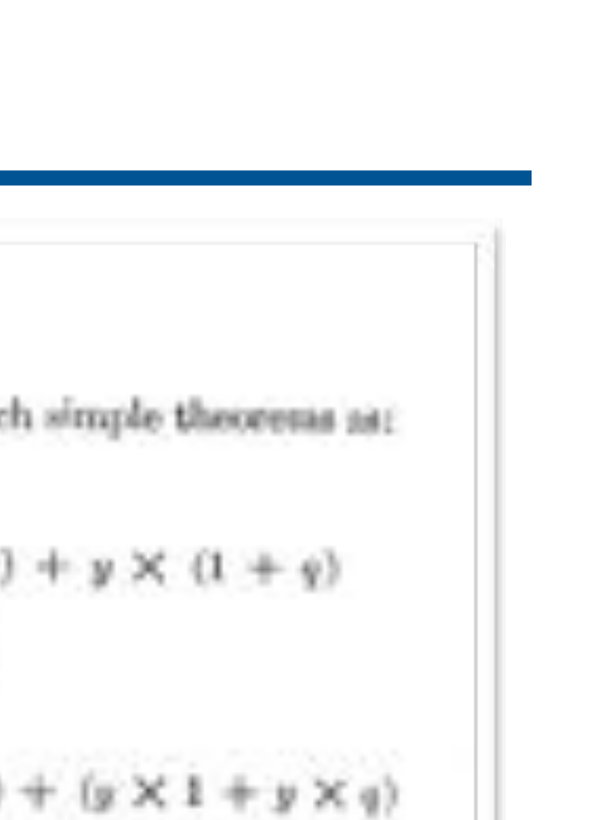
A9 $= (r - y) + (y + y \times q)$

A3 $= ((r - y) \ldots$

A6 $= r + y \times$

The axioms A1 to A9 are, of cou
tional infinite set of integers in ma
they are also true of the finite sets of
manipulated by computers provide
fined to nonnegative numbers. Their
of the size of the set; furthermore, it i
of the choice of technique applied i
flow"; for example:

(1) Strict interpretation: the res
operation does not exist; when overfl
ing program never completes its op
this case, the equalities of A1 to A9
that both sides exist or fail to exist



Simple Programming Language

E	::=	Expressions	
		num	Integer
	|	x	Variable
	|	$E + E \mid ...$	Integer operators
	|	$E < E \mid ...$	Relational operators
	|	E `and` $E ...$	Boolean operators

P	::=		Programs
		`skip`	No op
	|	$x := E$	Assignment
	|	$P; P$	Sequential Composition
	|	`if` E `then` P `else` P	Conditional
	|	`while` E `do` P	Iteration

States and State Transformers

- A program is a state transformer,
  it transforms an initial state into a target state
- What is a program state? a state is an assignment of values to state variables

$$\sigma = \{x \mapsto 1, y \mapsto 2, z \mapsto 3\}$$

- An imperative program transforms states into states

$$P \triangleq x := y + x; z := z - x$$

- If P is executed in state σ it yields state σ' where

$$\sigma' = \{x \mapsto 3, y \mapsto 2, z \mapsto 0\}$$

- We may say that P transforms σ in σ'
- P is only defined on states σ where vars(P) ⊆ dom(σ)

States and Assertions

- A (safety) property is a set of (safe) states
- Essentially an assertion is a boolean expression that only depends on observing program (state) variables
- Thus, an assertion is just a pure observation, it is either true or false, its evaluation does not change the state
- In general, one may use all the expressiveness of (first order) logic in assertions (e.g. quantifiers, etc...)
- The assertion language is part of the specification language, not of the programming language
- But in some cases, assertions may be expressed in the programming language (Java / Dafny).

Assertions in Dafny

dafny Microsoft Research

Is this program correct?

```
1  method strncpy(a:array<int>, n:int, b:array<int>)
2  requires a!=null && b!= null;
3  requires 0 <= n <= a.Length <= b.Length;
4  modifies b;
5  ensures forall j::(0<=j<n) ==> b[j] == a[j];
6  {
7  var i:int :=0;
8  while (i < n)
9  invariant 0 <= i <= n;
10 invariant forall j::(0<=j<i) ==> b[j] == a[j];
11 {
12   b[i] := a[i];
13   i := i + 1;
14 }
15 }
```

Some bits of history … (extra)

Kick off:

– **Checking a large routine**

Turing

Kick off:

- **"Checking a large routine"**

"How can one check a routine in the sense of making sure that it is right? In order that the man who checks may not have too difficult a task the programmer should make a number of definite assertions which can be checked individually, and from which the correctness of the whole programme easily follows."

