Securing Systems via Design and Proof

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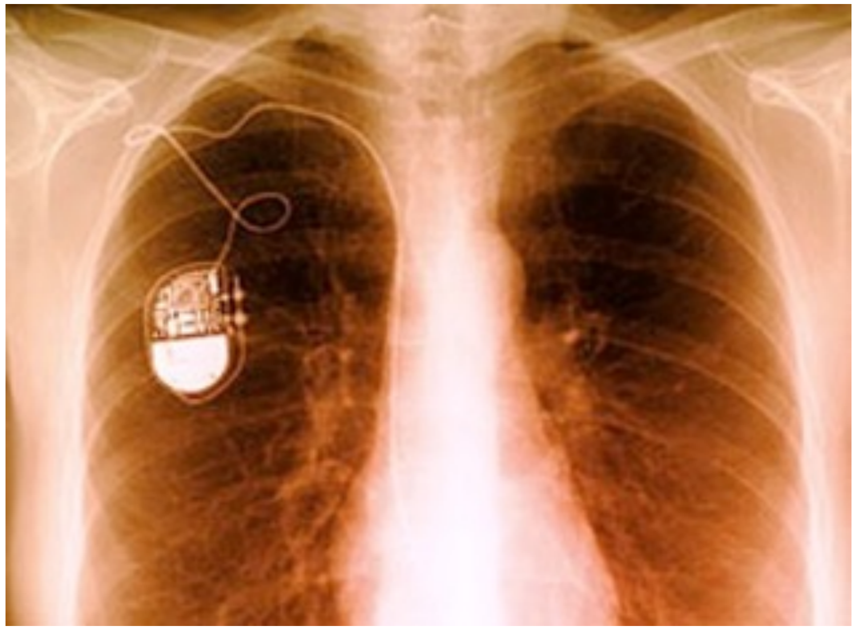
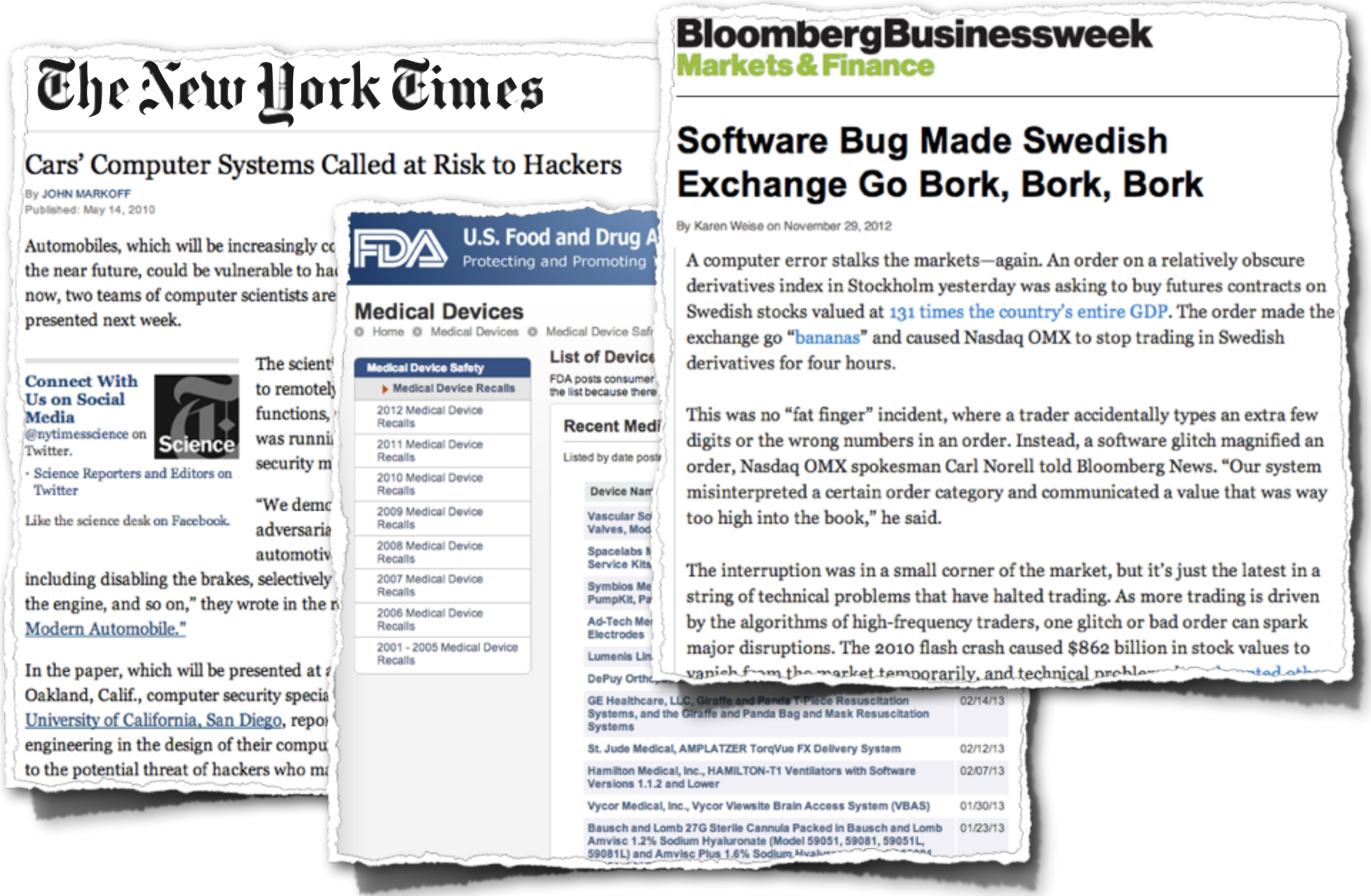
University of Washington Computer Science & Engineering

PLSE

Software Infrastructure



Software Infrastructure is Shaky



The New York Times

Cars' Computer Systems Called at Risk to Hackers

By JOHN MARKOFF
Published: May 14, 2010

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In the paper, which will be presented at a
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- 2010 Medical Device Recalls
- 2009 Medical Device Recalls
- 2008 Medical Device Recalls
- 2007 Medical Device Recalls
- 2006 Medical Device Recalls
- 2001 - 2005 Medical Device Recalls

List of Device

FDA posts consumer
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Listed by date poste

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GE Healthcare, LLC, Giraffe and Panda T-Piece Resuscitation Systems, and the Giraffe and Panda Bag and Mask Resuscitation Systems	02/14/13
St. Jude Medical, AMPLATZER TorqVue FX Delivery System	02/12/13
Hamilton Medical, Inc., HAMILTON-T1 Ventilators with Software Versions 1.1.2 and Lower	02/07/13
Vycor Medical, Inc., Vycor Viewsite Brain Access System (VBAS)	01/30/13
Bausch and Lomb 27G Sterile Cannula Packed in Bausch and Lomb Amvisc 1.2% Sodium Hyaluronate (Model 59051, 59081, 59051L, 59081L) and Amvisc Plus 1.6% Sodium Hyalur	01/23/13

BloombergBusinessweek
Markets & Finance

Software Bug Made Swedish Exchange Go Bork, Bork, Bork

By Karen Weise on November 29, 2012

A computer error stalks the markets—again. An order on a relatively obscure derivatives index in Stockholm yesterday was asking to buy futures contracts on Swedish stocks valued at 131 times the country's entire GDP. The order made the exchange go "bananas" and caused Nasdaq OMX to stop trading in Swedish derivatives for four hours.

This was no "fat finger" incident, where a trader accidentally types an extra few digits or the wrong numbers in an order. Instead, a software glitch magnified an order, Nasdaq OMX spokesman Carl Norell told Bloomberg News. "Our system misinterpreted a certain order category and communicated a value that was way too high into the book," he said.

The interruption was in a small corner of the market, but it's just the latest in a string of technical problems that have halted trading. As more trading is driven by the algorithms of high-frequency traders, one glitch or bad order can spark major disruptions. The 2010 flash crash caused $862 billion in stock values to vanish from the market temporarily, and technical proble

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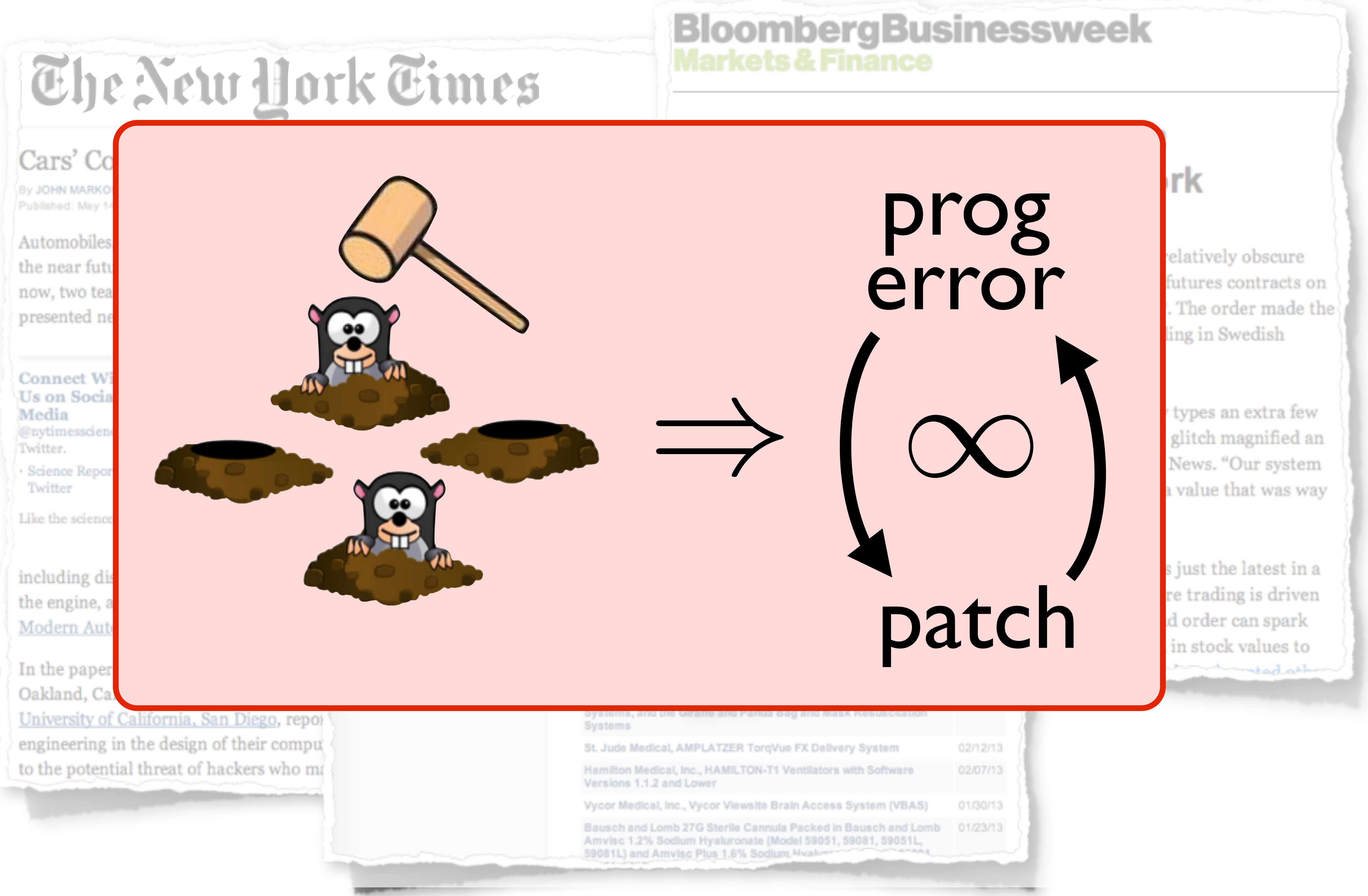

The New York Times

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By JOHN MARKO

Published: May 14

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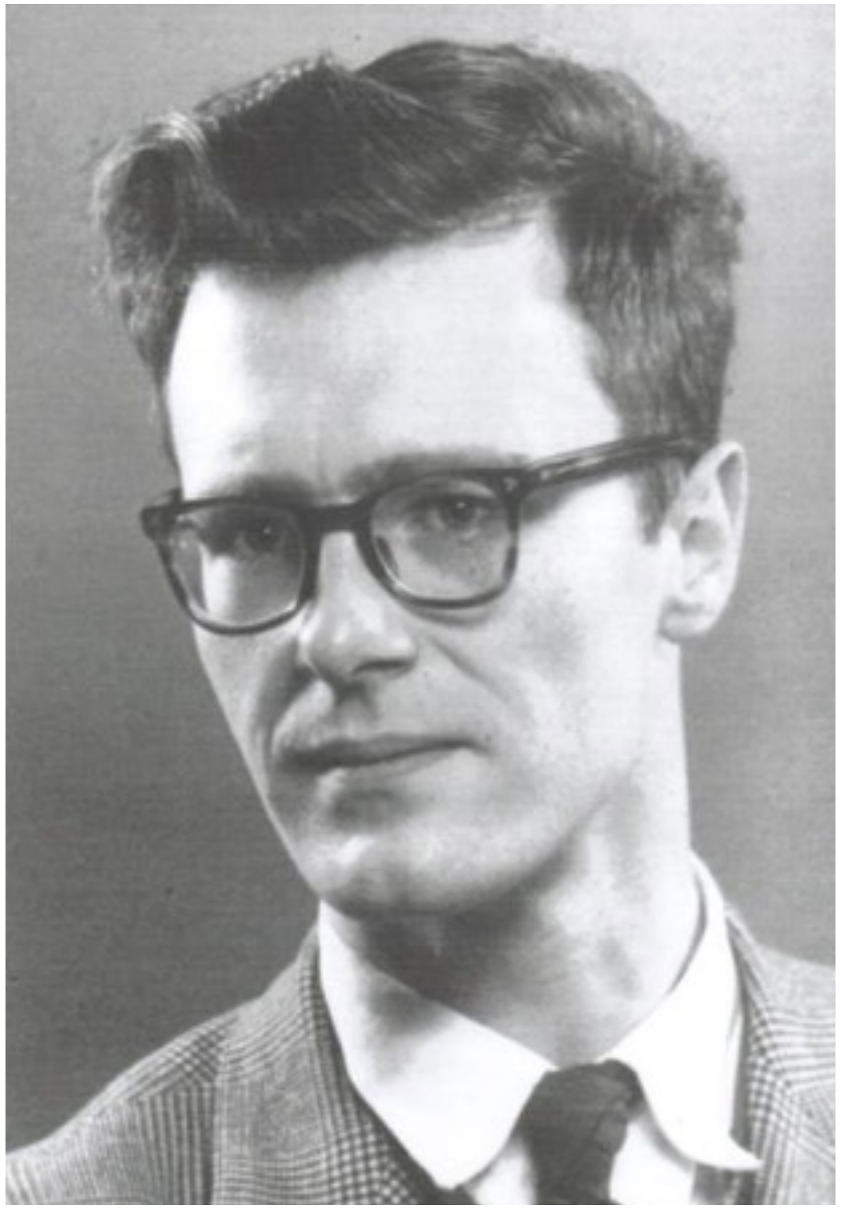
$\Rightarrow$

prog
error

∞

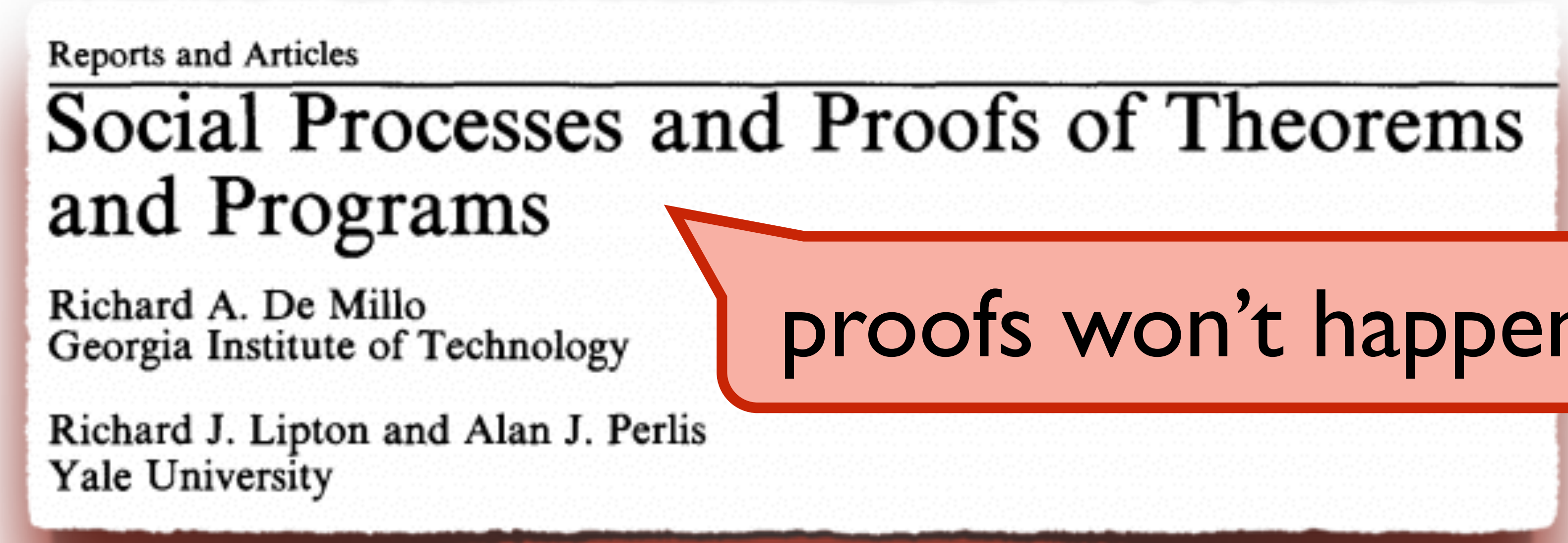
patch

When exhaustive testing is impossible, our trust can only be based on proof.



Edsger W. Dijkstra

Under the Spell of Leibniz's Dream



Reports and Articles

Social Processes and Proofs of Theorems and Programs

Richard A. De Millo
Georgia Institute of Technology

Richard J. Lipton and Alan J. Perlis
Yale University

proofs won’t happen

... not just a dream!

Proof Assistant Based Verification

Code in language suited for reasoning

Develop correctness proof in synch

Fully formal, *machine checkable* proof

Proof Assistant Based Verification

Verified Compiler: CompCert *[Leroy POPL 06]*

Compiler	*Bugs Found*
GCC	122
LLVM	181
CompCert	**?**

[Yang et al. PLDI 11]

Proof Assistant Based Verification

Verified Compiler: CompCert [*Leroy POPL 06*]

Compiler	*Bugs Found*
GCC	122
LLVM	181
CompCert	0

[*Yang et al. PLDI 11*]
[*Vu et al. PLDI 14*]

Verified OS kernel: seL4 [*Klein et al. SOSP 09*]

realistic implementation guaranteed bug free

Proof Assistant Based Verification

Verified Compiler: CompCert [Leroy POPL 06]

Compiler	*Bugs Found*

Proof ⇒ no prog errors

DI 11]

Verified OS kernel: seL4 [Klein et al. SOSP 09]

realistic implementation guaranteed bug free

Promise

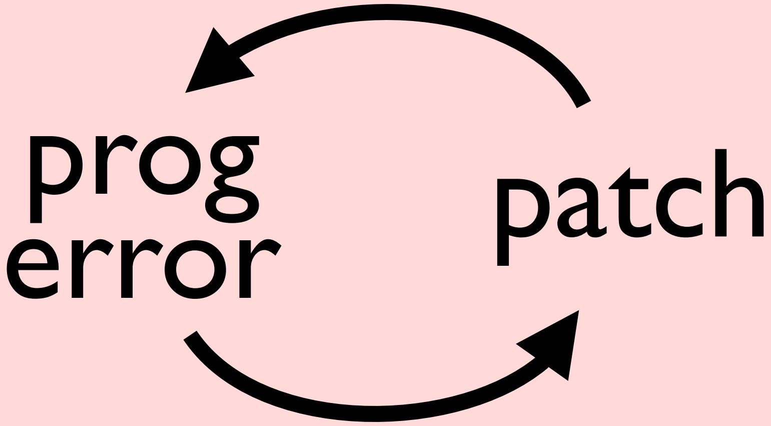
Proof

⇓

no prog
errors

Today

⇓



prog error

patch

Promise

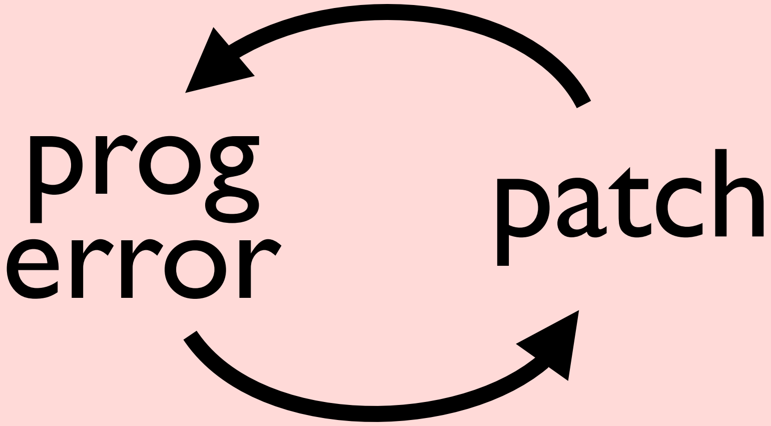
Proof

⇓

no prog errors

Today

⇓



Promise

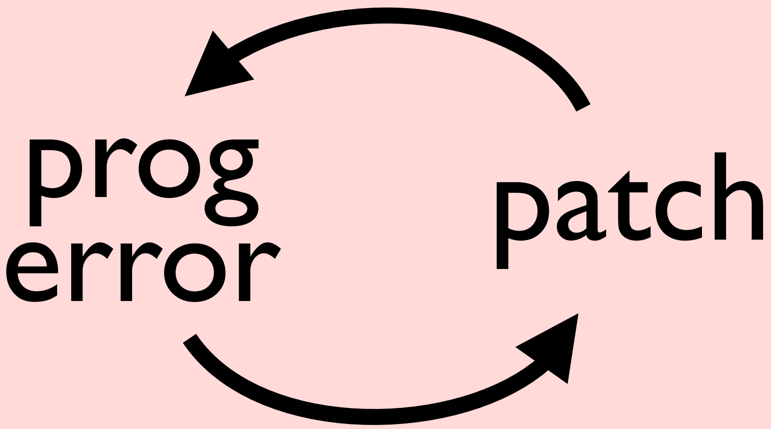
Proof

⇓

no prog
errors

Today

⇓



Proof Burden

Promise

Proof

⇓

no prog errors

The Burden of Proof

1. Initial proofs require heroic effort

   CompCert: *70% proof, vast majority of effort*

   seL4: *200,000 line proof for 9,000 lines of C*

2. Code updates require re-proving

   CompCert: *adding opts* [*Tristan POPL 08, PLDI 09, POPL 10*]

   seL4: *changing RPC took 17% of proof effort*

Mitigating the Burden of Proof

1: Scaling proofs to critical infrastructure

➡ *Formal shim verification for large apps*

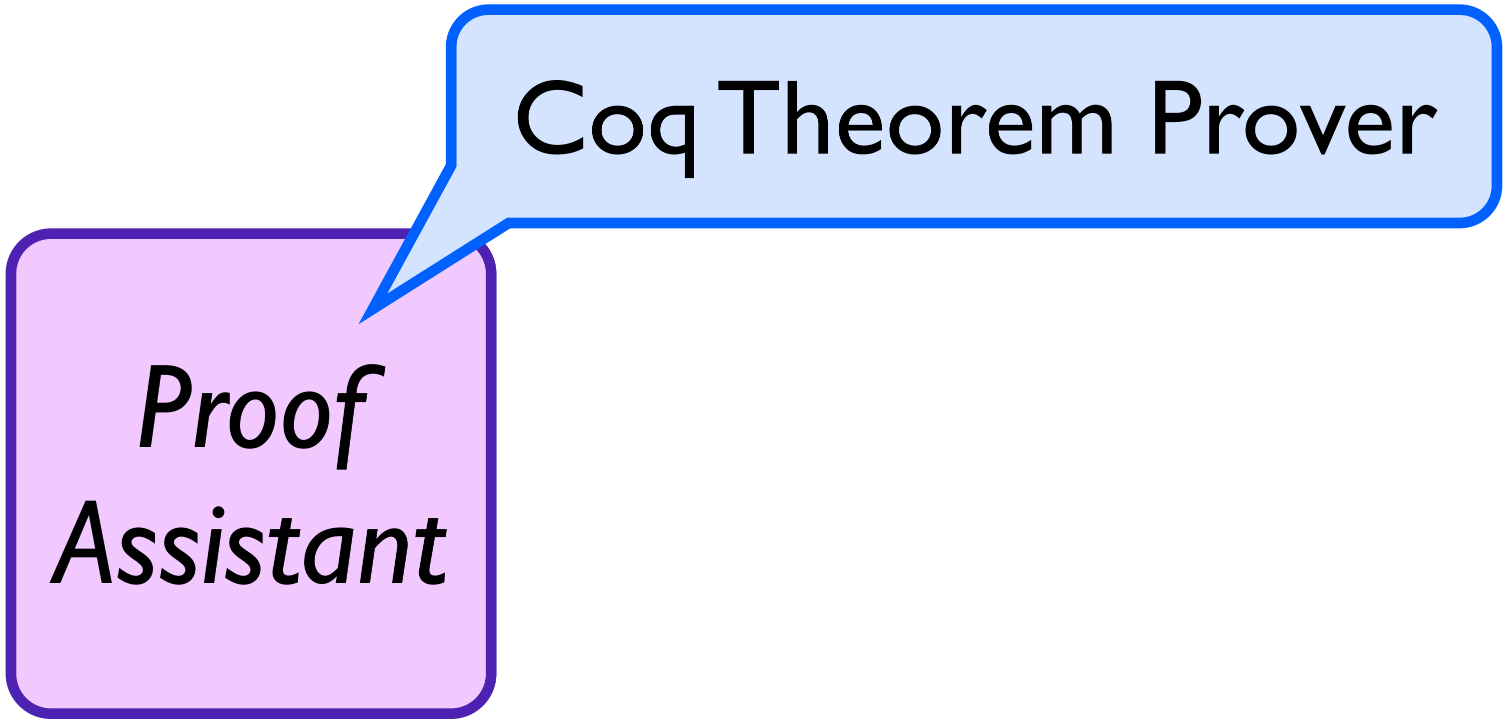
QUARK: browser with security guarantees

2: Evolving formally verified systems

Reflex DSL exploits domain for proof auto

Fully Formal Verification

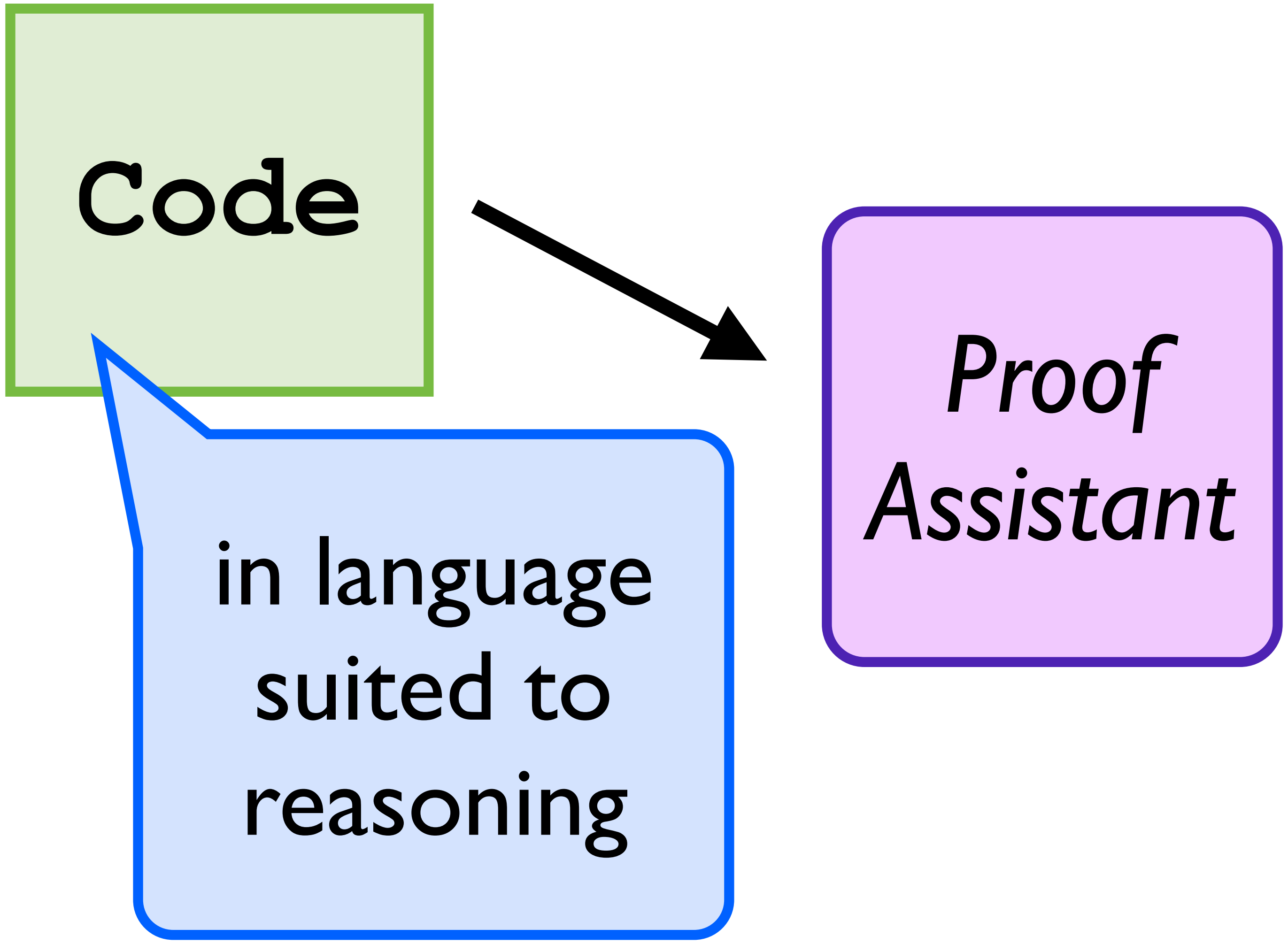
Fully Formal Verification



Coq Theorem Prover

Proof Assistant

Fully Formal Verification

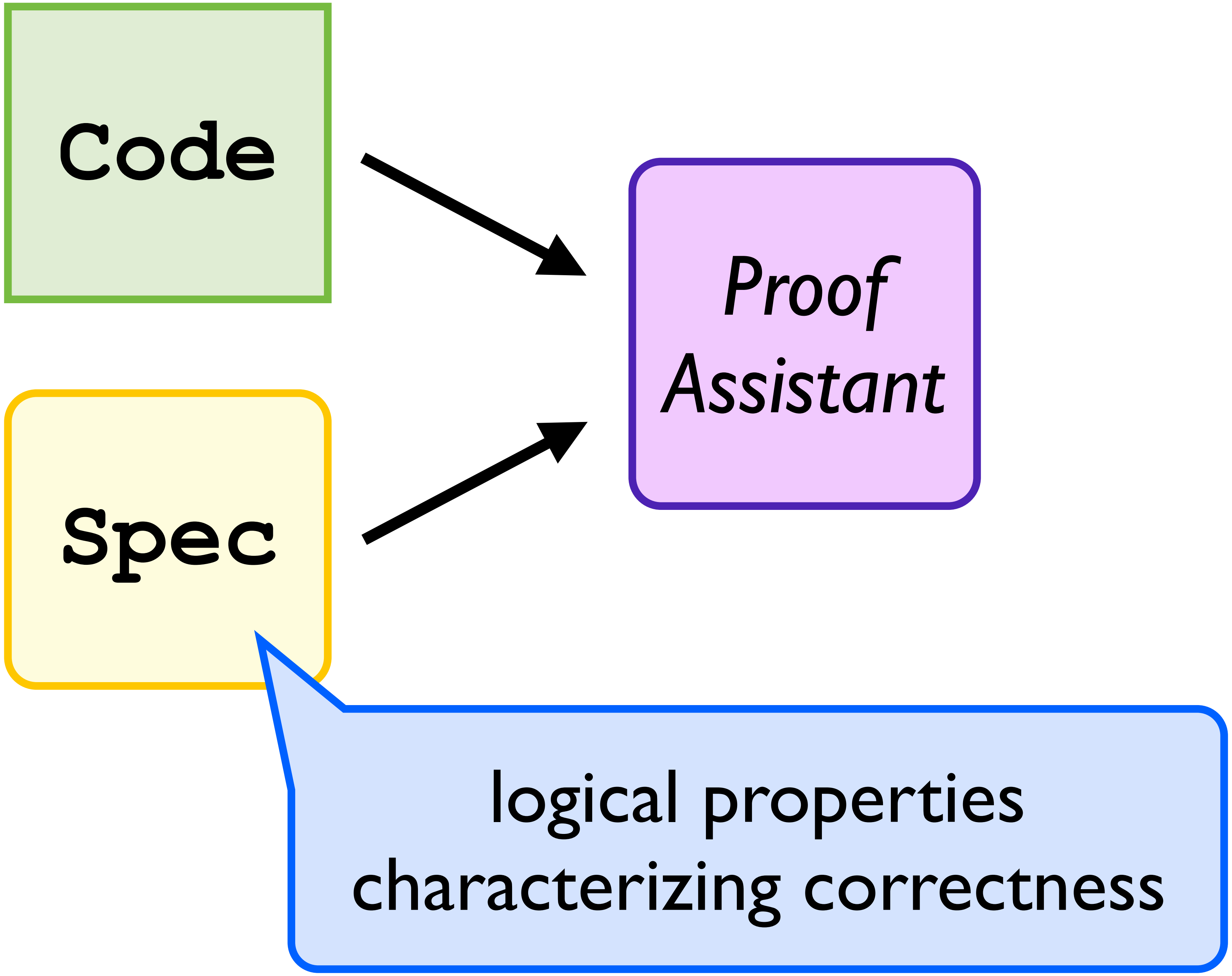


`Code`

in language suited to reasoning

Proof Assistant

Fully Formal Verification



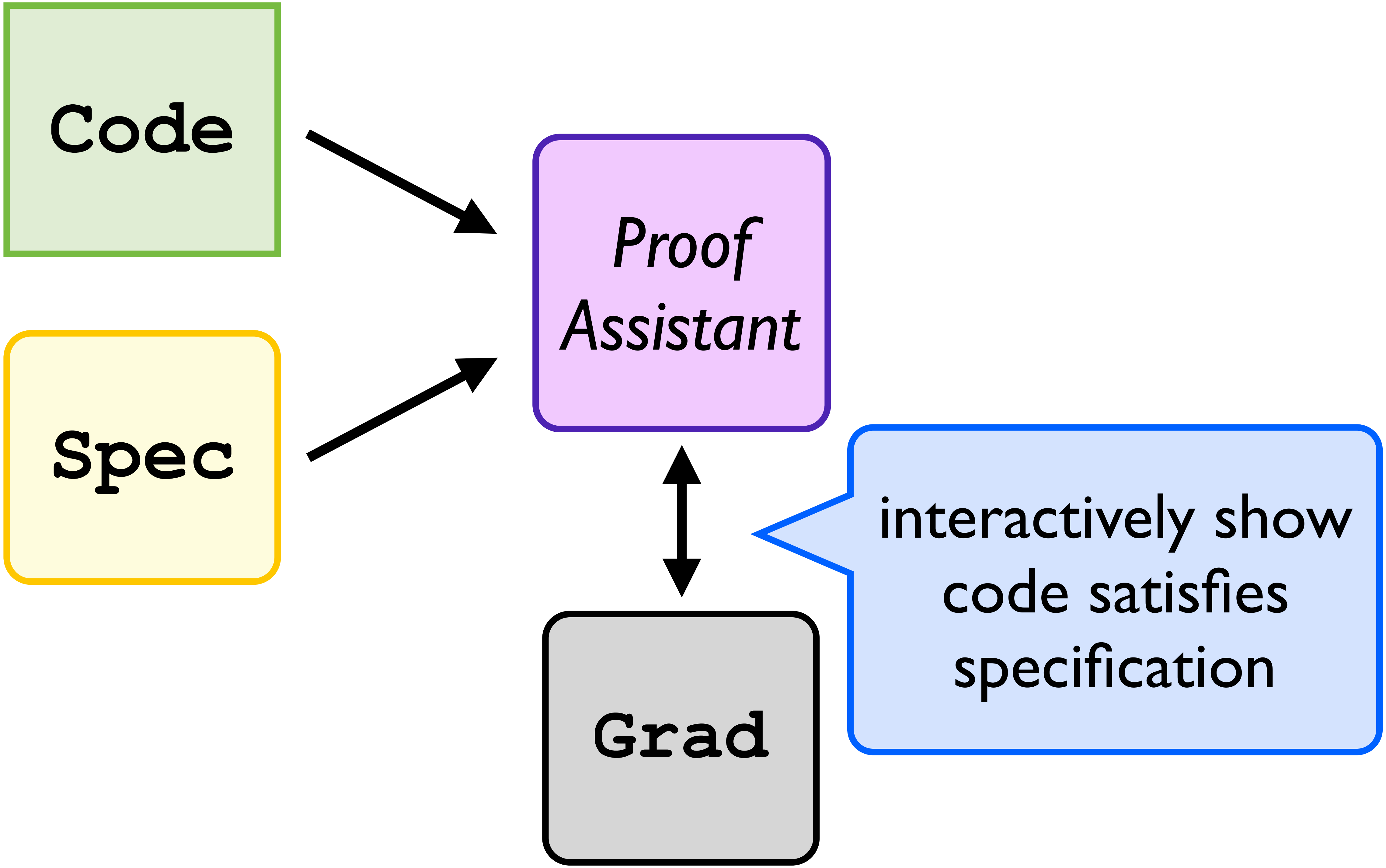
Code

Spec

Proof Assistant

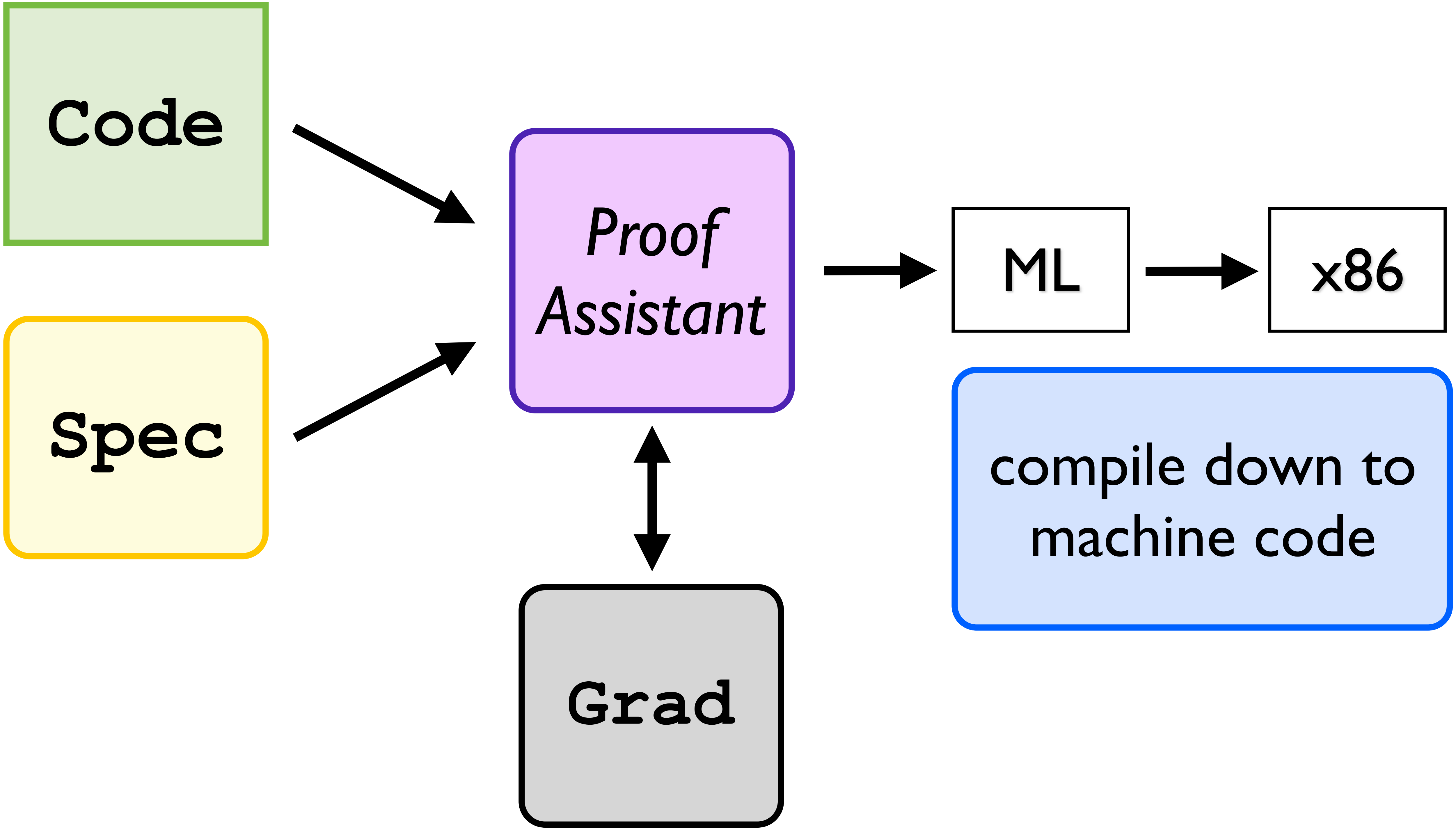
logical properties characterizing correctness

Fully Formal Verification



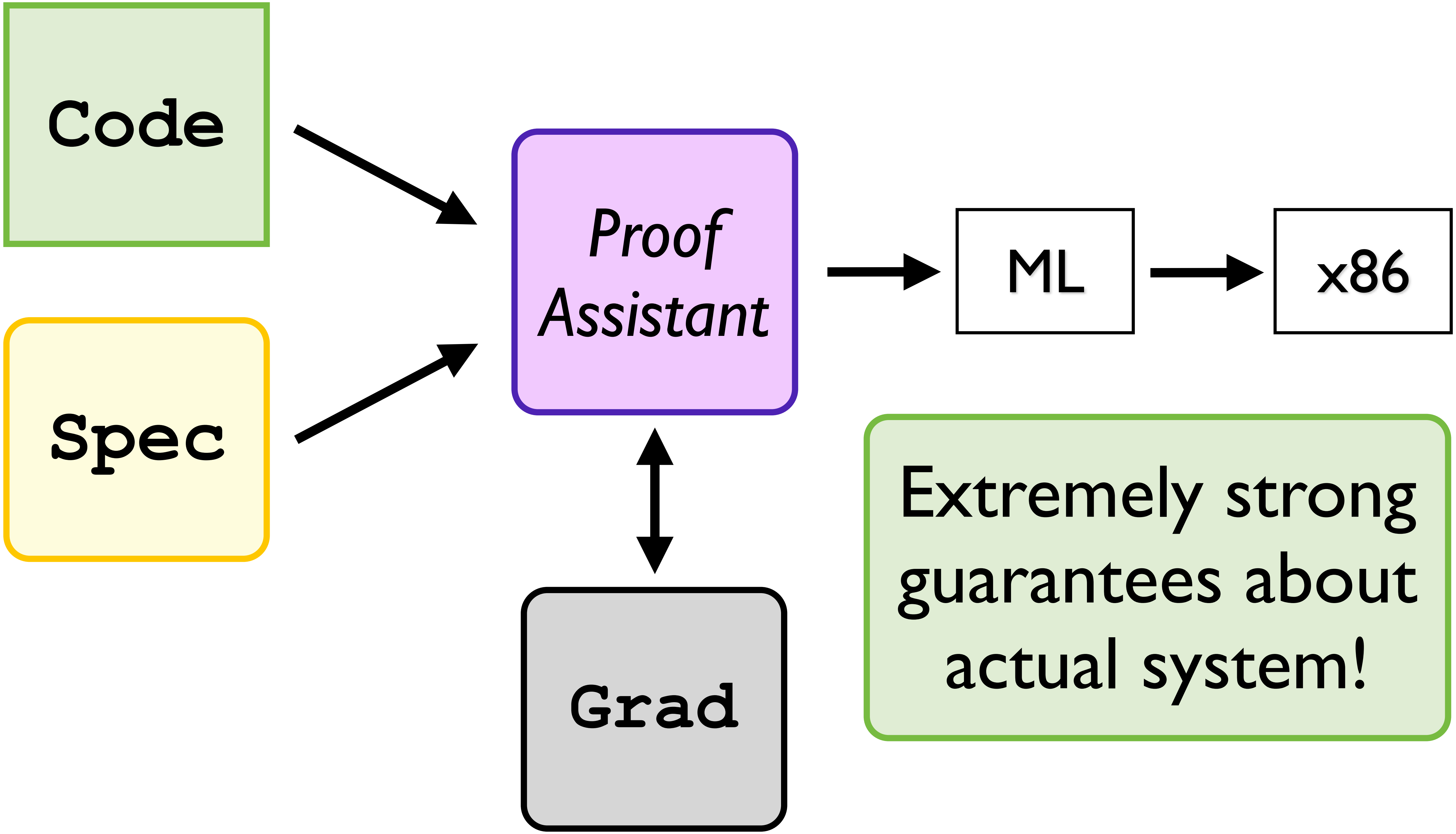
interactively show code satisfies specification