Alan Turing, 24th June 1949

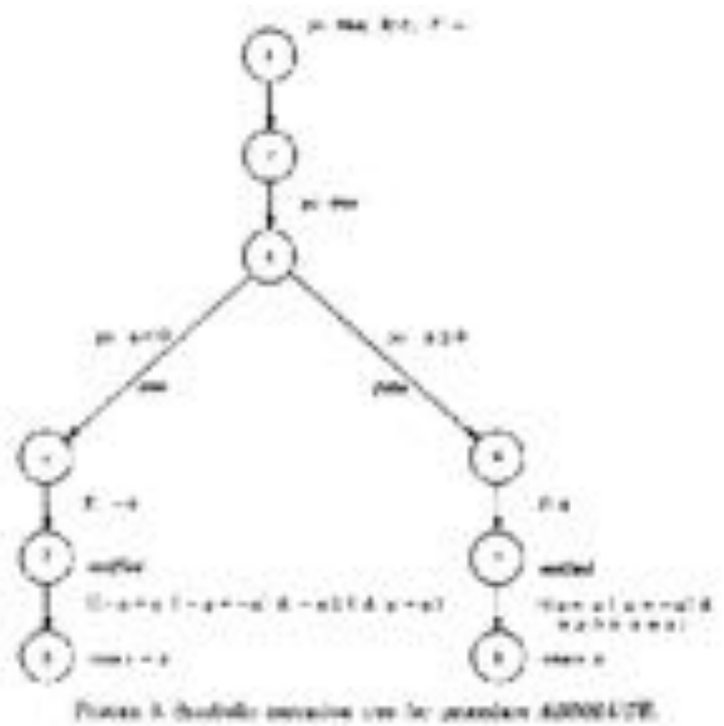
Assertions

Second boost:

– **Floyd's Assertion Method**

Robert Floyd's, "Assigning Meanings to Programs," opened the field of program verification. His basic idea was to attach so-called "tags" in the form of logical assertions to individual program statements or branches that would define the effects of the program based on a formal semantic definition of the programming language.

R. Floyd, MFCS, June 1967



Assertions

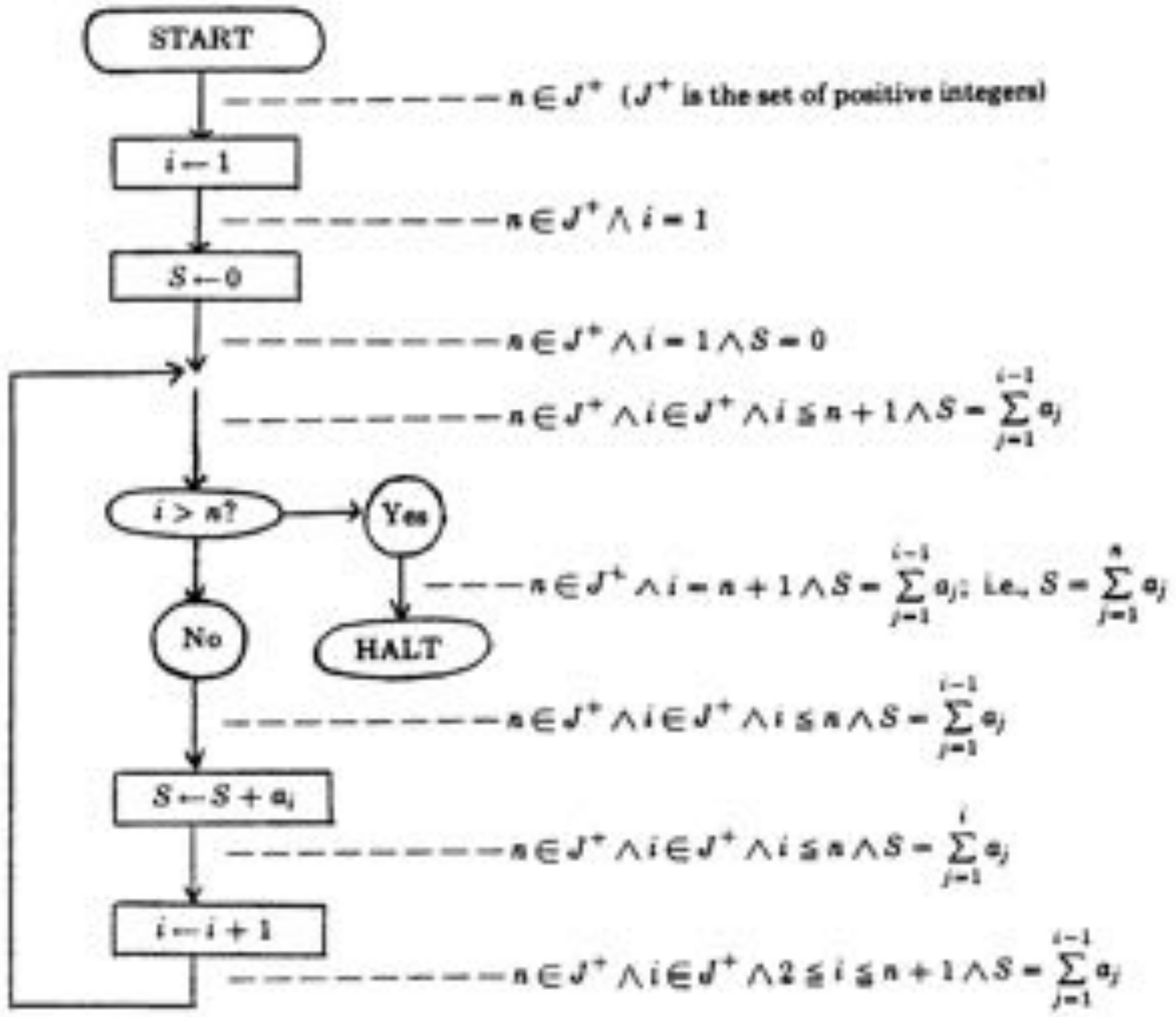


FIGURE 1. Flowchart of program to compute $S = \sum_{j=1}^{n} a_j$ ($n \geq 0$)

Language Based Program Specs

Lift Off:

– Hoare Logic

"Computer Programming is an exact science in that all the properties of a program and all consequences of executing it in any given environment can, in principle, be found out from the text of the program itself by means of purely deductive reasoning."

Tony Hoare, CACM 1969

AXIOM 1: ASSIGNMENT AXIOM

$$\{p[t/x]\}\ x := t\ \{p\}.$$

RULE 2: COMPOSITION RULE

$$\frac{\{p\}\ S_1\ \{r\},\ \{r\}\ S_2\ \{q\}}{\{p\}\ S_1; S_2\ \{q\}}.$$

RULE 3: **if-then-else** RULE

$$\frac{\{p \wedge e\}\ S_1\ \{q\},\ \{p \wedge \neg e\}\ S_2\ \{q\}}{\{p\}\ \textbf{if}\ e\ \textbf{then}\ S_1\ \textbf{else}\ S_2\ \textbf{fi}\ \{q\}}$$

RULE 4: **while** RULE

$$\frac{\{p \wedge e\}\ S\ \{p\}}{\{p\}\ \textbf{while}\ e\ \textbf{do}\ S\ \textbf{od}\ \{p \wedge \neg e\}}$$

Hoare Logic Today

Still hot ...

– Hoare Logic

“ The axiomatic method gives an objective criterion of the quality of a programming language, and the ease with which programmers could use it. The latest response comes from hardware designers, who are using axioms in anger to define the properties of modern multicore chips with weak memory consistency.”

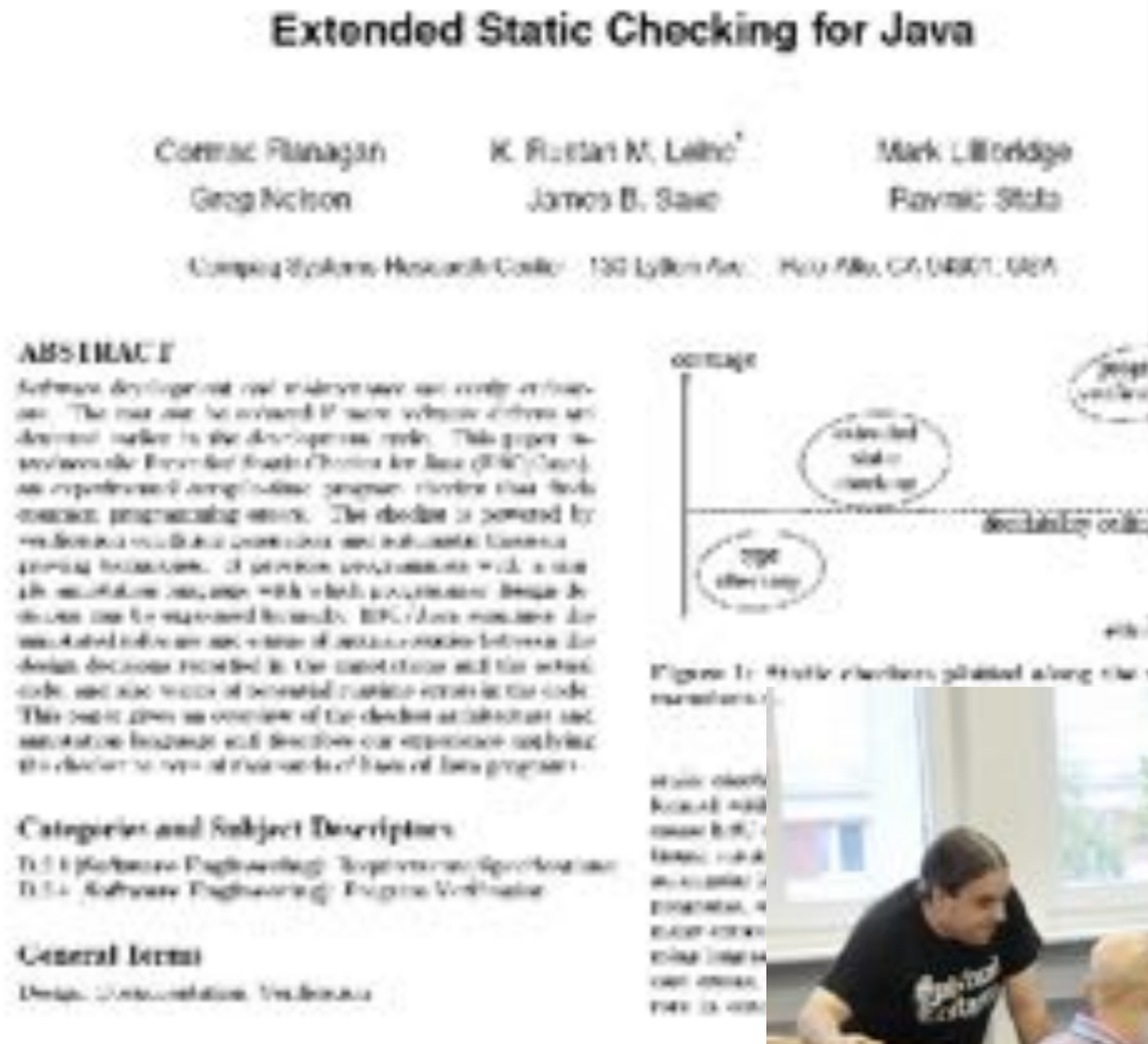
Tony Hoare, CACM 2009

Extended Static Checking

JML and Extended Static Checking for Java