Fully Formal Verification



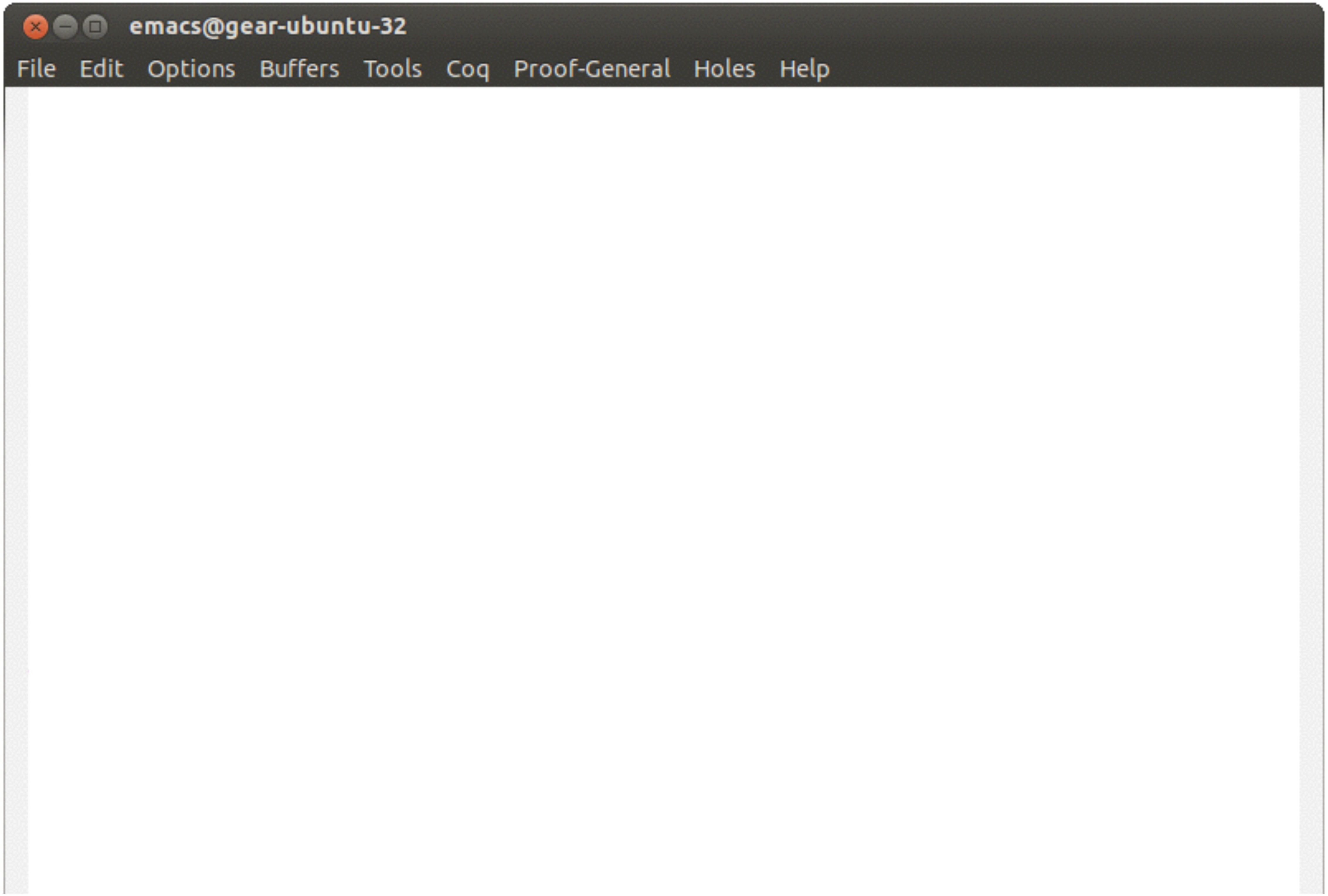
compile down to machine code

Fully Formal Verification



Extremely strong guarantees about actual system!

Fully Formal Verification



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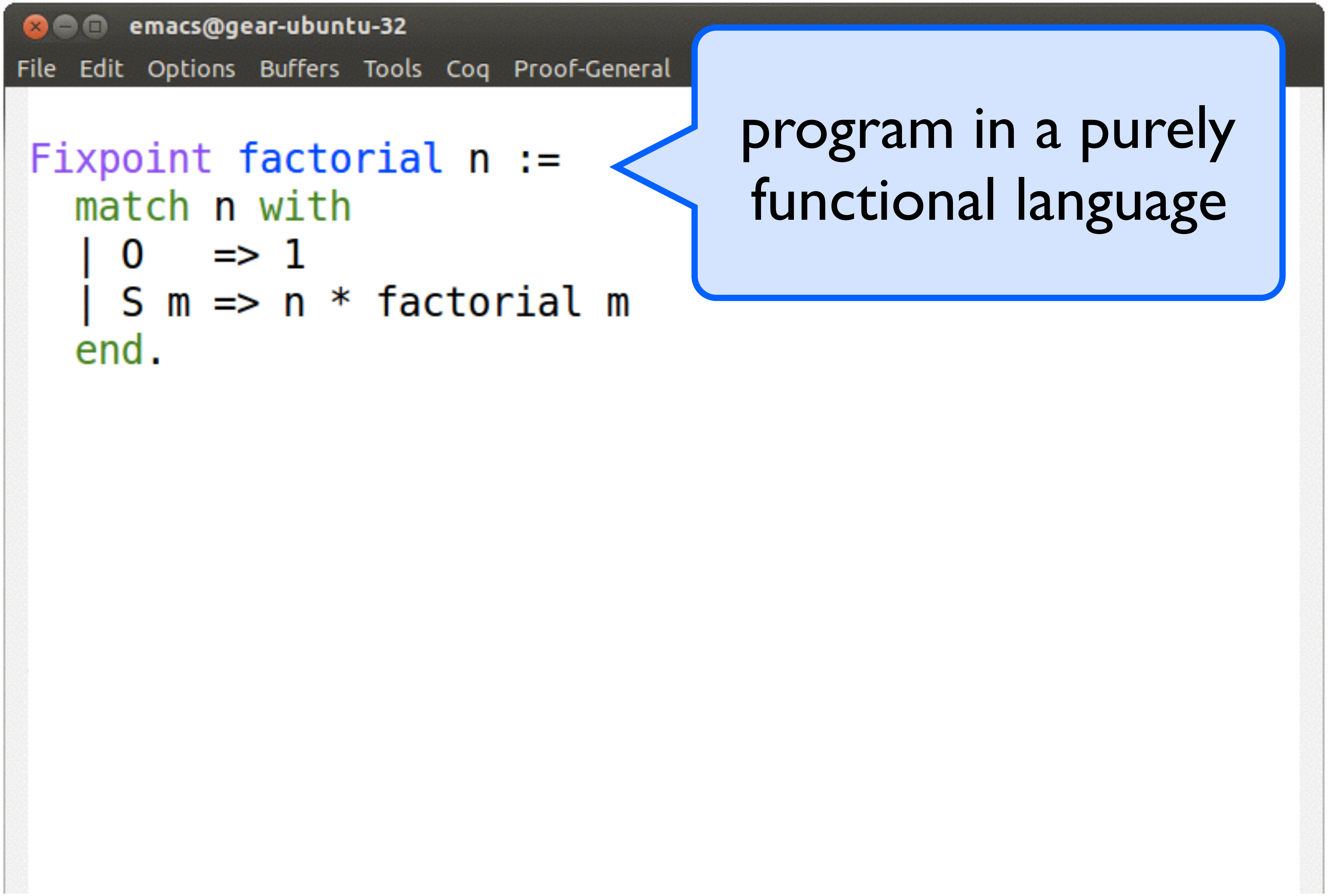
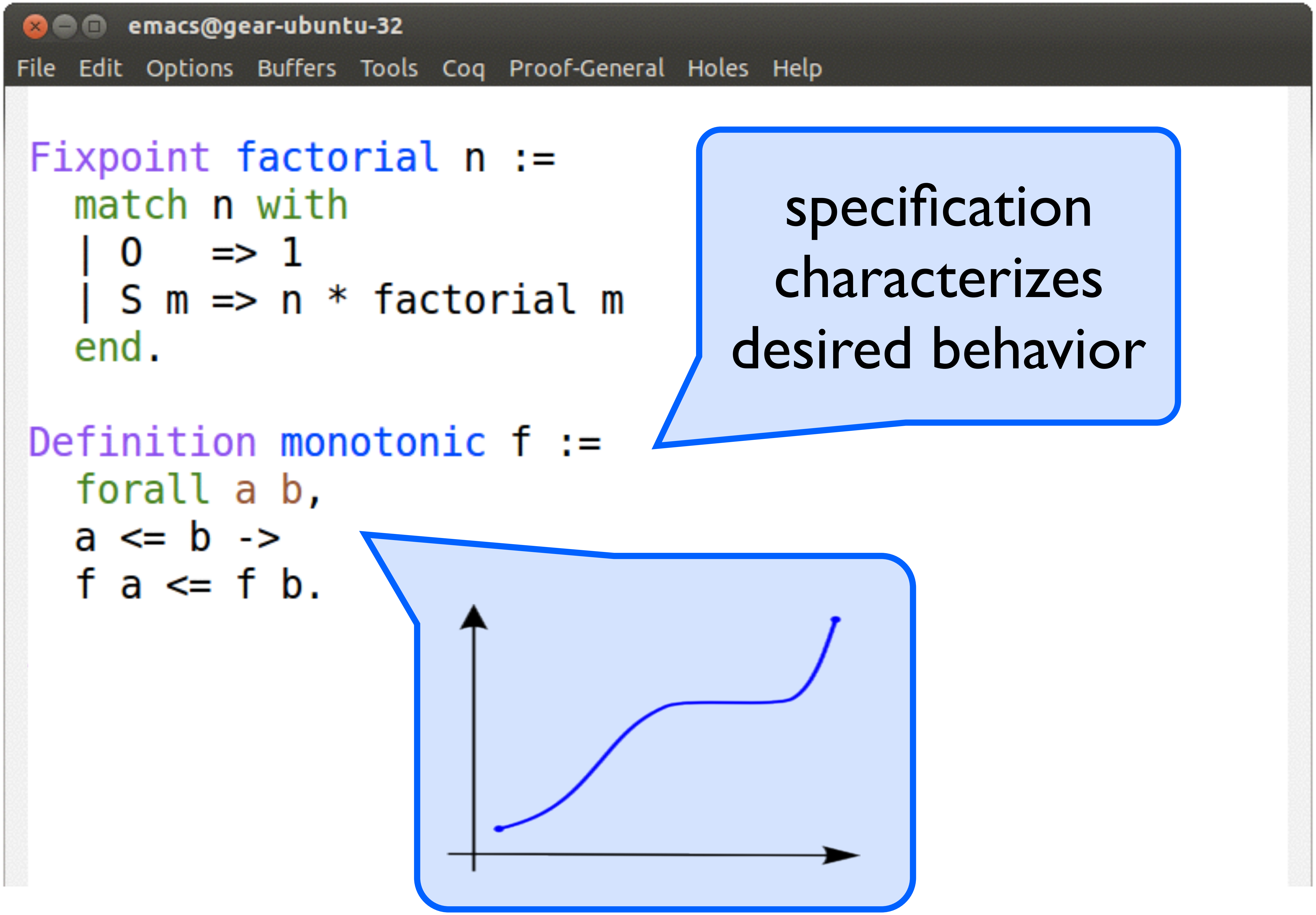


```
Fixpoint factorial n :=
  match n with
  | 0   => 1
  | S m => n * factorial m
  end.
```

program in a purely functional language

Fully Formal Verification


emacs@gear-ubuntu-32
File Edit Options Buffers Tools Coq Proof-General Holes Help

```
Fixpoint factorial n :=
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  | O   => 1
  | S m => n * factorial m
  end.

Definition monotonic f :=
  forall a b,
  a <= b ->
  f a <= f b.
```
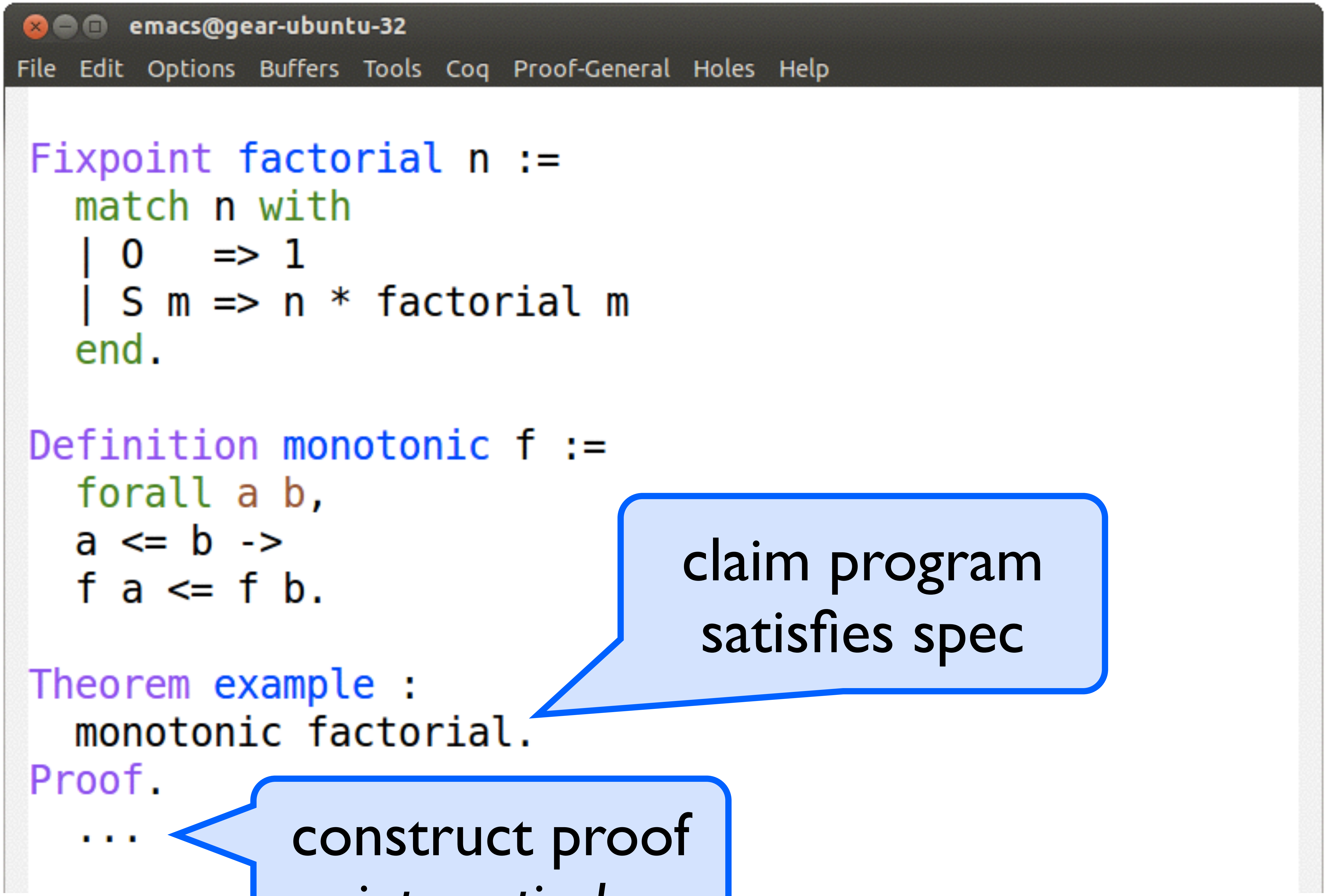

specification characterizes desired behavior

Fully Formal Verification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Definition monotonic f :=
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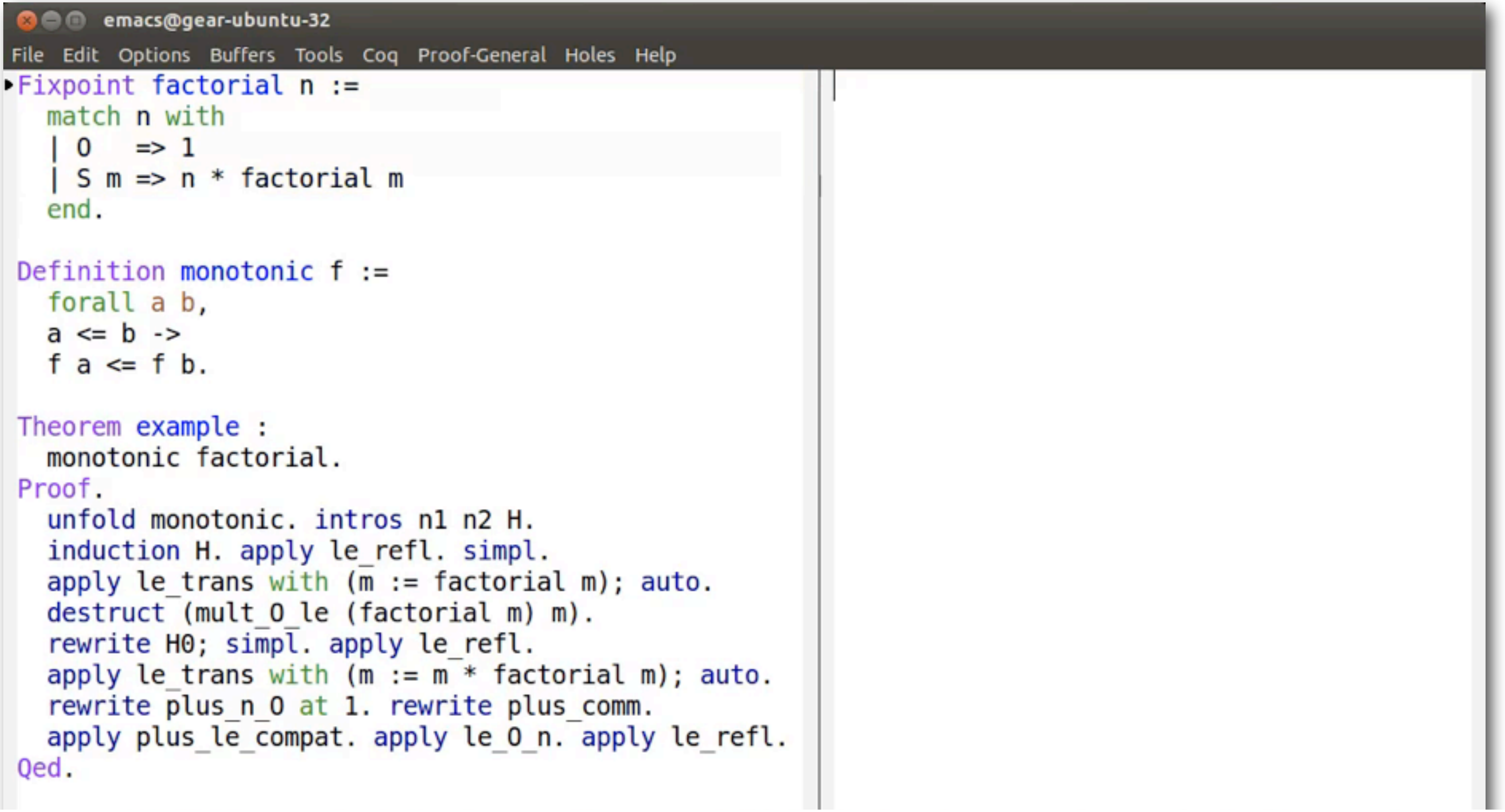
  a <= b ->
  f a <= f b.

Theorem example :
  monotonic factorial.
Proof.
  ...
```

claim program satisfies spec

construct proof *interactively*

Fully Formal Verification



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Definition monotonic f :=
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  f a <= f b.

Theorem example :
  monotonic factorial.
Proof.
  unfold monotonic. intros n1 n2 H.
  induction H. apply le_refl. simpl.
  apply le_trans with (m := factorial m); auto.
  destruct (mult_O_le (factorial m) m).
  rewrite H0; simpl. apply le_refl.
  apply le_trans with (m := m * factorial m); auto.
  rewrite plus_n_O at 1. rewrite plus_comm.
  apply plus_le_compat. apply le_O_n. apply le_refl.
Qed.
```
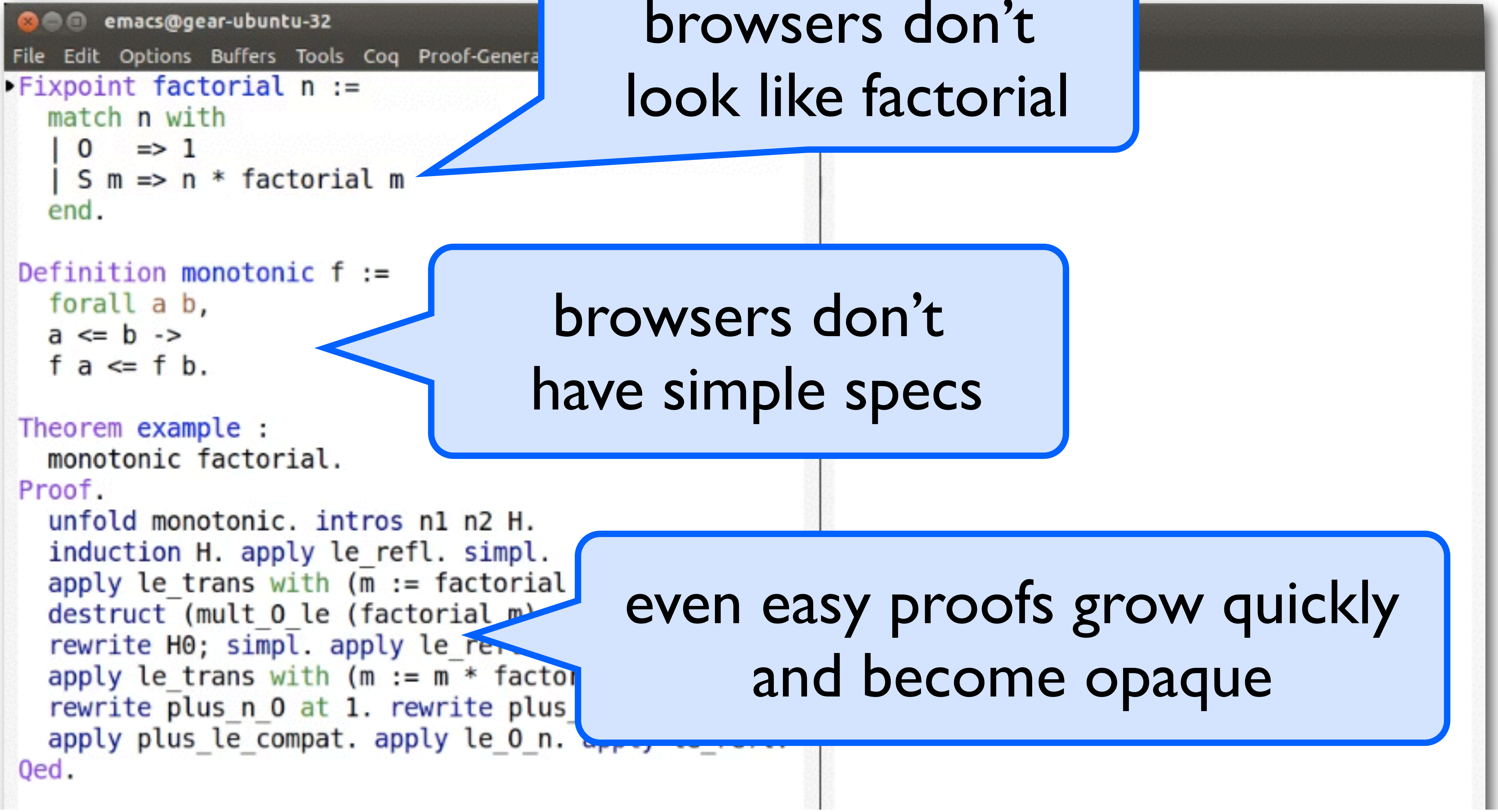

Fully Formal Verification



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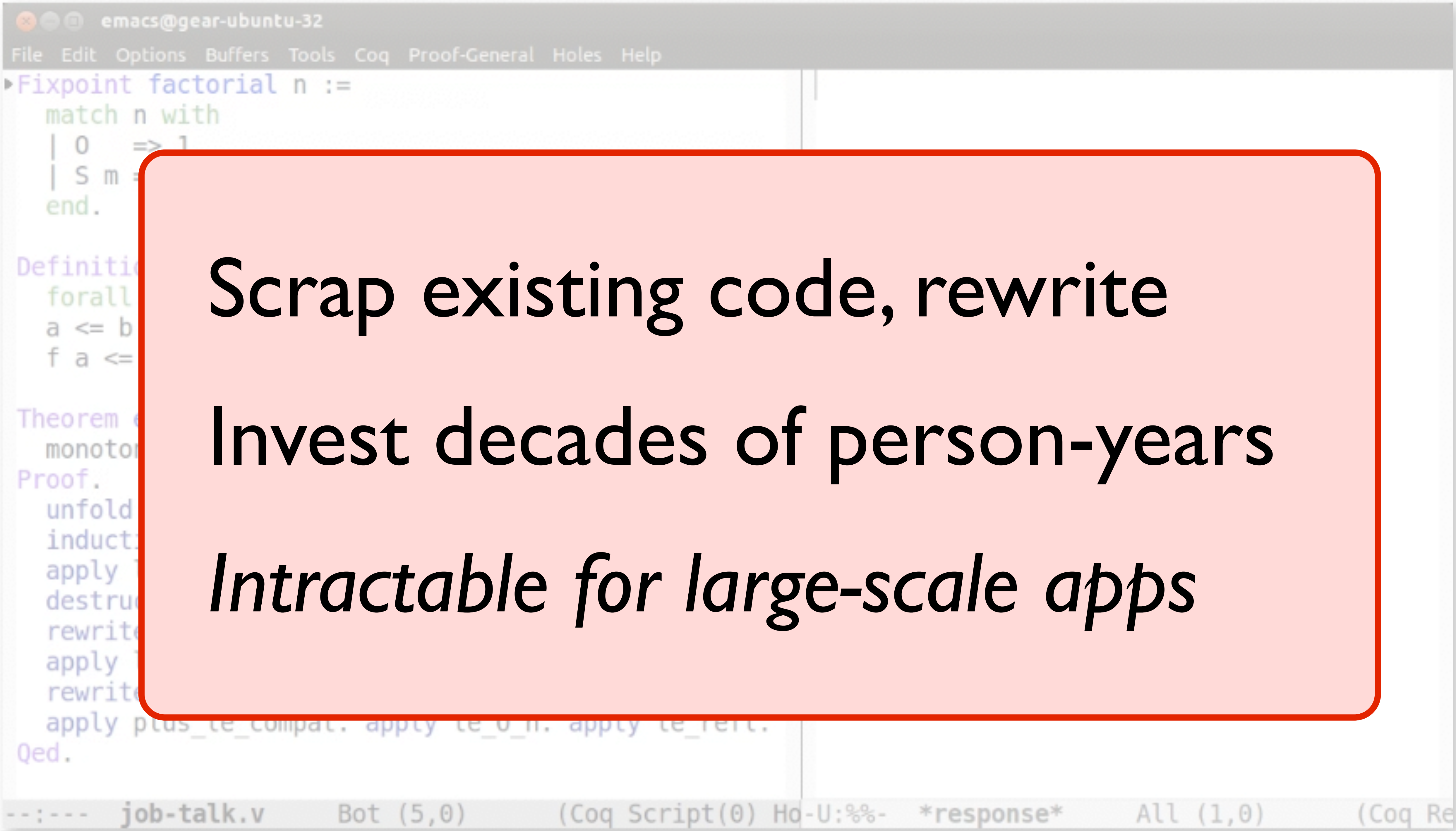
  apply le_trans with (m := m * facto
  rewrite plus_n_O at 1. rewrite plus
  apply plus_le_compat. apply le_O_n.
Qed.
```

browsers don't look like factorial

browsers don't have simple specs

even easy proofs grow quickly and become opaque

Fully Formal Verification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Fixpoint factorial n :=
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  | S m =
  end.

Definiti
  forall
  a <= b
  f a <=

Theorem e
  monoto
Proof.
  unfold
  induct
  apply l
  destru
  rewrite
  apply l
  rewrite
  apply plus_le_compat. apply le_0_n. apply le_refl.
Qed.
```

```
--:---  job-talk.v     Bot (5,0)      (Coq Script(0) Ho-U:%%-  *response*     All (1,0)      (Coq Re
```

Scrap existing code, rewrite

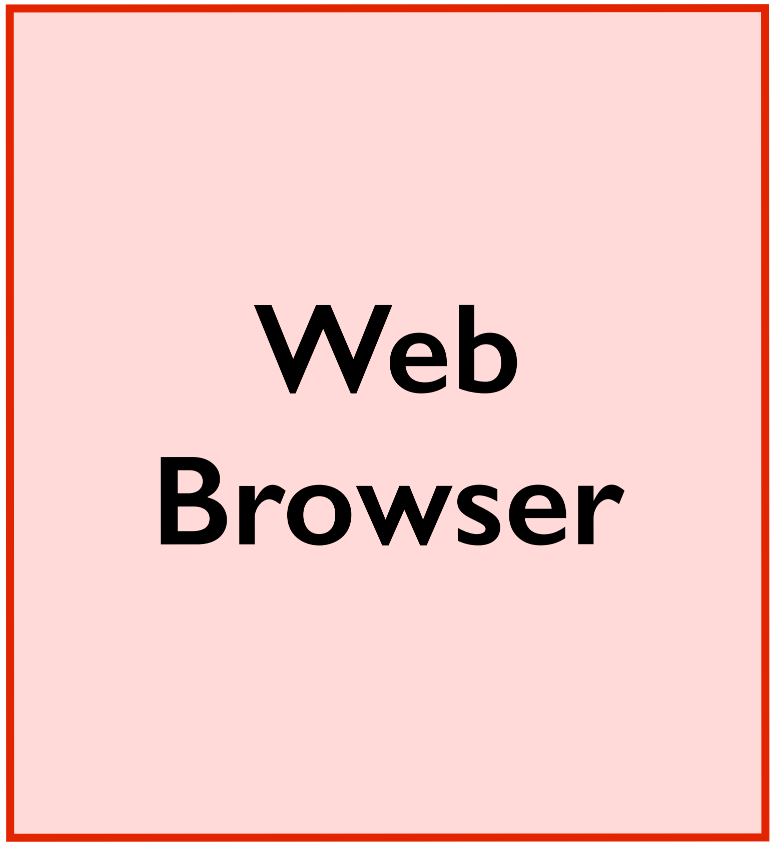
Invest decades of person-years

Intractable for large-scale apps

Formally Verify a Browser?!

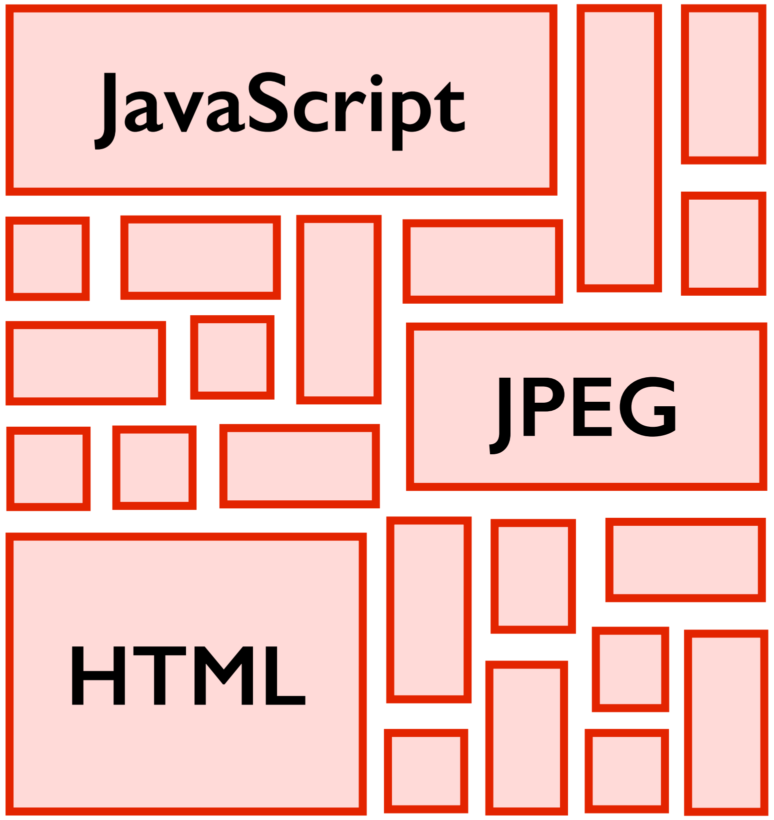
Formally Verify a Browser?!

Millions of LOC



Web Browser

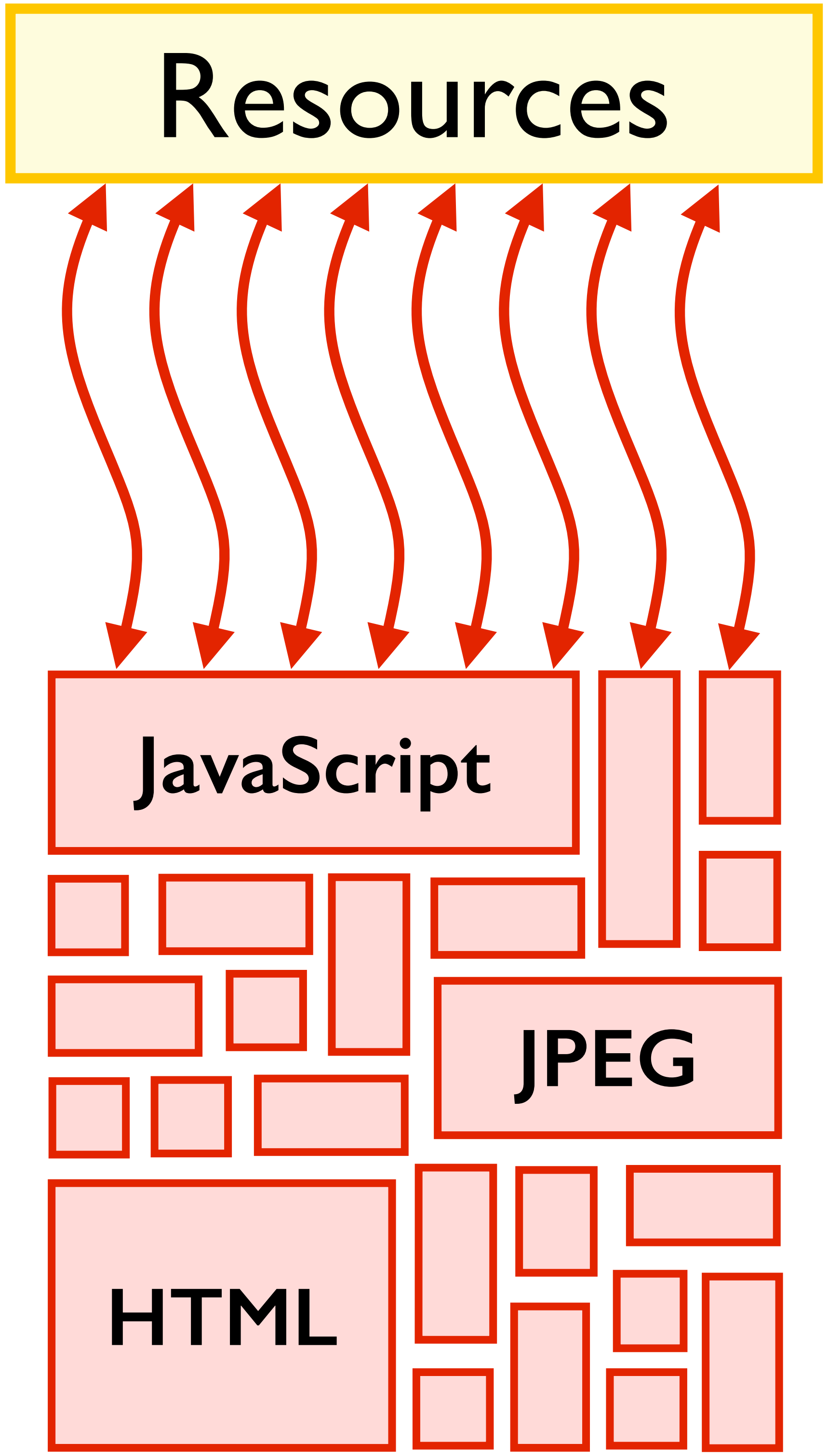
Formally Verify a Browser?!



Millions of LOC

High performance

Formally Verify a Browser?!

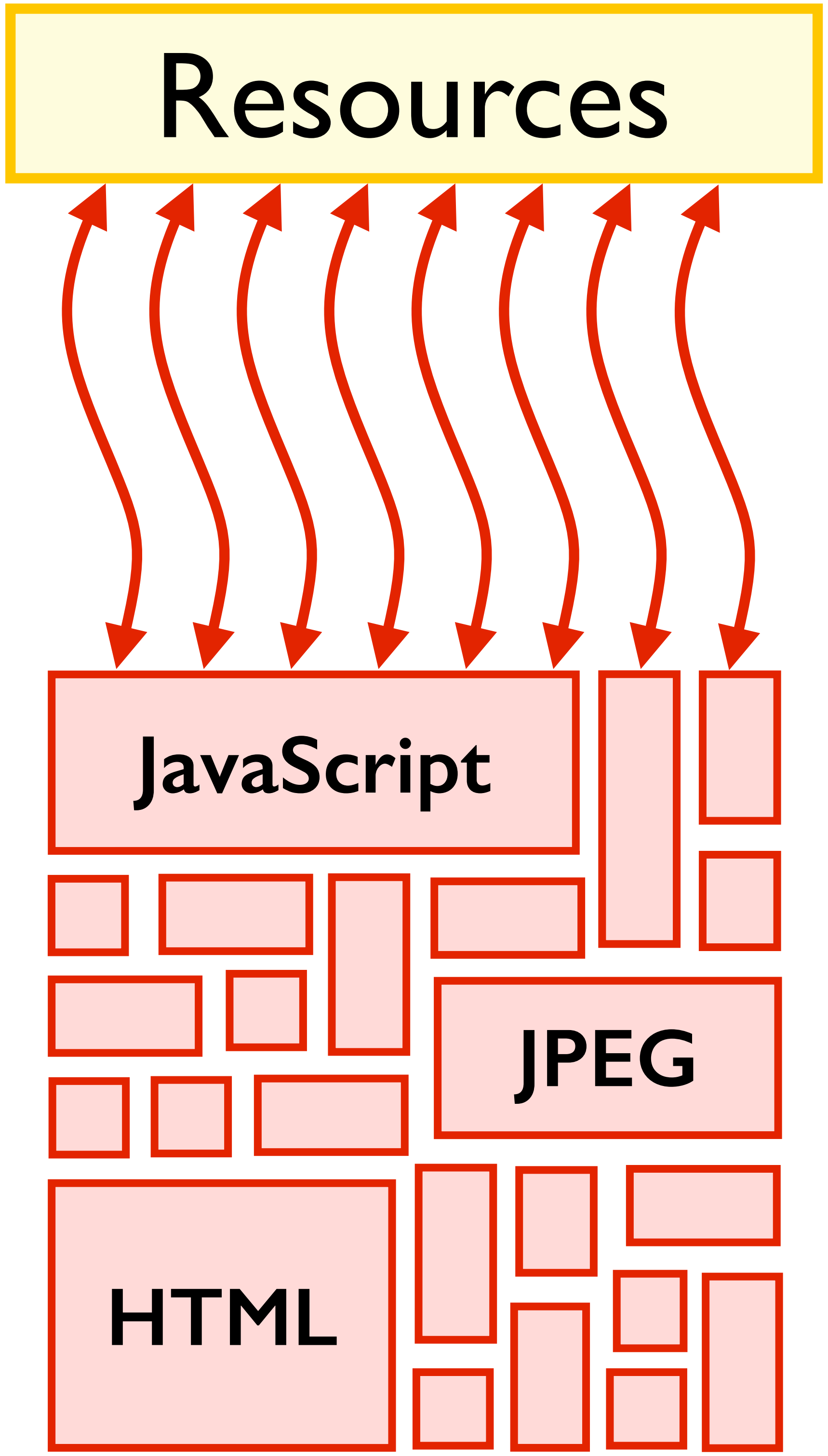


Millions of LOC

High performance

Loose access policy

Formally Verify a Browser?!



Millions of LOC

High performance

Loose access policy

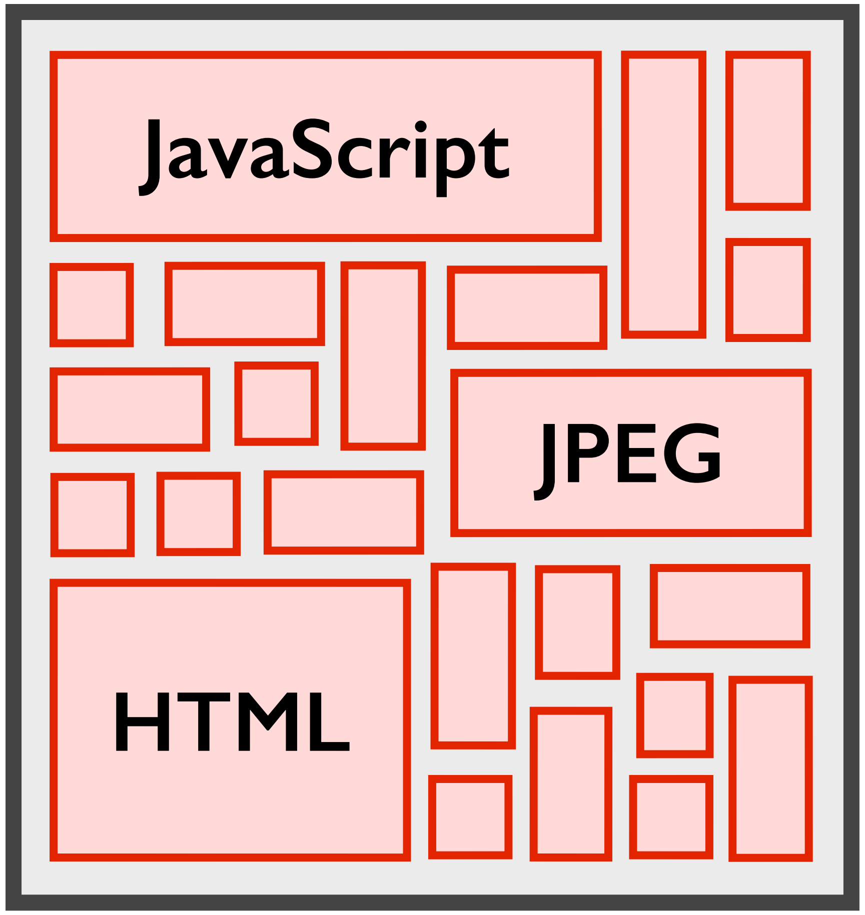
Constant evolution

Formally Verify a Browser?!

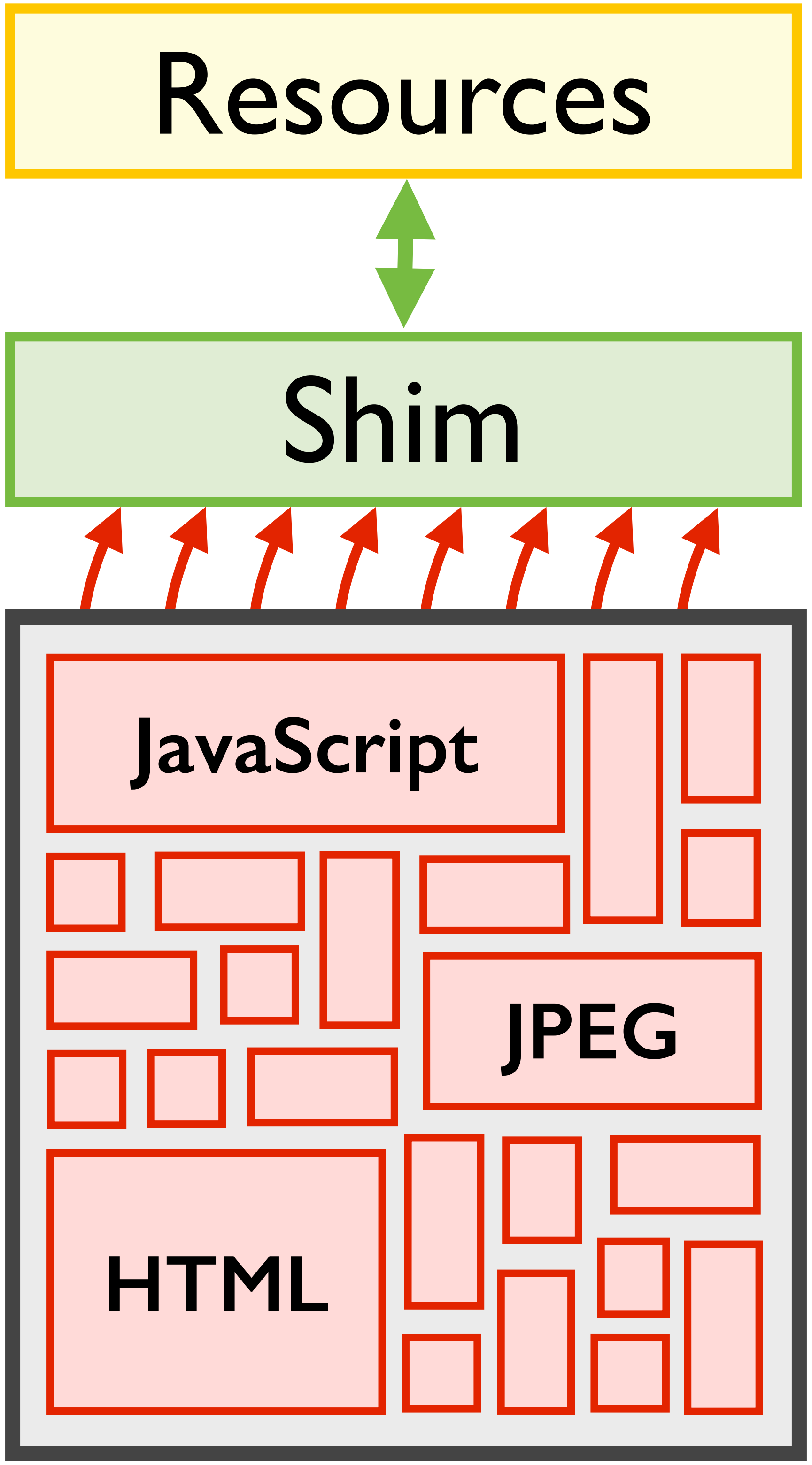
Resources

Isolate

sandbox untrusted code



Formally Verify a Browser?!