ESC/Java2 is a programming tool that uses static analysis to verify the correctness of Java programs, using an extension of Hoare Logic called JML.

G.T. Leavens, 2000



Extended Static Checking for Java

Cormac Flanagan, K. Rustan M. Leino, Mark Lillibridge
Greg Nelson, James B. Saxe, Raymie Stata

ABSTRACT

Categories and Subject Descriptors

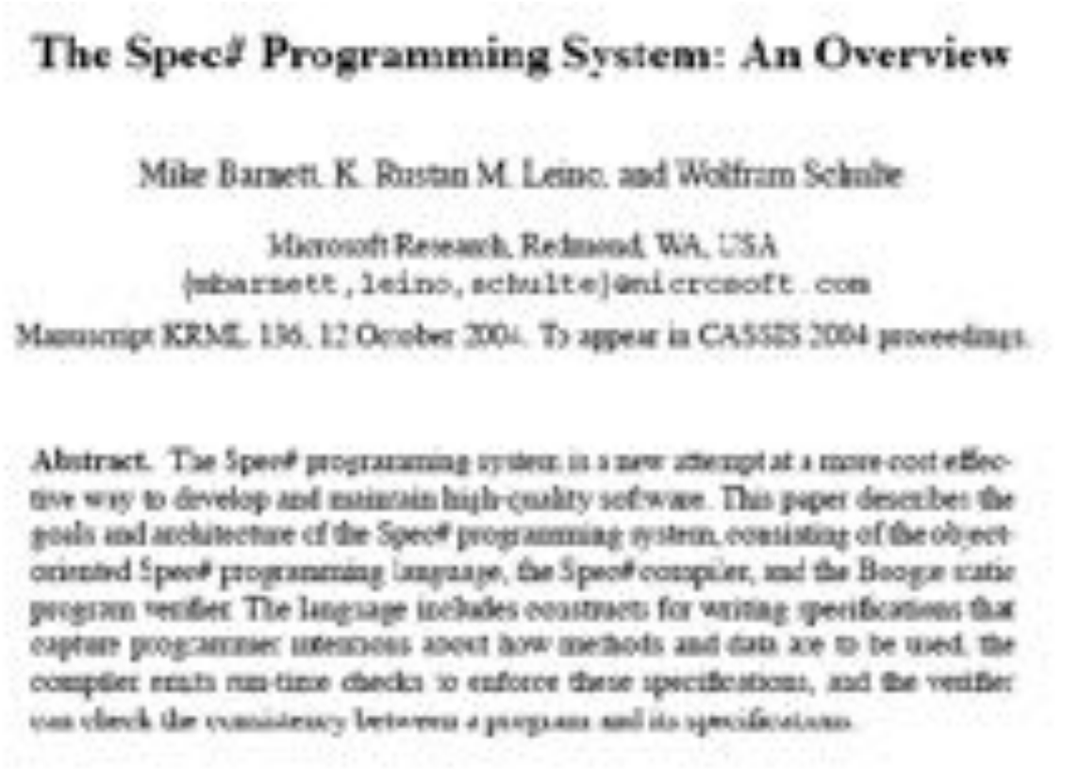
General Terms

Extended Static Checking

Spec

Spec# is an extension of the object-oriented language C#. It extends the type system to include non-null types and checked exceptions. It provides method contracts in the form of pre- and postconditions as well as object invariants.

Barnett, Leino, Schulte, 2004



The Spec# Programming System: An Overview

Mike Barnett, K. Rustan M. Leino, and Wolfram Schulte

Microsoft Research, Redmond, WA, USA
{mbarnett,leino,schulte}@microsoft.com

Manuscript KRML 136, 12 October 2004. To appear in CASSIS 2004 proceedings.