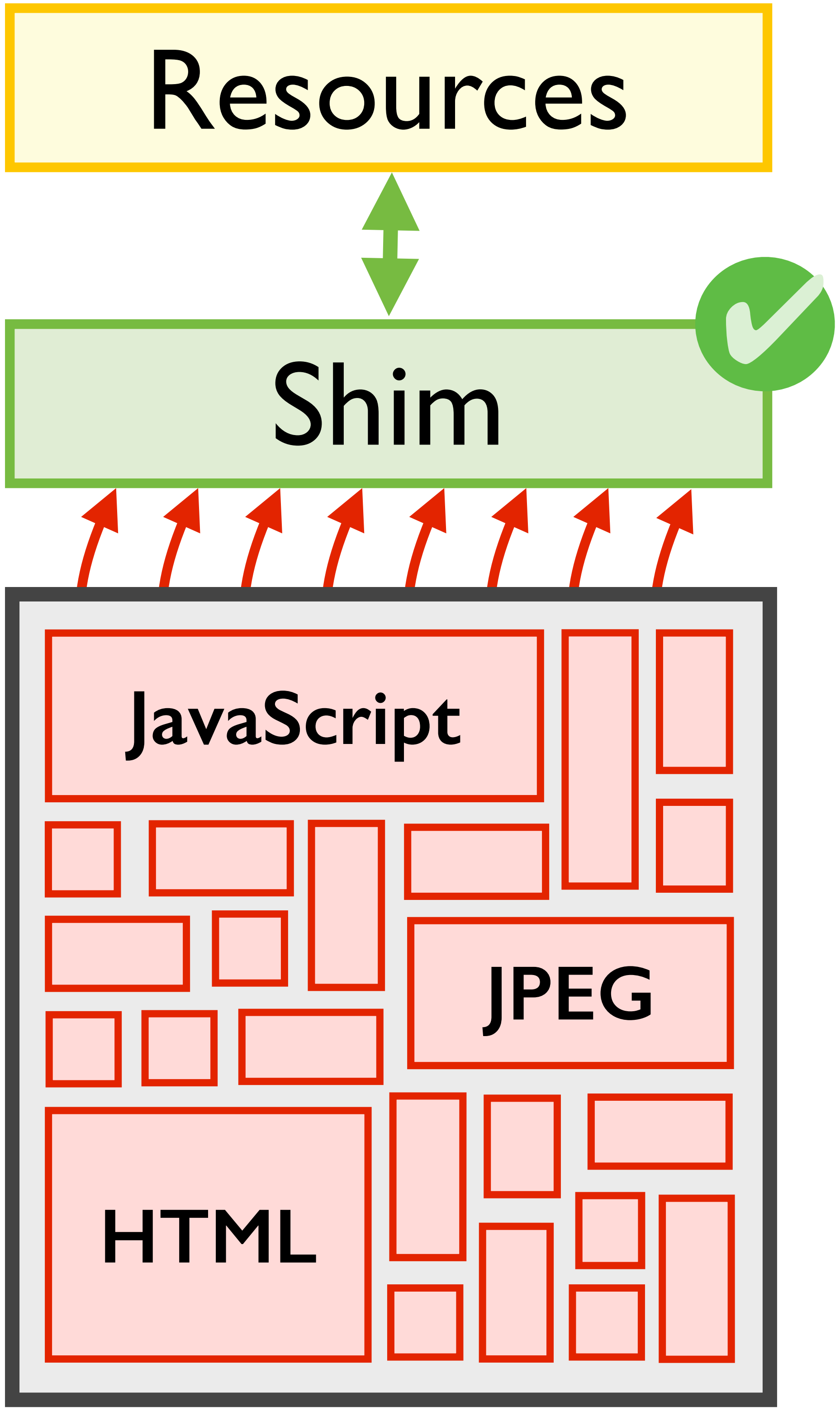
Isolate

sandbox untrusted code

Implement shim

guards resource access

Formally Verify a Browser?!



Isolate

sandbox untrusted code

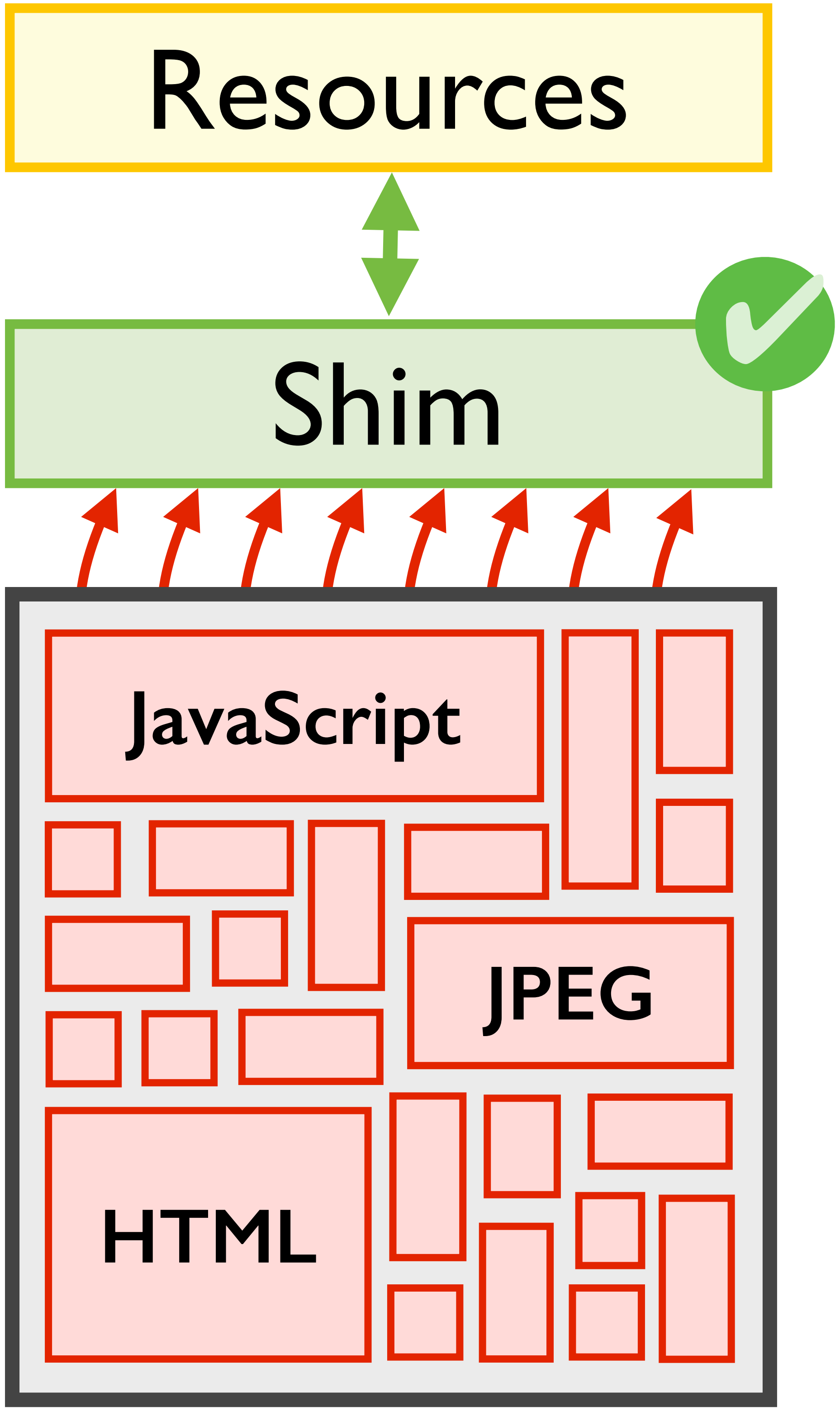
Implement shim

guards resource access

Verify shim

prove security policy

Formal Shim Verification



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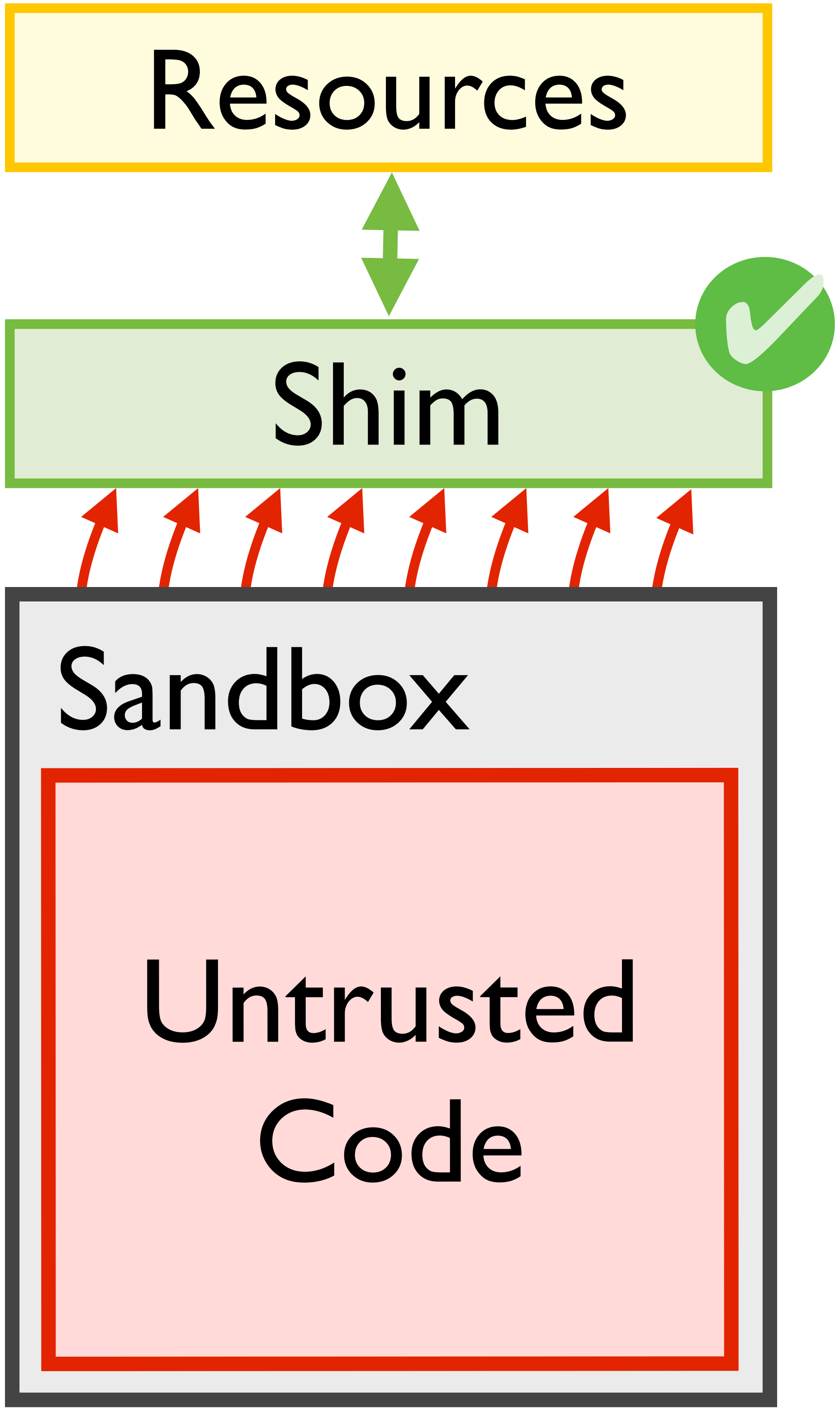
Formal Shim Verification



Isolate

Implement shim

Verify shim

Applies when:

1. sys fits architecture

2. policy over resources

browser, httpd, sshd, ...

Formal Shim Verification

Key Insight: *Focus Effort*

Guarantee sec props for entire system

Only implement and prove small shim

Radically ease verification burden

Prove *actual code* correct

Mitigating the Burden of Proof

1: Scaling proofs to critical infrastructure

⇨ *Formal shim verification for large apps*

QUARK: browser with security guarantees

2: Evolving formally verified systems

Reflex DSL exploits domain for proof auto

Mitigating the Burden of Proof

1: Scaling proofs to critical infrastructure

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Reflex DSL exploits domain for proof auto

Browsers: Critical Infrastructure

MasterCard

VISA

WELLS FARGO

CHASE

ING

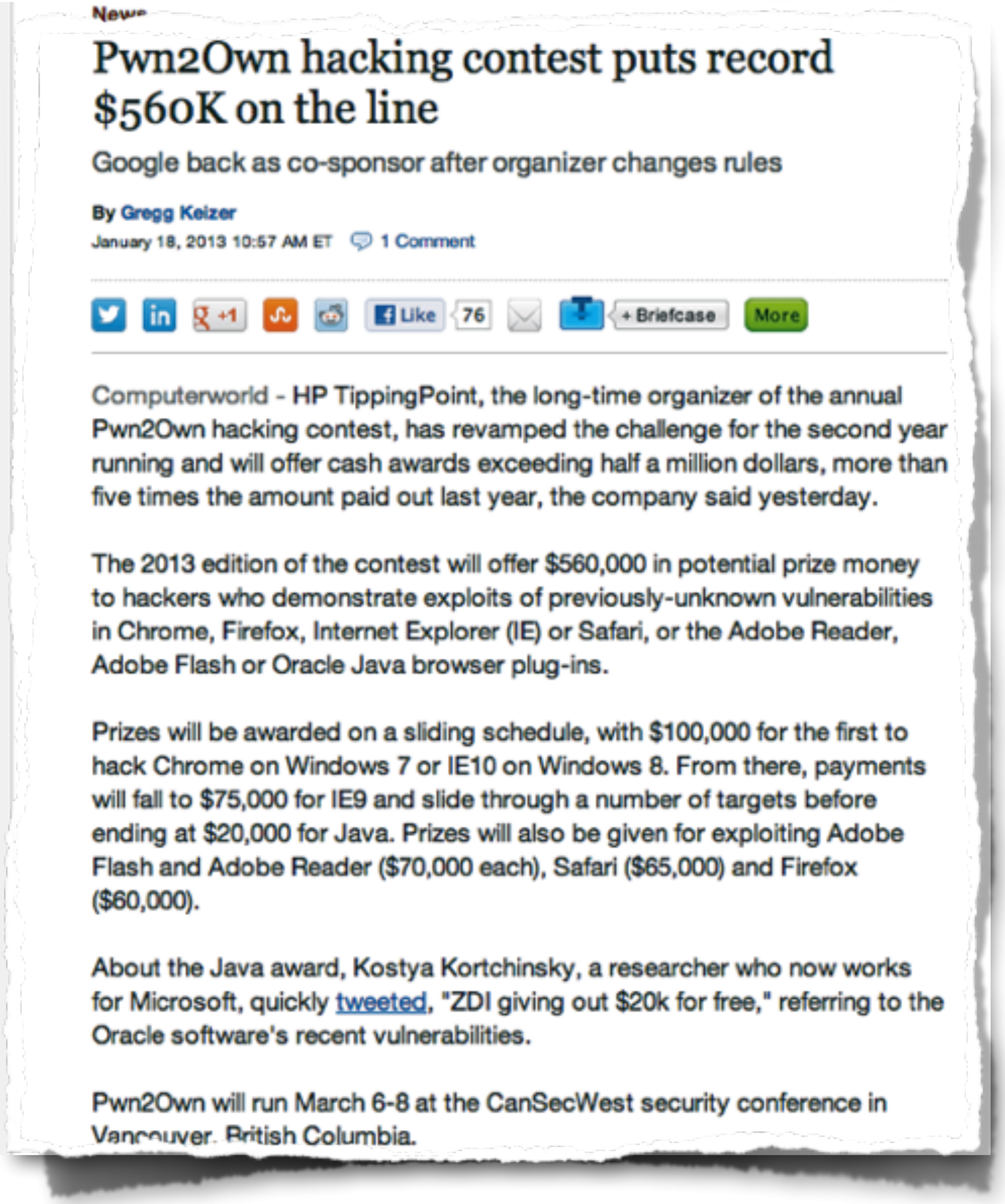
E*TRADE

Gmail

Hotmail

Y!

Browsers: Vulnerable



News

Pwn2Own hacking contest puts record $560K on the line

Google back as co-sponsor after organizer changes rules

By Gregg Keizer
January 18, 2013 10:57 AM ET 1 Comment

Computerworld - HP TippingPoint, the long-time organizer of the annual Pwn2Own hacking contest, has revamped the challenge for the second year running and will offer cash awards exceeding half a million dollars, more than five times the amount paid out last year, the company said yesterday.

The 2013 edition of the contest will offer $560,000 in potential prize money to hackers who demonstrate exploits of previously-unknown vulnerabilities in Chrome, Firefox, Internet Explorer (IE) or Safari, or the Adobe Reader, Adobe Flash or Oracle Java browser plug-ins.

Prizes will be awarded on a sliding schedule, with $100,000 for the first to hack Chrome on Windows 7 or IE10 on Windows 8. From there, payments will fall to $75,000 for IE9 and slide through a number of targets before ending at $20,000 for Java. Prizes will also be given for exploiting Adobe Flash and Adobe Reader ($70,000 each), Safari ($65,000) and Firefox ($60,000).

About the Java award, Kostya Kortchinsky, a researcher who now works for Microsoft, quickly tweeted, "ZDI giving out $20k for free," referring to the Oracle software's recent vulnerabilities.

Pwn2Own will run March 6-8 at the CanSecWest security conference in Vancouver, British Columbia.

Defenses / Policies:

[*Jang et al. W2SP*]

[*Stamm et al. WWW*]

[*Jackson et al. W2SP*]

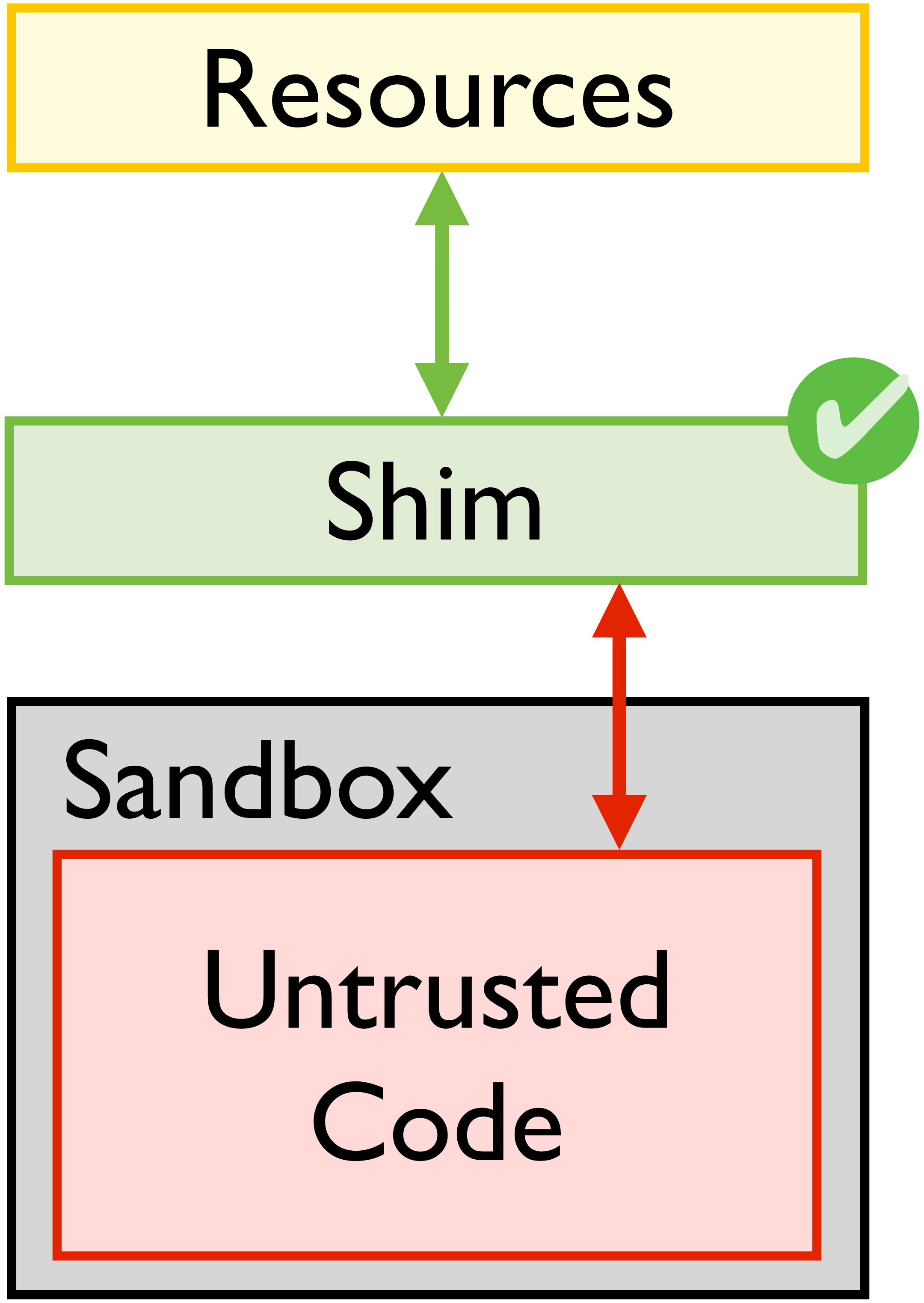
[*Barth et al. CCS*]

[*Singh et al. OAKLAND*]