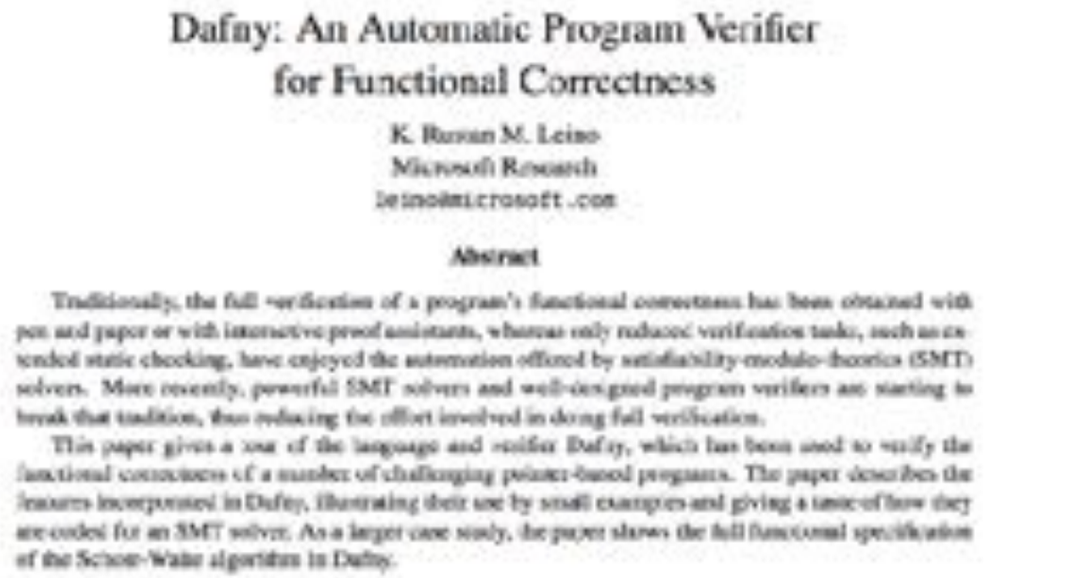
Abstract. The Spec# programming system is a new attempt at a more cost effective way to develop and maintain high-quality software. This paper describes the goals and architecture of the Spec# programming system, consisting of the object-oriented Spec# programming language, the Spec# compiler, and the Boogie static program verifier. The language includes constructs for writing specifications that capture programmer intentions about how methods and data are to be used, the compiler emits run-time checks to enforce these specifications, and the verifier can check the consistency between a program and its specifications.

Dafny

Dafny

Dafny is an imperative object-based language with built-in specification constructs. The Dafny static program verifier can be used to verify the functional correctness of programs. The specifications include pre- and postconditions, frame specifications (read and write sets), and termination metrics

Leino, Koenig, 2010



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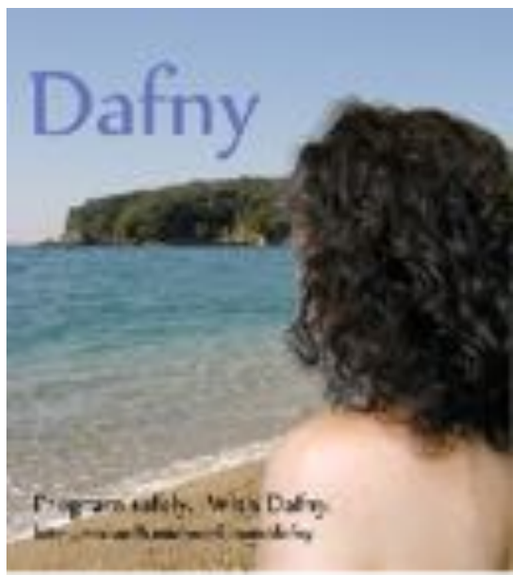

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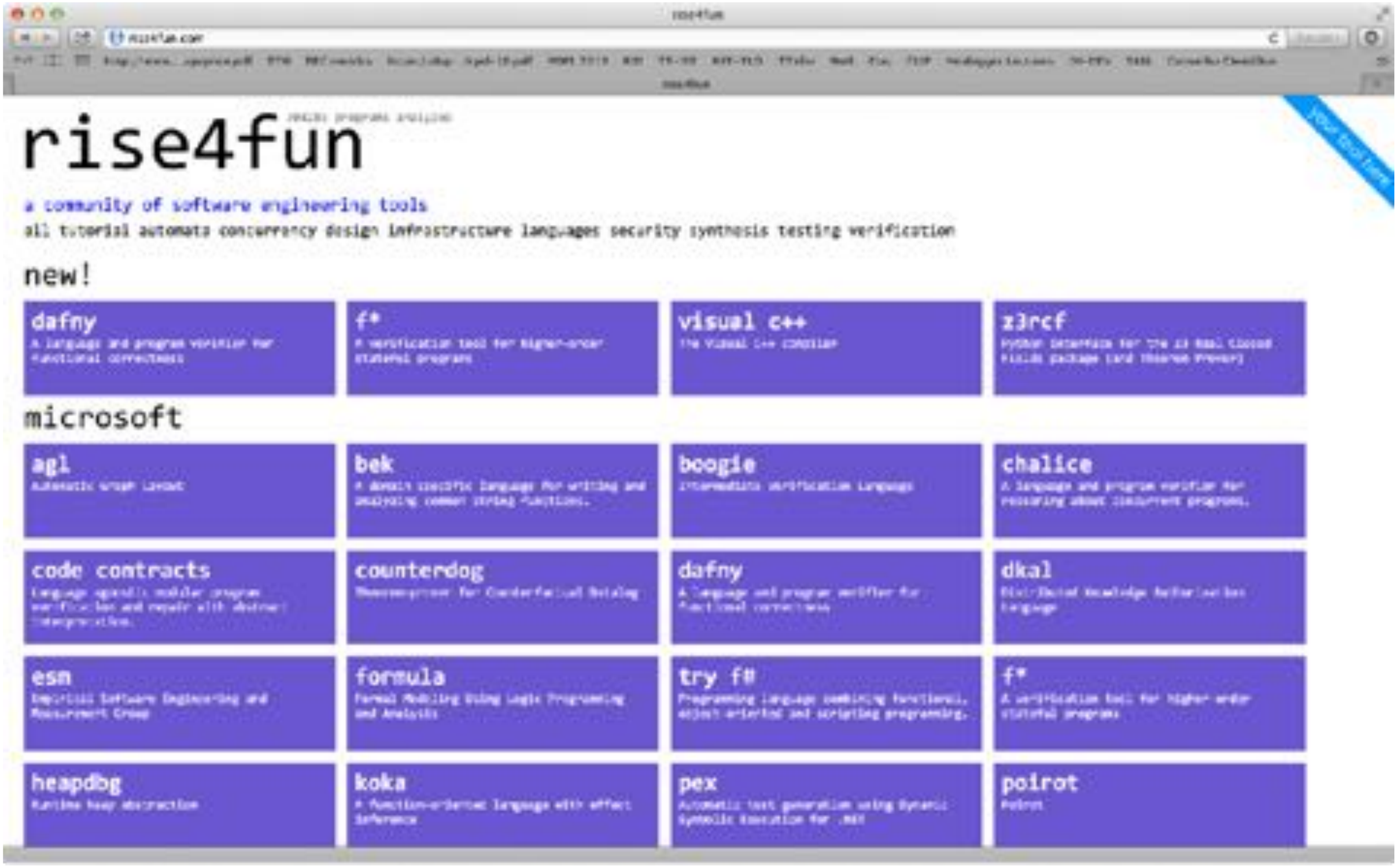
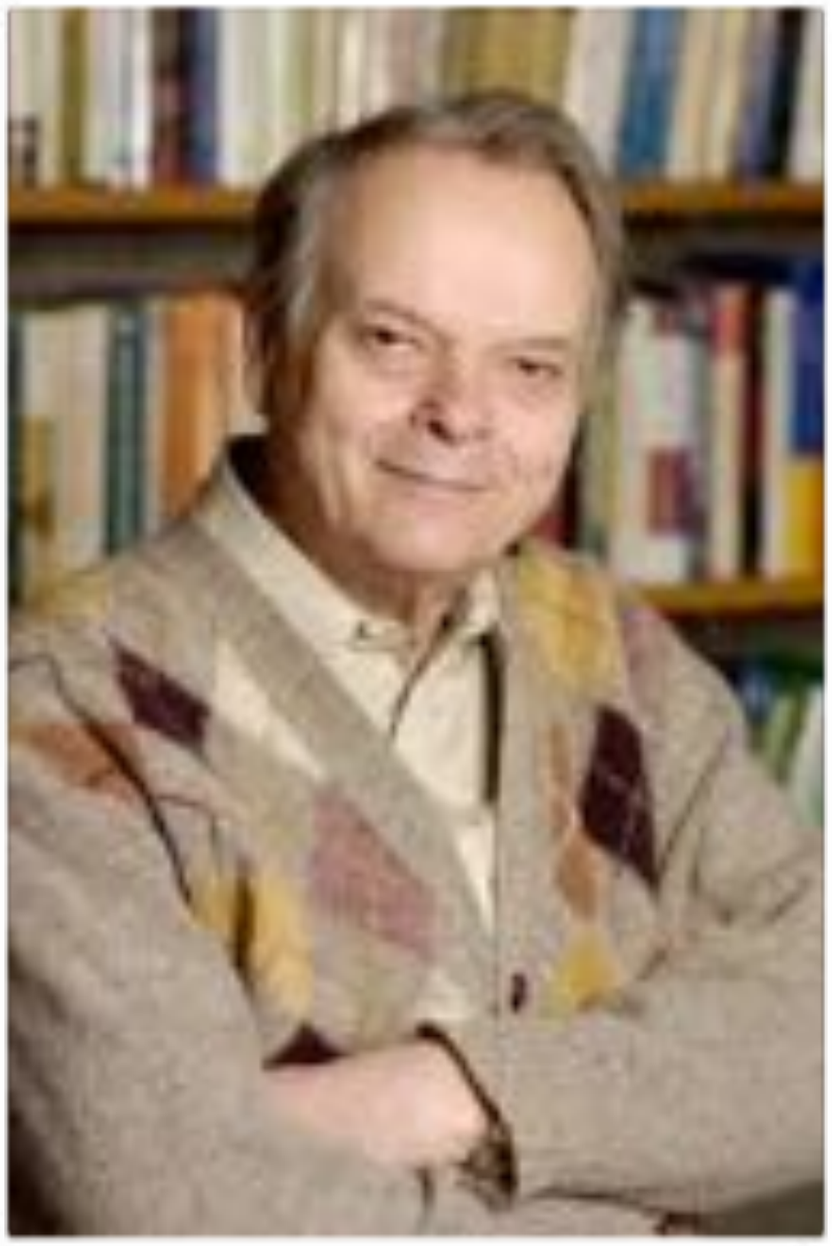


Separation Logic



John C. Reynolds

$$\frac{s, h \models P * (P \mathrel{-\!\!*} Q)}{s, h \models Q} \qquad \frac{\{P\}\ C\ \{Q\}}{\{P * R\}\ C\ \{Q * R\}}\ \mathsf{mod}(C) \cap \mathsf{fv}(R) = \emptyset$$

Peter O'Hearn

Verifast

Verifast

VeriFast is a verifier for single-threaded and multithreaded C and Java programs annotated with preconditions and postconditions written in separation logic.