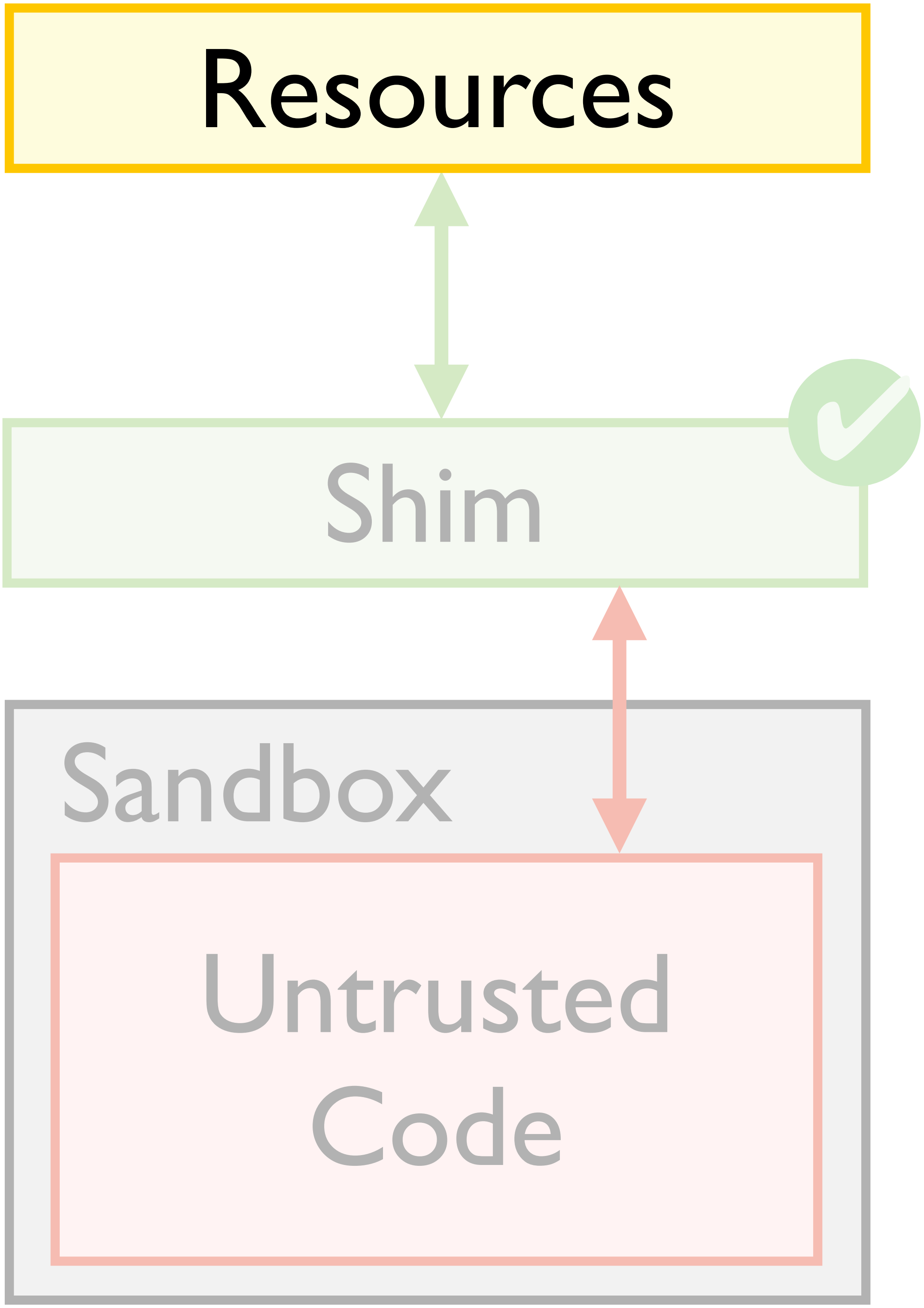
…

Complex + Implementation Bugs

Quark: Verified Browser



Quark: Verified Browser

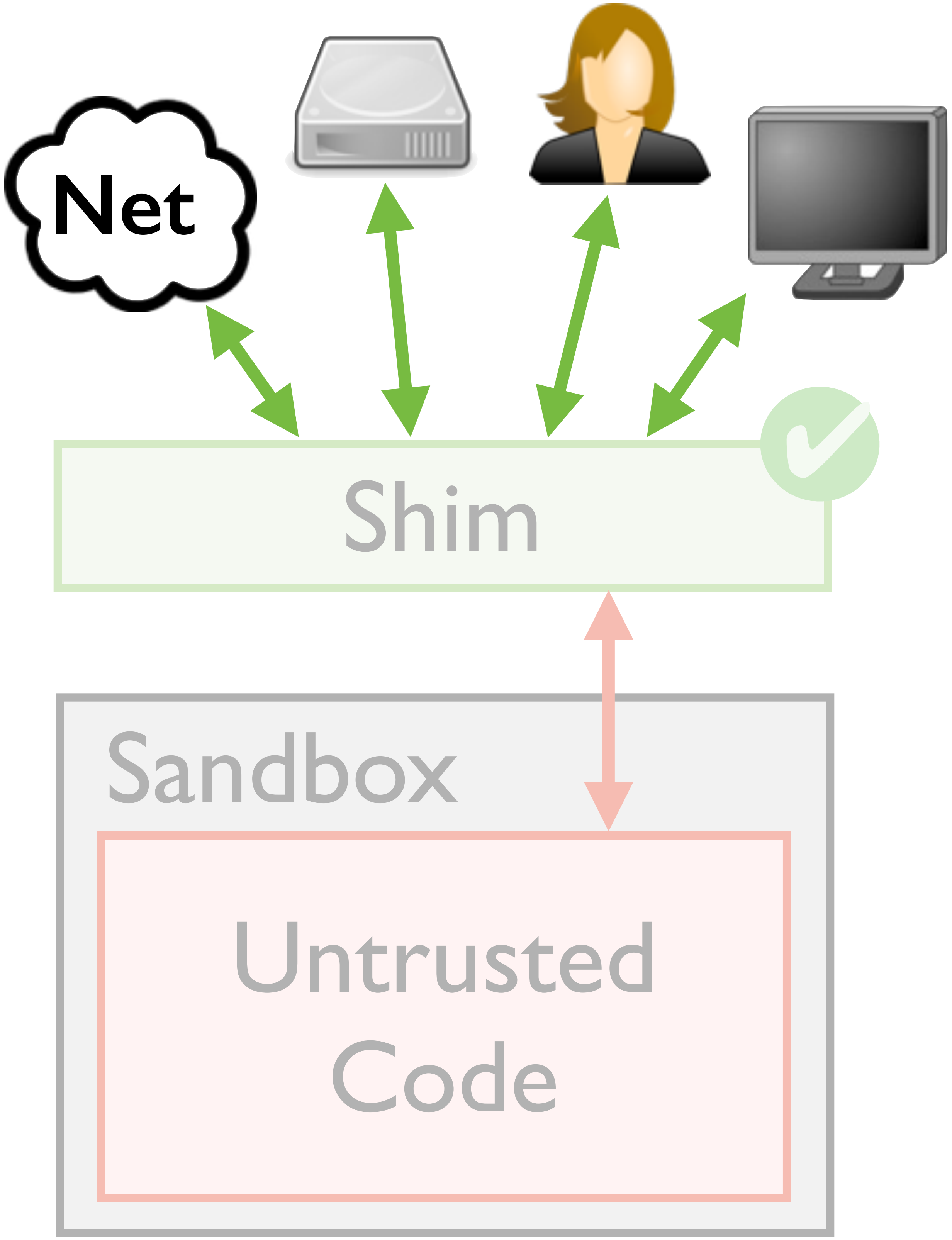

Resources

Shim

Sandbox

Untrusted Code

Quark: Verified Browser



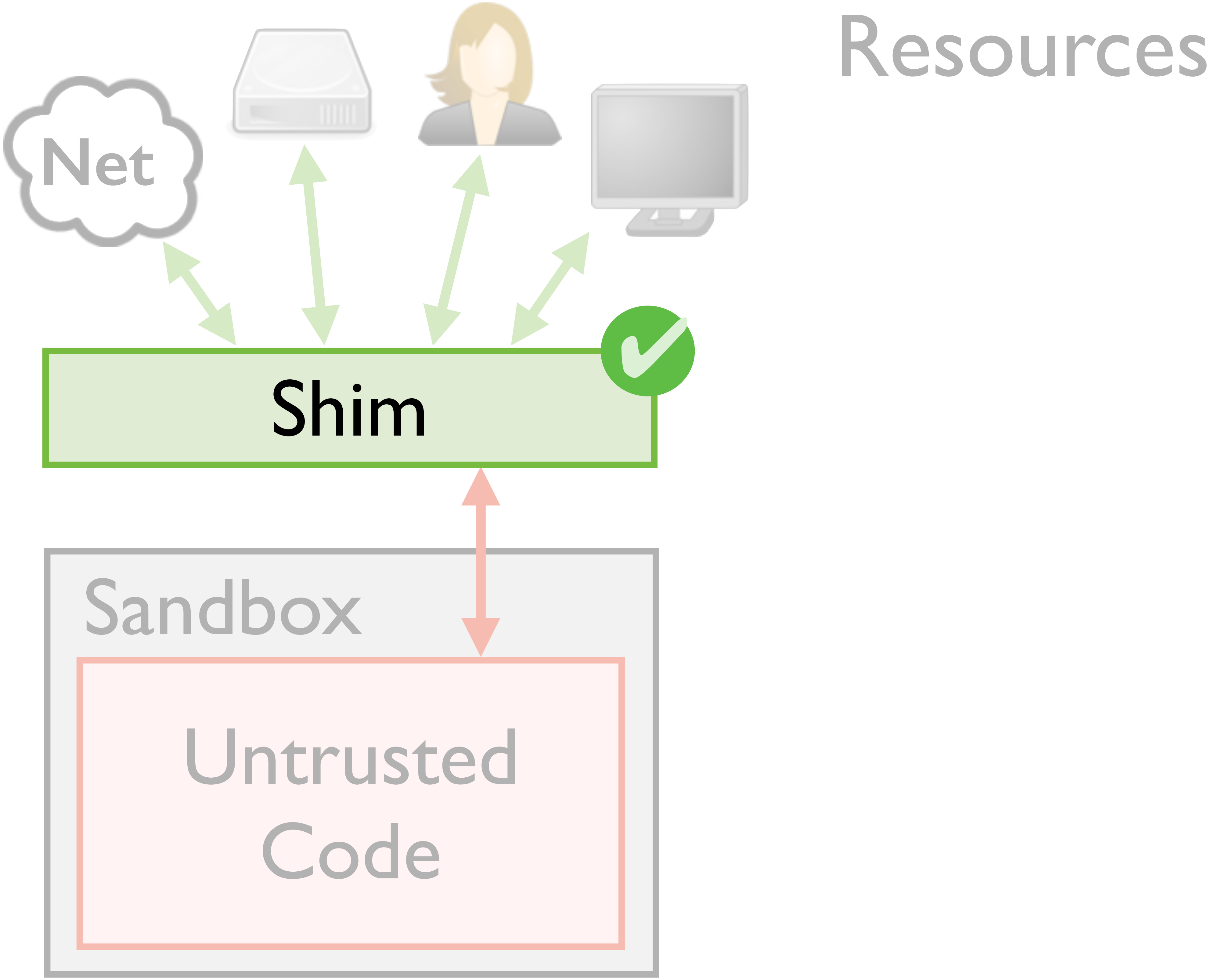
Resources

network

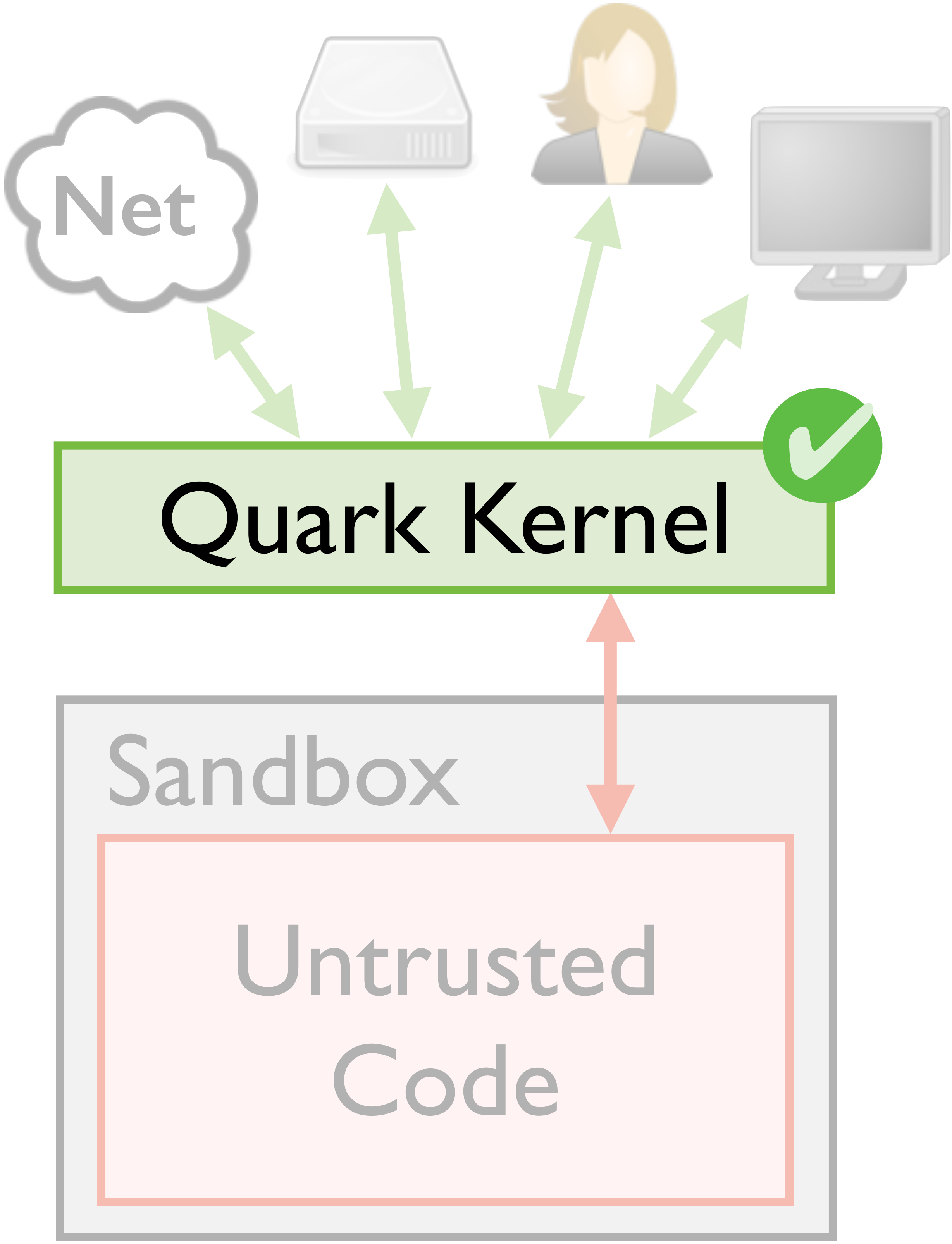
persistent storage

user interface

Quark: Verified Browser



Quark: Verified Browser



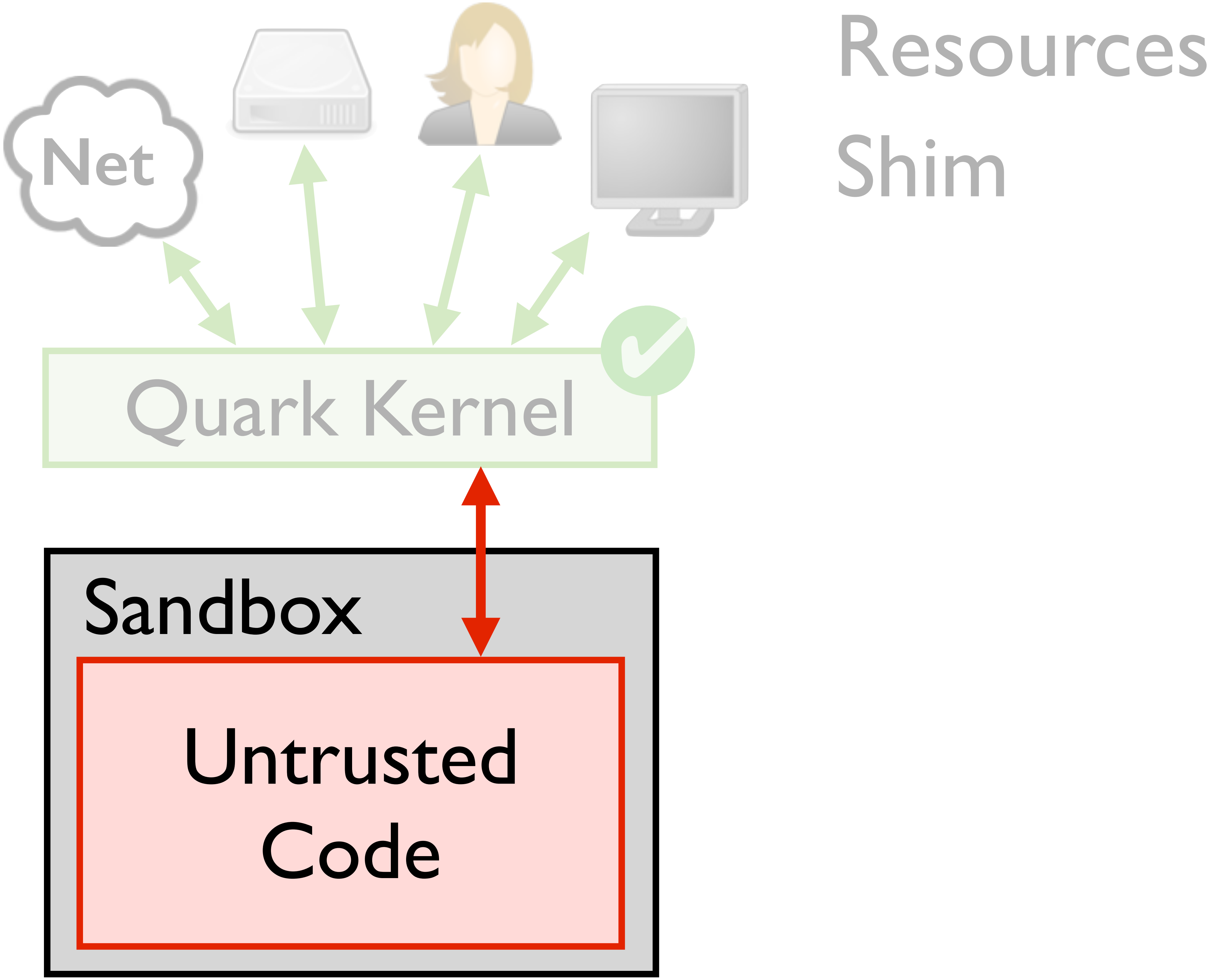
Resources

Shim

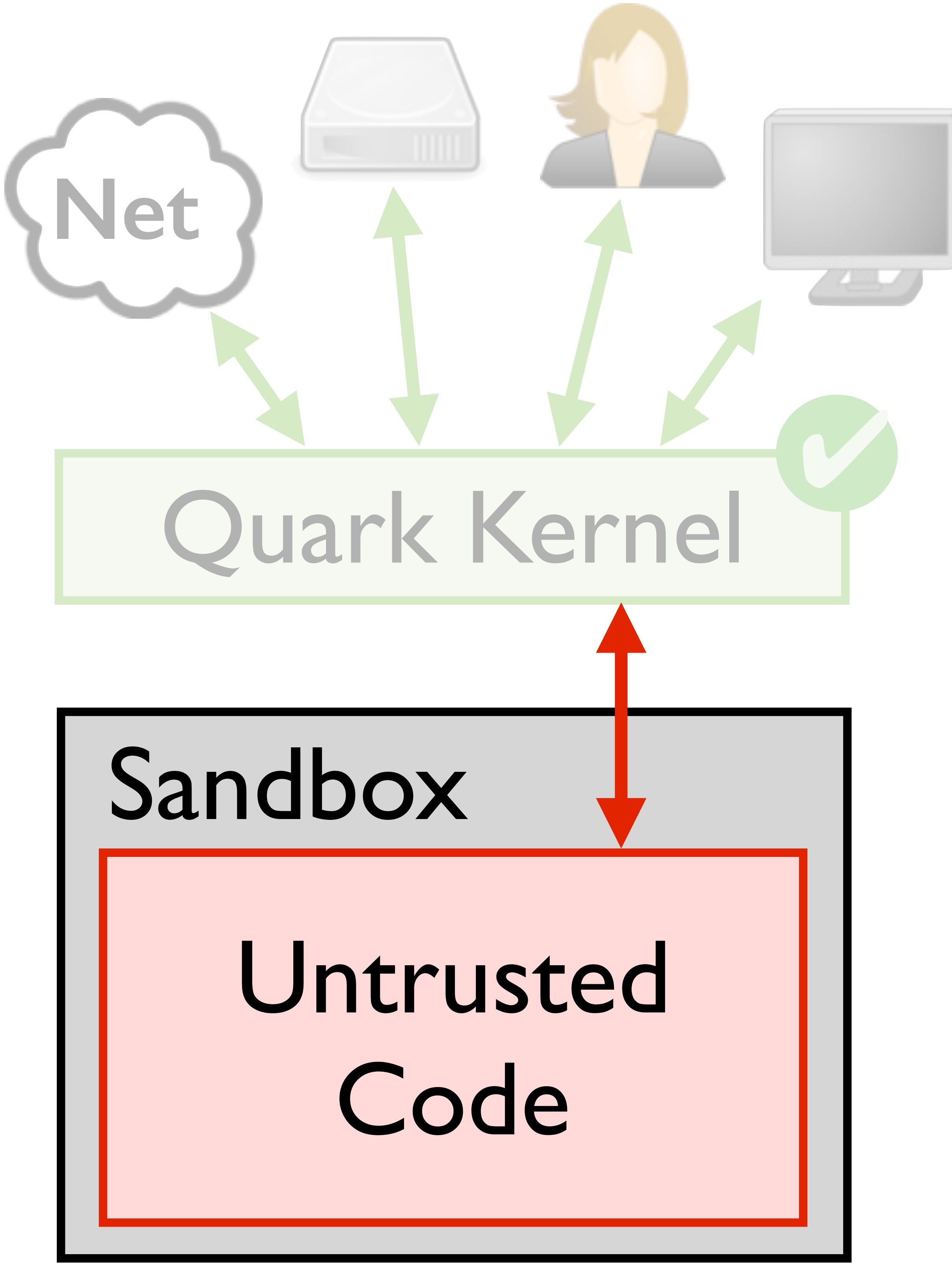
Quark browser kernel

code, spec, proof in Coq

Quark: Verified Browser



Quark: Verified Browser



Resources

Shim

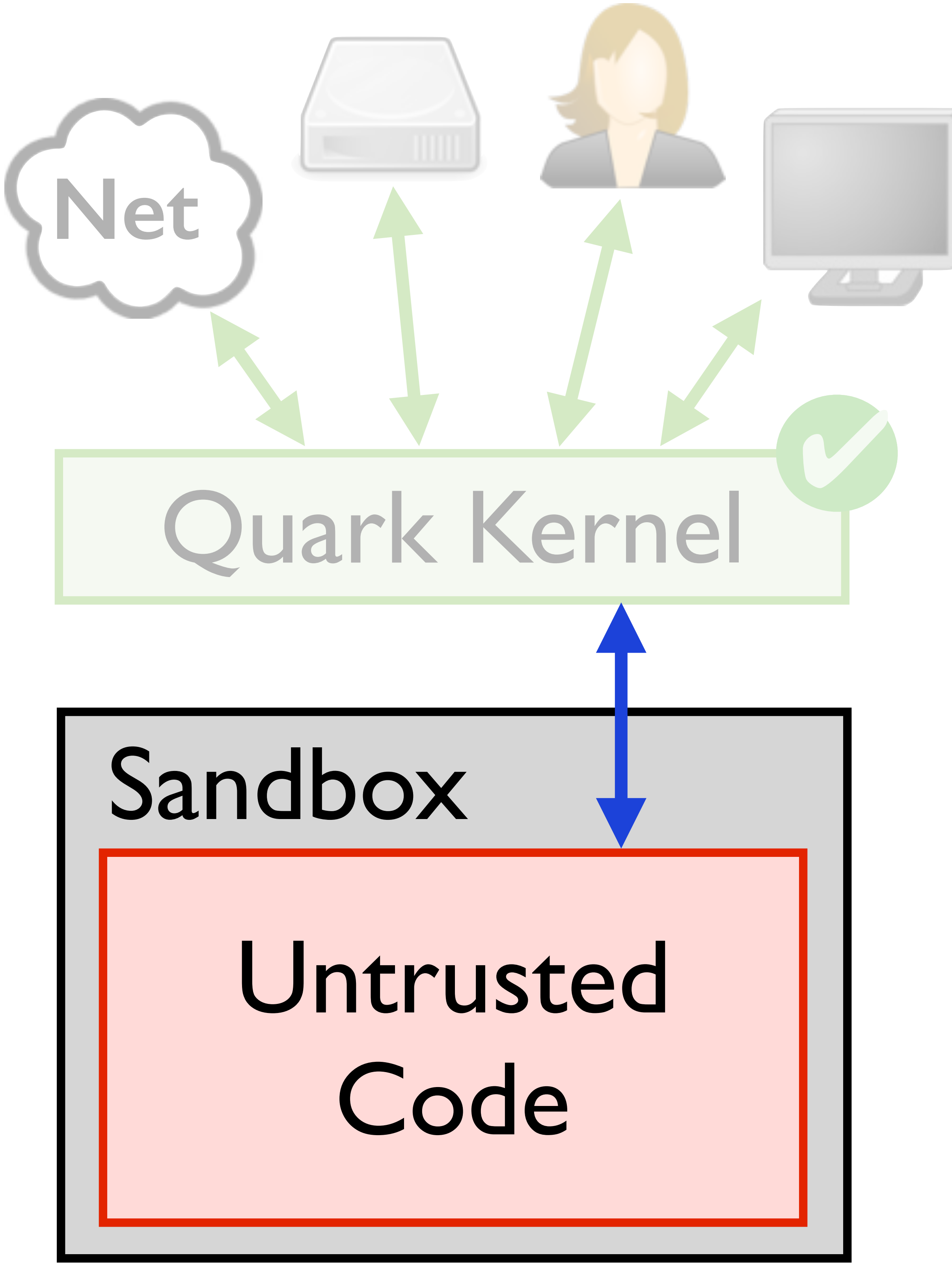
Untrusted Code

browser components

run as separate procs

strictly sandboxed

Quark: Verified Browser



Resources

Shim

Untrusted Code

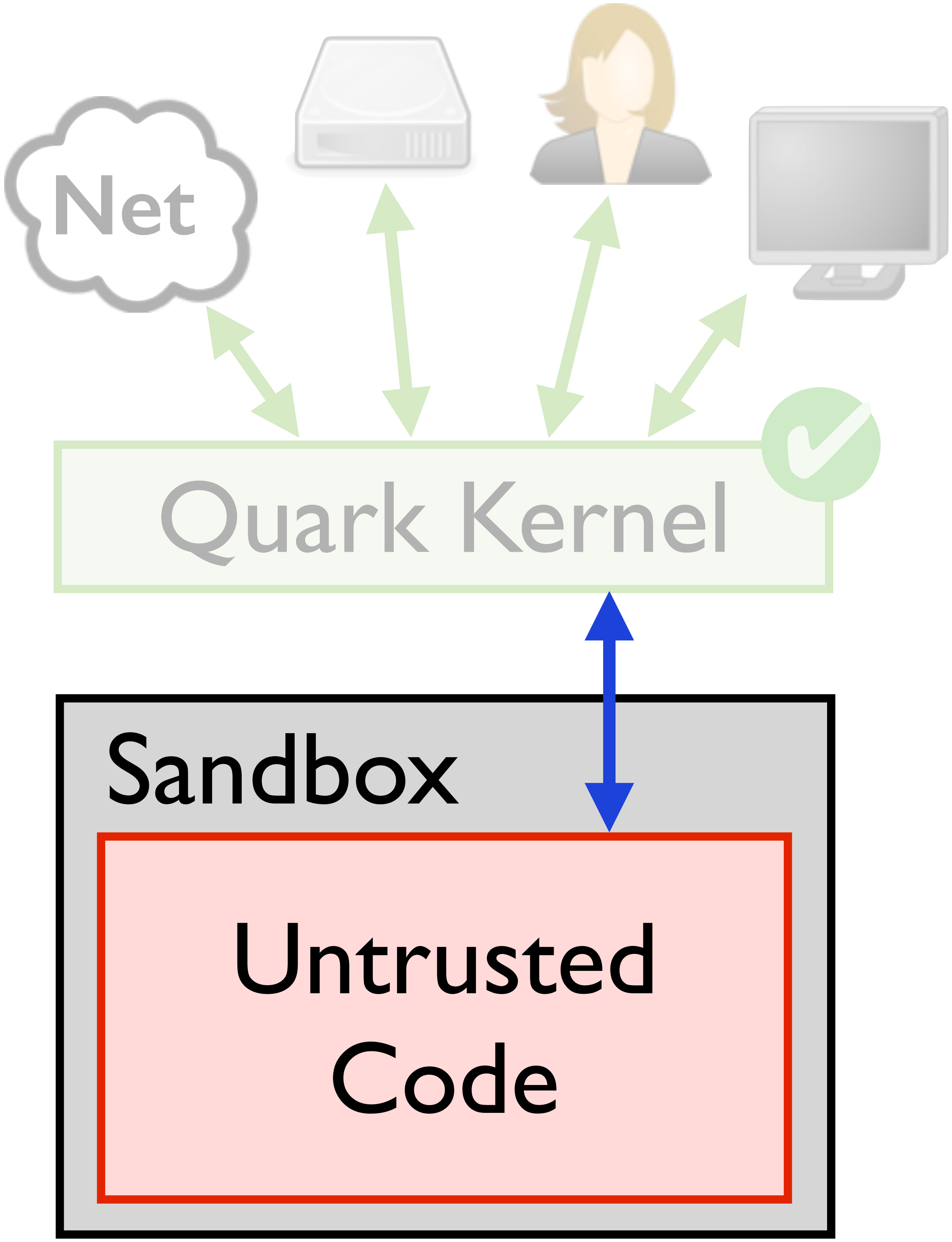
browser components

run as separate procs

strictly sandboxed

talk to kernel over pipe

Quark: Verified Browser



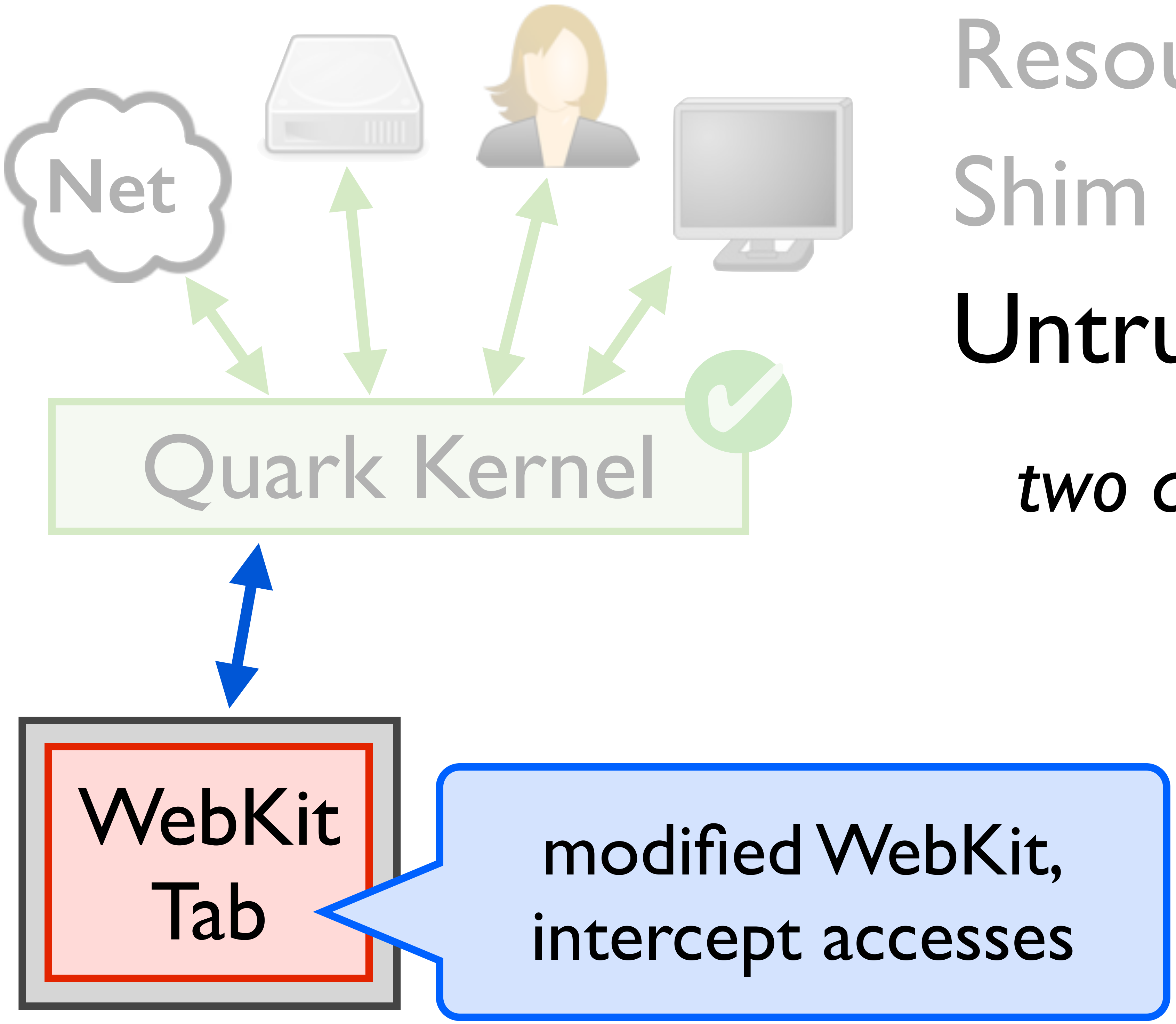
Resources

Shim

Untrusted Code

two component types

Quark: Verified Browser



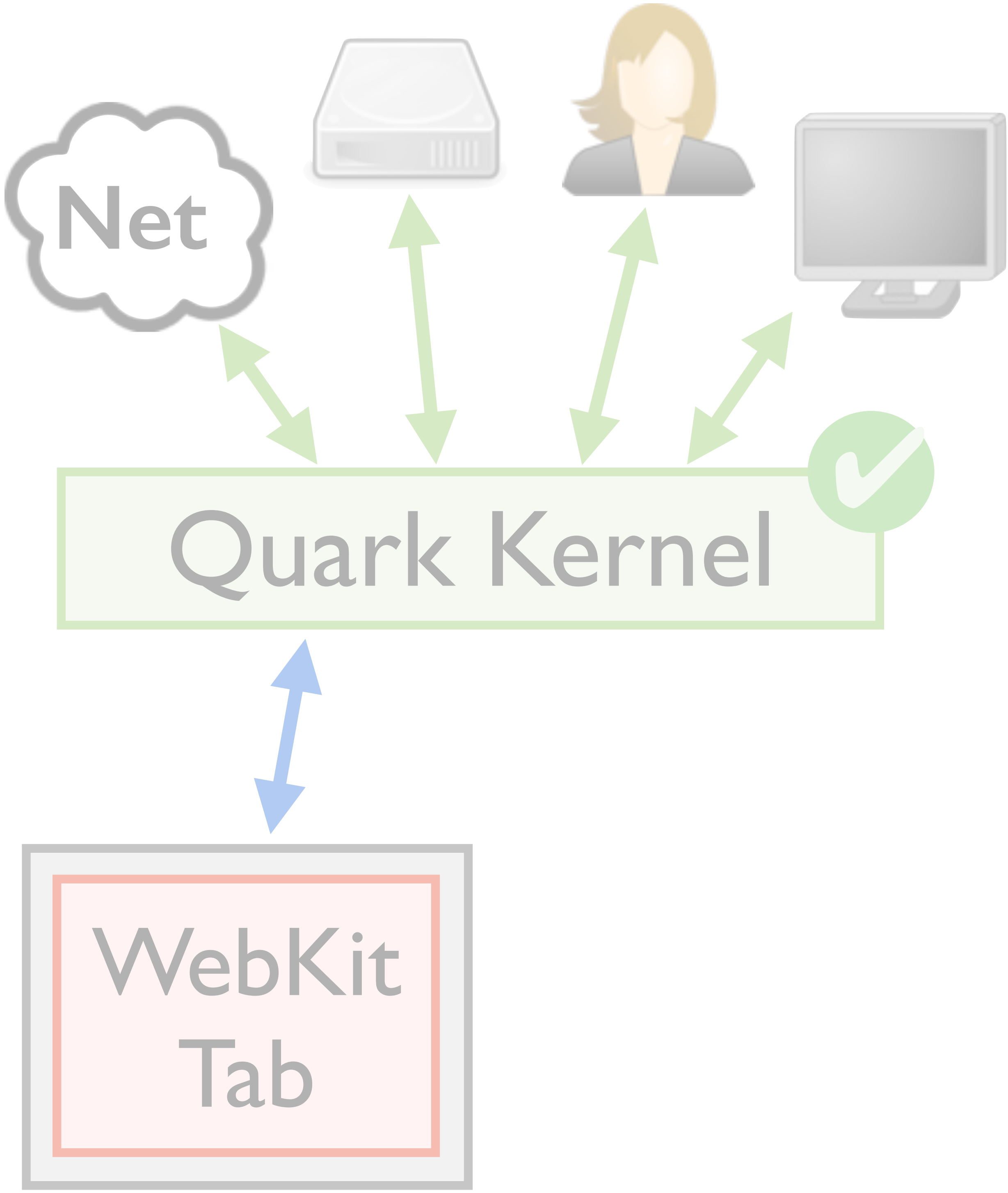
Resources

Shim

Untrusted Code

two component types

Quark: Verified Browser



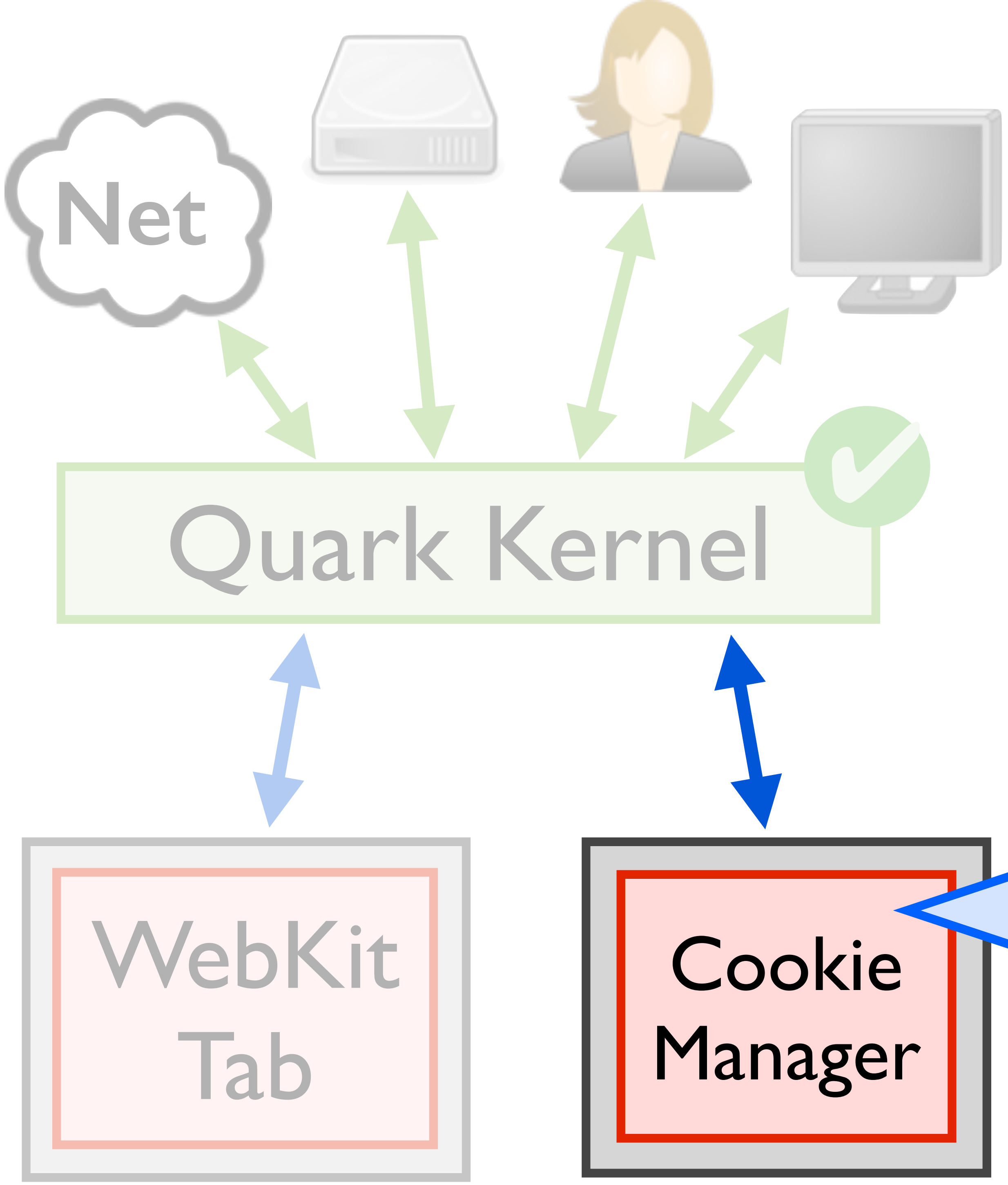
Resources

Shim

Untrusted Code

two component types

Quark: Verified Browser



Resources

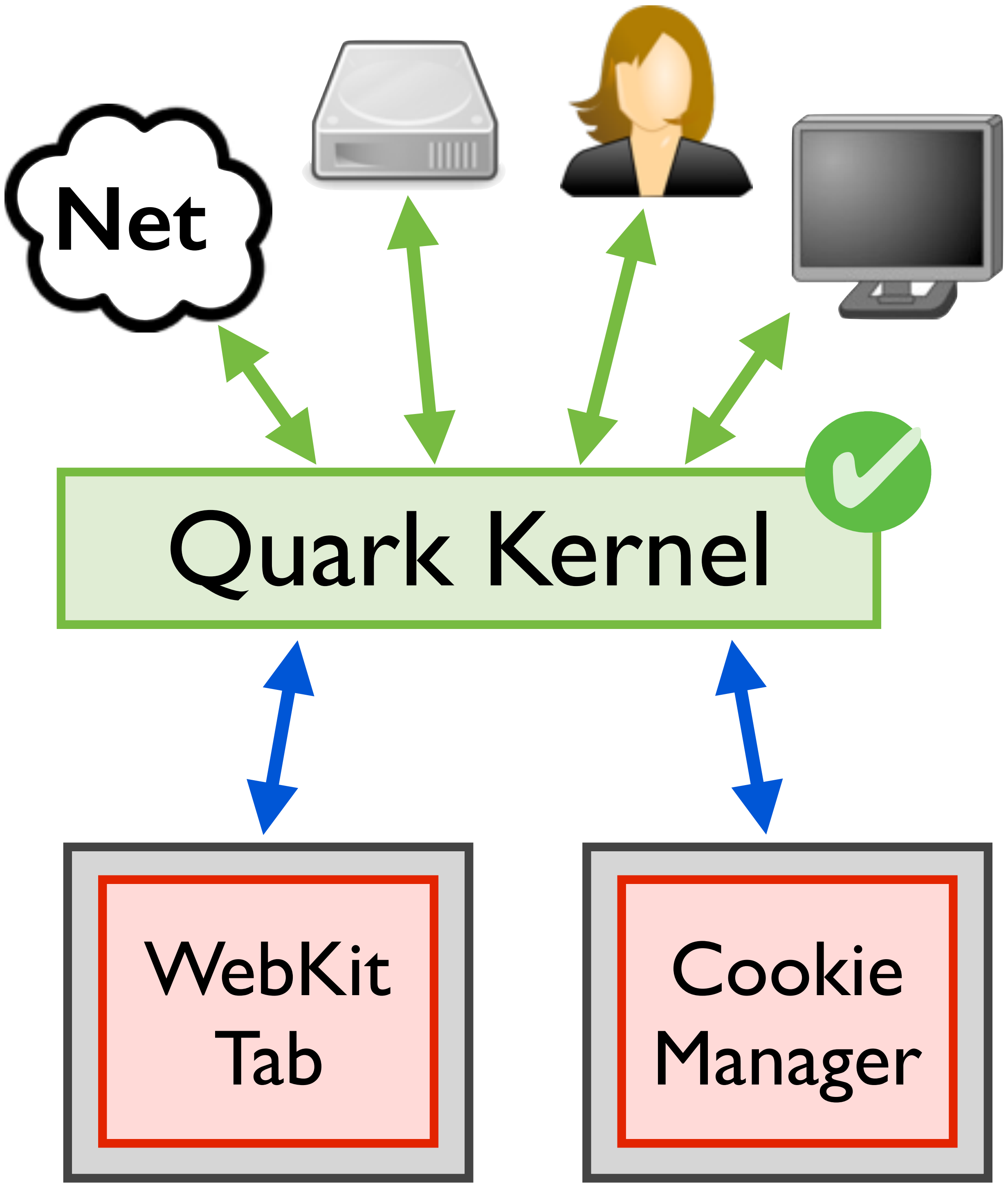
Shim

Untrusted Code

two component types

written in Python, manages single domain

Quark: Verified Browser



Resources

Shim

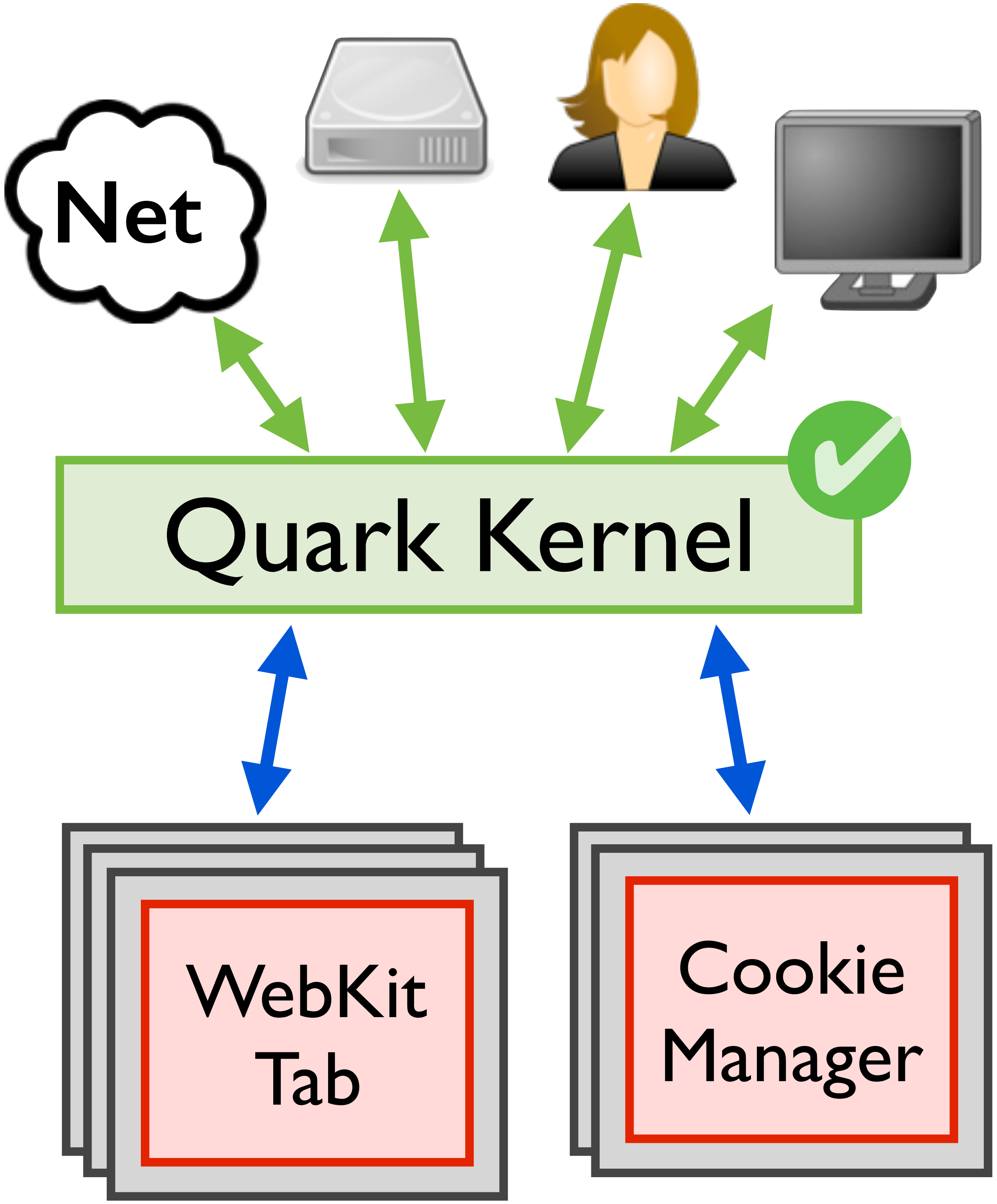
Untrusted Code

two component types

WebKit tabs

cookie managers

Quark: Verified Browser



Resources

Shim

Untrusted Code

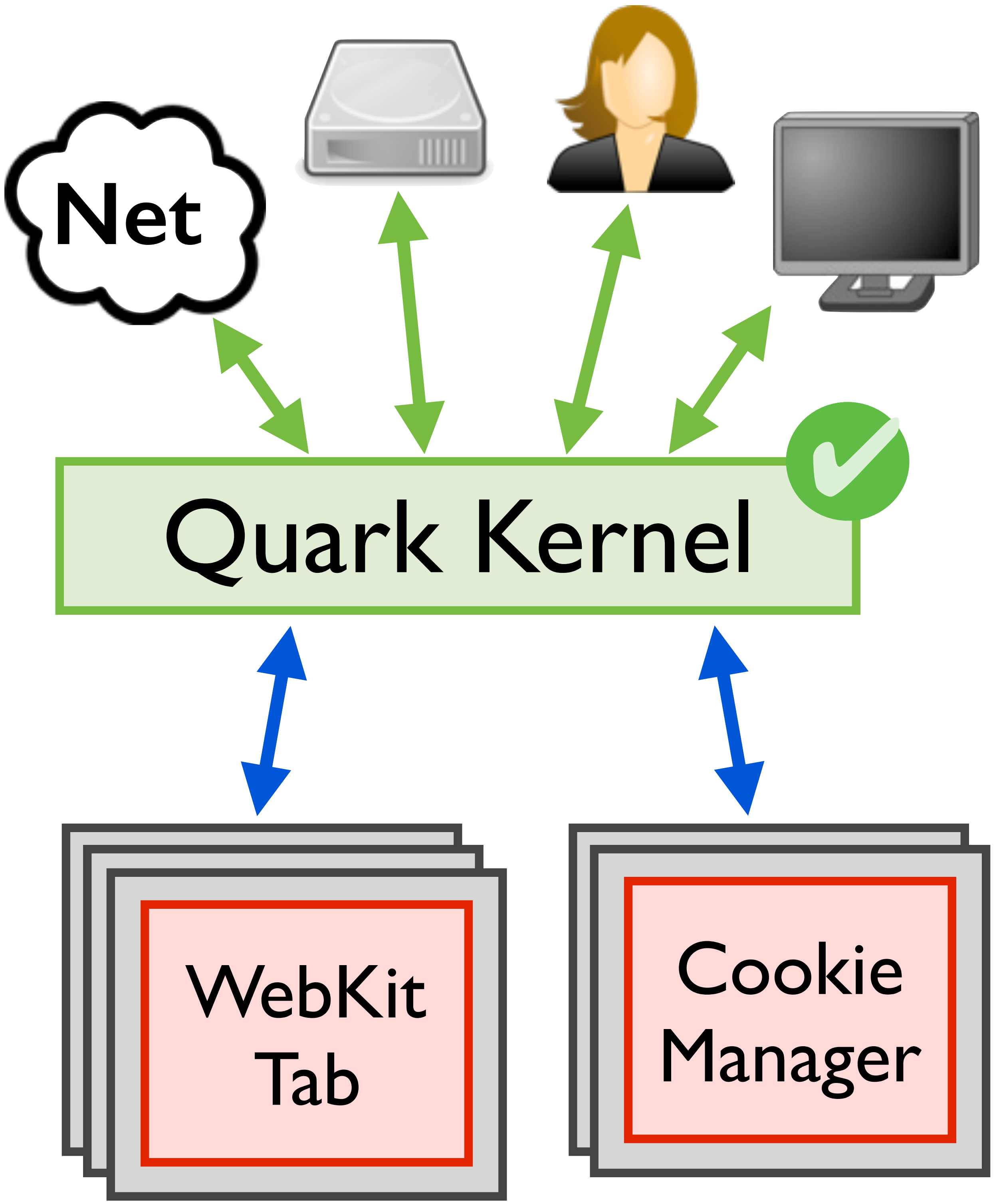
two component types

WebKit tabs

cookie managers

several instances each

Quark: Verified Browser



Quark: Verified Browser

Quark Kernel

Quark Kernel

Quark Kernel

Quark Kernel: Code, Spec, Proof

Quark Kernel ✓

Quark Kernel: *Code*, Spec, Proof

Quark Kernel ✓

Quark Kernel: *Code*, Spec, Proof

Quark Kernel: *Code*, Spec, Proof

```
Definition kstep ...
```

Quark Kernel: *Code*, Spec, Proof

```
Definition kstep(focused_tab, tabs) :=
  ...
```

kernel state

Quark Kernel: *Code*, Spec, Proof

```
Definition kstep(focused_tab, tabs) :=
  f <- select(stdin, tabs);
  ...
```

Unix-style select to find a component pipe ready to read

Quark Kernel: *Code*, Spec, Proof

```
Definition kstep(focused_tab, tabs) :=
  f <- select(stdin, tabs);
  match f with
  | Stdin =>
      ...
  | Tab t =>
      ...
```

case: **f** is user input

case: **f** is tab pipe

Quark Kernel: *Code*, Spec, Proof

```
Definition kstep(focused_tab, tabs) :=
  f <- select(stdin, tabs);
  match f with
  | Stdin =>