Jacobs, Smans, Piessens, 2010

NB: separation logic is a spec language for talking about programs that allocate memory and use references

```
public void broadcast_message(String message) throws IOException
    //@ requires room(this) &*& message != null;
    //@ ensures room(this);
{
    //@ open room(this);
    //@ assert foreach(members0, _);
    List membersList = this.members;
    Iterator iter = membersList.iterator();
    boolean hasNext = iter.hasNext();
    //@ length_nonnegative(members0);
    while (hasNext)
        /*@
        invariant
            foreach<Member>(members, @Member) &*& iter(iter, membersList, members, ?i) &*&
            hasNext == (i < length(members)) &*& 0 <= i &*& i <= length(members);
        @*/
    {
        Object o = iter.next();
        Member member = (Member)o;
        //@ mem_nth(i, members);
        //@ foreach_remove<Member>(member, members);
        //@ open member(member);
        Writer writer = member.writer;
        writer.write(message);
        writer.write("\r\n");
        writer.flush();
        //@ close member(member);
        //@ foreach_unremove<Member>(member, members);
        hasNext = iter.hasNext();
    }
    //@ iter_dispose(iter);
    //@ close room(this);
}
```



Rules of Hoare Logic

Program Proofs in Hoare Logic

- A program proof in Hoare logic adds assertions between program statements, making sure that all Hoare triples are satisfied.
- For example, consider the code snippet

```
if (x>y) {
    z := x
} else {
    z := y
}
```

Program Proofs in Hoare Logic

- A Hoare Logic “proof” may look like

```
{ true }
if (x>y) {
    { (x > y)  }
    z := x;
    { (x>y) && (z == x) }
}
else {
    { (x <= y) }
    z := y;
    { (x<=y) && (z == y) }
}
{ (x>y) && (z == x) || (x<=y) && (z == y)}
{ z == max(x,y) }
```

Example: Rule for Sequence

- A sequence defines a dependency on the effects of both program statements.

$$\frac{\{A\}\ P\ \{B\} \quad \{B\}\ Q\ \{C\}}{\{A\}\ P;Q\ \{C\}}$$

Rules of Hoare Logic (general form)

- The inference rules of Hoare logic are used to derive (valid) Hoare triples given some already derived Hoare triples

$$\frac{\{A_1\}\ P_1\ \{B_1\}\ \ldots\ \{A_n\}\ P_n\ \{B_n\}}{\{A\}\ C(P1, \ldots, P_n)\ \{B\}}$$

- What is nice here:
  - the program in the conclusion contains the subprograms $P_1, \ldots, P_n$ as components
  - we derive properties of the composite from the properties of its parts (compositionality)
  - pretty much the same as with a type system

“Structural” Proof Rules

- Basic logic proof systems operate on propositions, e.g.

$$\frac{A \quad A \implies B}{B} \qquad \frac{A \quad B}{A \wedge B} \qquad \frac{A}{A \vee B} \qquad \frac{B}{A \vee B}$$

- Hoare logic proof system operates on Hoare triples, e.g.

$$\frac{\{A\}\ P\ \{B\} \quad \{B\}\ Q\ \{C\}}{\{A\}\ P;Q\ \{C\}}$$

One rule for each PL construct

Axiom 1: Assignment Axiom

$$\{p[t/x]\}\ x := t\ \{p\}.$$

Rule 2: Composition Rule

$$\frac{\{p\}\ S_1\ \{r\},\ \{r\}\ S_2\ \{q\}}{\{p\}\ S_1; S_2\ \{q\}}.$$

Rule 3: if-then-else Rule

$$\frac{\{p \wedge e\}\ S_1\ \{q\},\ \{p \wedge \neg e\}\ S_2\ \{q\}}{\{p\}\ \textbf{if}\ e\ \textbf{then}\ S_1\ \textbf{else}\ S_2\ \textbf{fi}\ \{q\}}$$

Rule 4: while Rule

$$\frac{\{p \wedge e\}\ S\ \{p\}}{\{p\}\ \textbf{while}\ e\ \textbf{do}\ S\ \textbf{od}\ \{p \wedge \neg e\}}$$

- A really cool idea:
  - every programmer can use the Hoare rules informally to mentally check her code while coding
  - tools exist that automate most of the process
  - we now go through each rule, one by one

Simple Programming Language

RECAP

E	::=	Expressions	
		num	Integer
	|	x	Variable
	|	$E + E \mid ...$	Integer operators
	|	$E < E \mid ...$	Relational operators
	|	E `and` $E ...$	Boolean operators

P	::=		Programs
		`skip`	No op
	|	$x := E$	Assignment
	|	$P; P$	Sequential Composition
	|	`if` E `then` P `else` P	Conditional
	|	`while` E `do` P	Iteration

Rule for Skip

$$\{A\}\ \texttt{skip}\ \{A\}$$

Rule for Skip

$$\{A\}\ \texttt{skip}\ \{A\}$$

```
if x < 0
  { x := -x; }
```

```
if x < 0
  { x := -x; }
else
  skip
```

Example: Rule for Sequence

- A sequence defines a dependency on the effects of both program statements.

$$\frac{\{A\}\ P\ \{B\} \quad \{B\}\ Q\ \{C\}}{\{A\}\ P;Q\ \{C\}}$$

Rule for Conditional

$$\frac{\{A \wedge E\}\ P\ \{B\} \quad \{A \wedge \neg E\}\ Q\ \{B\}}{\{A\}\ \texttt{if}\ E\ \texttt{then}\ P\ \texttt{else}\ Q\ \{B\}}$$

Rule for Deduction

$$\frac{A' \implies A \quad \{A\}\ P\ \{B\} \quad B \implies B'}{\{A'\}\ P\ \{B'\}}$$

- A ⇒ B means “A logically implies B”
- We prove A ⇒ B using the principles of first order logic,

  plus basic properties of the domain data types, e.g. properties of integers, arrays, etc.

Rule for Assignment

$$\{A[^{E}/_{x}]\}\ x := E\ \{A\}$$

- A[E/x] means:
  - the result of replacing all free occurrences of variable x in assertion A by the expression E
- For this rule to be sound, we require E to be an expression without side effects (a pure expression)

Rule for Assignment

$$\{A[^{E}/_{x}]\}\ x := E\ \{A\}$$

- We can think of A as a condition where “x” appears in some places. A is a condition dependent on “x”.

- The assignment x := E changes the value of x to E, but leaves everything else unchanged
- So everything that could be said of E in the precondition, can be said of x in the postcondition, since the value of x after the assignment is E
- Example: { x + 1 > 0 } x := x + 1 { x > 0 }

Rule for Assignment

$$\{A[^{E}/_{x}]\}\ x := E\ \{A\}$$

- Example, let's check { x > -1 } x := x + 1 { x > 0 }

{ (x+1 > 0) } x := x+1 { x > 0 } by the := Rule

that is, { (x > 0)[x+1/x] } x := (x+1) { x > 0 }

{ x > -1 } x := x + 1 { x > 0 } by deduction

Rule for Assignment

$$\{A[^{E}/_{x}]\}\ x := E\ \{A\}$$

- Trick: if x does not appear in E or A.

We can always write { A && E == E } x := E { x == E }

So, if x does not occur in E, A the triple

{ A } x := E { A && x == E }

is always valid

Rule for Assignment

$$\{A[^{E}/_{x}]\}\ x := E\ \{A\}$$

- Exercises. Derive:
  - { y > 0 } x := y { x > 0 && y == x }
  - { x == y } x := 2*x { y == x div 2 }
  - { P(y) && Q(z) } (here P and Q are any properties)

    x := y ; y := z; z:= x

    { P(z) && Q(y) }

Example

- Consider the program

  P ≜ if (x>y) then z := x else z := y

- We (mechanically) check the triple

  { true } P { z == max(x,y) }

Example

- Consider the program

  P ≜ if (x>y) then z := x else z := y

- We (mechanically) check the triple

  { true } P { z == max(x,y) }

  { x == max(x,y) } z := x { z == max(x,y) }
  { x > y } z := x { z == max(x,y) }

  { y == max(x,y) } z := y { z == max(x,y) }
  { y >= x } z := y { z == max(x,y) }

Construction and Verification of Software

2017 - 2018

MIEI - Integrated Master in Computer Science and Informatics

Consolidation block

Lab Assignment 1 - Introduction to Dafny

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based on previous editions by **Luís Caires** (lcaires@fct.unl.pt)

Laboratory Assignment 1 - Dafny

- Install command line tool in your local machine
  - Alternatively use the browser in rise4fun
- Adopt an editor and corresponding plug-ins (Visual Studio, Visual Studio Code, Atom, Sublime)
- Get familiar with the Dafny language tutorials

```
// Test your instalation with this example
method dup(x:int) returns (y:int)
  ensures y == 2*x
{
  assert 3 < 10;
  return 2*x;
}
```

Laboratory Assignment 1 - Dafny

- Implement and fully verify the methods in the next slides.
- Define the strongest postconditions you can think of
- Define the weakest preconditions you can think of that are needed for the postconditions to hold.

Laboratory Assignment 1 - Exercises

```
1 - method Abs(x: int) returns (y: int)

2 - method Min2(x: int, y:int) returns (w:int)

3 - method Max2(x: int, y:int) returns (w:int)

4 - method Max3(x: int, y:int, z:int) returns (w:int)

5 - method CompareTo(x:int, y:int) returns (c:int)
```

Exercise

```
function fib(n : int) : int
// this is the recursive spec of fibonacci
requires n>=0;
{
  if (n==0) then 1 else
  if (n==1) then 1 else fib(n-1)+fib(n-2)
}
```

```
// the method fibo below should implement fib efficiently
// “bottom up” using a while loop
method fibo(n : int) returns (f : int)
requires n>=0;
ensures f == fib(n);
{
    …
}
```