      cmd <- read_cmd(stdin);
      ...



  | Tab t =>
      ...
```

read command from user over **`stdin`**

Quark Kernel: *Code*, Spec, Proof

```
Definition kstep(focused_tab, tabs) :=
  f <- select(stdin, tabs);
  match f with
  | Stdin =>
      cmd <- read_cmd(stdin);
      match cmd with
      | AddTab =>
          ...


      | ...
  | Tab t =>
      ...
```

user wants to create and focus a new tab

Quark Kernel: *Code*, Spec, Proof

```
Definition kstep(focused_tab, tabs) :=
  f <- select(stdin, tabs);
  match f with
  | Stdin =>
      cmd <- read_cmd(stdin);
      match cmd with
      | AddTab =>
          t <- mk_tab();
          ...

      | ...
  | Tab t =>
      ...
```

create a new tab

Quark Kernel: *Code*, Spec, Proof

```
Definition kstep(focused_tab, tabs) :=
  f <- select(stdin, tabs);
  match f with
  | Stdin =>
      cmd <- read_cmd(stdin);
      match cmd with
      | AddTab =>
          t <- mk_tab();
          write_msg(t, Render);
          ...
      | ...
  | Tab t =>
      ...
```

tell new tab to render itself

Quark Kernel: *Code*, Spec, Proof

```
Definition kstep(focused_tab, tabs) :=
  f <- select(stdin, tabs);
  match f with
  | Stdin =>
      cmd <- read_cmd(stdin);
      match cmd with
      | AddTab =>
          t <- mk_tab();
          write_msg(t, Render);
          return (t, t::tabs)
      | ...
  | Tab t =>
      ...
```

return updated state

Quark Kernel: *Code*, Spec, Proof

```
Definition kstep(focused_tab, tabs) :=
  f <- select(stdin, tabs);
  match f with
  | Stdin =>
      cmd <- read_cmd(stdin);
      match cmd with
      | AddTab =>
          t <- mk_tab();
          write_msg(t, Render);
          return (t, t::tabs)
      | ...
  | Tab t =>
      ...
```

Quark Kernel: *Code*, Spec, Proof

```
Definition kstep(focused_tab, tabs) :=
  f <- select(stdin, tabs);
  match f with
  | Stdin =>
      cmd <- read_cmd(stdin);
      match cmd with
      | AddTab =>
          t <- mk_tab();
          write_msg(t, Render);
          return (t, t::tabs)
      | ...
  | Tab t =>
      ...
```

handle other user commands

Quark Kernel: *Code*, Spec, Proof

```
Definition kstep(focused_tab, tabs) :=
  f <- select(stdin, tabs);
  match f with
  | Stdin =>
      cmd <- read_cmd(stdin);
      match cmd with
      | AddTab =>
          t <- mk_tab();
          write_msg(t, Render);
          retu
      | ...
  | Tab t =>
      ...
```

handle requests from tabs

Quark Kernel: Code, Spec, Proof

```
Definition kstep(focused_tab, tabs) :=
  f <- select(stdin, tabs);
  match f with
  | Stdin =>
      cmd <- read_cmd(stdin);
      match cmd with
      | AddTab =>
          t <- mk_tab();
          write_msg(t, Render);
          return (t, t::tabs)
      | ...
  | Tab t =>
      ...
```

Quark Kernel: *Code*, Spec, Proof

Quark Kernel: Code, *Spec*, Proof

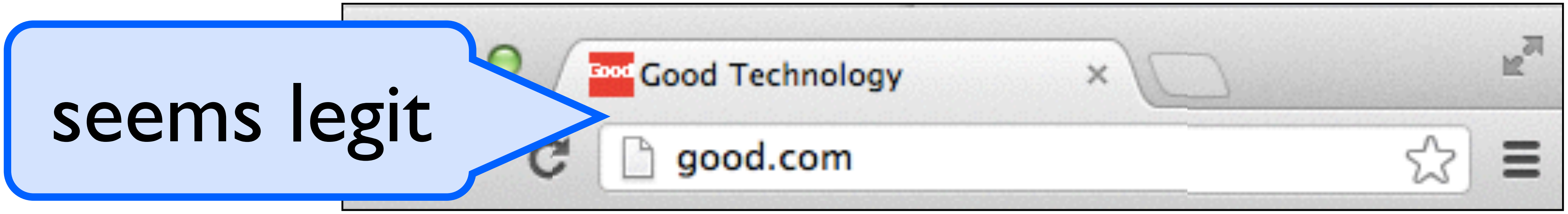
Quark Kernel: Code, Spec, Proof

Safety properties to mitigate attacks

restrict kernel behavior to only safe executions

Example: mitigate phishing attacks

prevent tricks that get users to divulge secrets



Quark Kernel: Code, Spec, Proof

Safety properties to mitigate attacks

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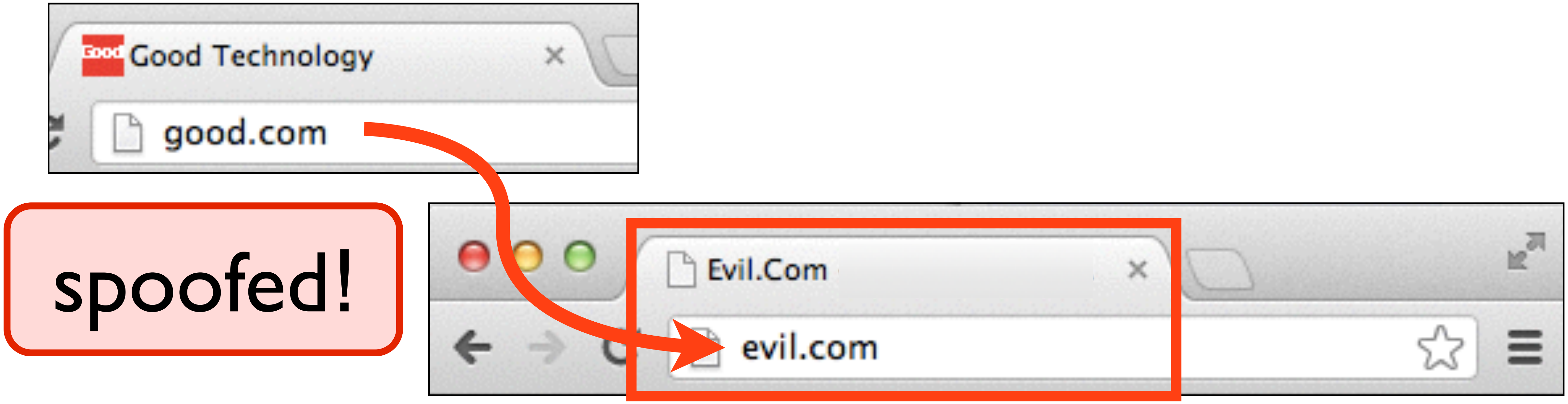


spoofed!

Quark Kernel: Code, *Spec*, Proof

Specify correct behavior wrt syscall seqs

```
read(), write(), open(), write(), ...
```

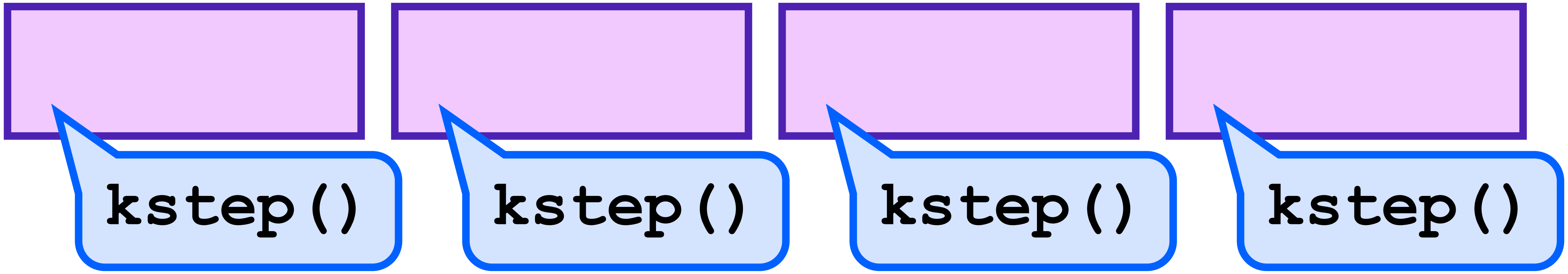
Quark Kernel: Code, Spec, Proof

Specify correct behavior wrt syscall seqs

trace: all syscalls made by Quark kernel during execution

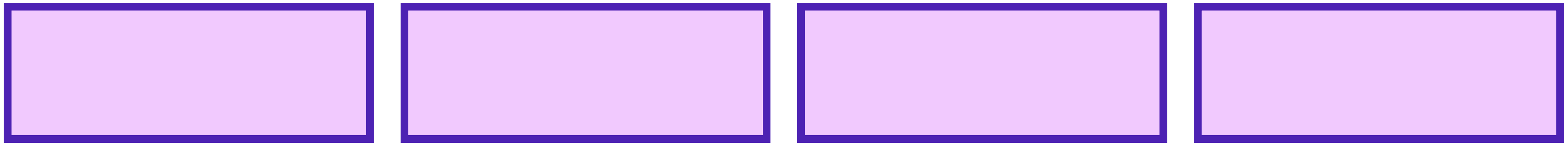
Quark Kernel: Code, *Spec*, Proof

Specify correct behavior wrt syscall seqs



Quark Kernel: Code, Spec, Proof

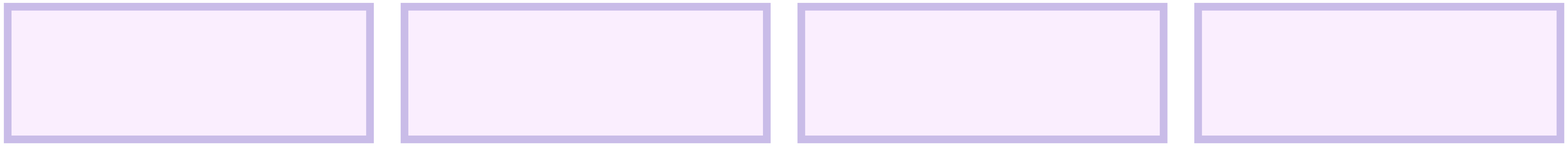
Specify correct behavior wrt syscall seqs



structure of produceable traces supports spec & proof

Quark Kernel: Code, *Spec*, Proof

Specify correct behavior wrt syscall seqs

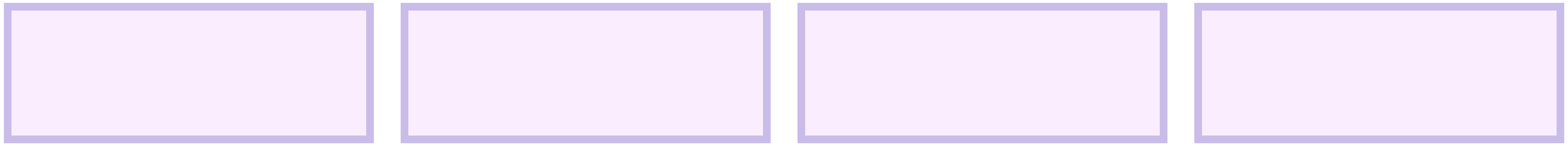


structure of produceable traces supports spec & proof

Example: address bar correctness

Quark Kernel: Code, Spec, Proof

Specify correct behavior wrt syscall seqs



structure of produceable traces supports spec & proof

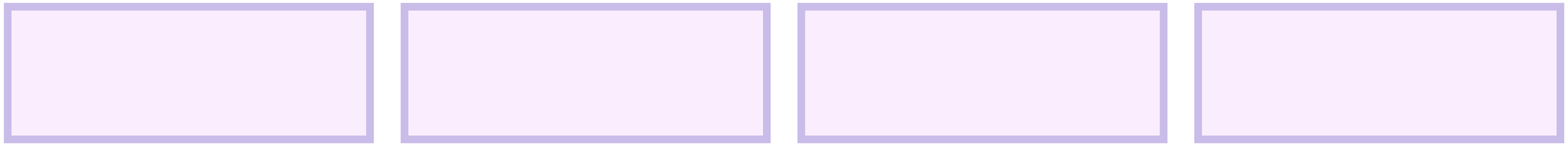
Example: address bar correctness

```
forall trace tab domain,
```

for *any* trace, tab, and domain

Quark Kernel: Code, Spec, Proof

Specify correct behavior wrt syscall seqs



structure of produceable traces supports spec & proof

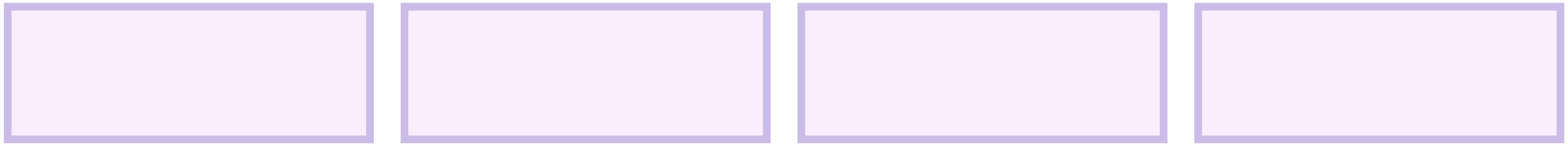
Example: address bar correctness

```
forall trace tab domain,
  quark_produced(trace)    ∧
  ...
```

if Quark could have produced this trace

Quark Kernel: Code, Spec, Proof

Specify correct behavior wrt syscall seqs



structure of produceable traces supports spec & proof

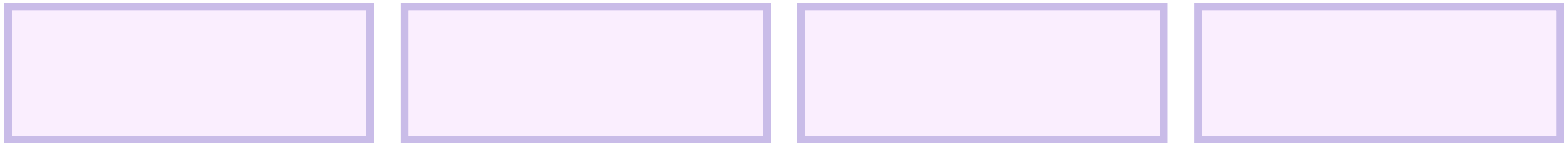
Example: address bar correctness

```
forall trace tab domain,
  quark_produced(trace)    ∧
  tab = cur_tab(trace)     ∧
  ...
```

and **`tab`** is the selected tab in this trace

Quark Kernel: Code, Spec, Proof

Specify correct behavior wrt syscall seqs



structure of produceable traces supports spec & proof

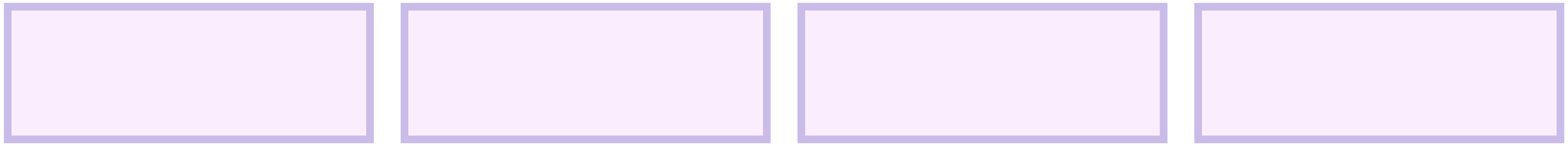
Example: address bar correctness

```
forall trace ta
  quark_produce
  tab = cur_tab(trace)      /\
  domain = addr_bar(trace) ->
  ...
```

and **domain** displayed in address bar for this trace

Quark Kernel: Code, Spec, Proof

Specify correct behavior wrt syscall seqs



structure of produceable traces supports spec & proof

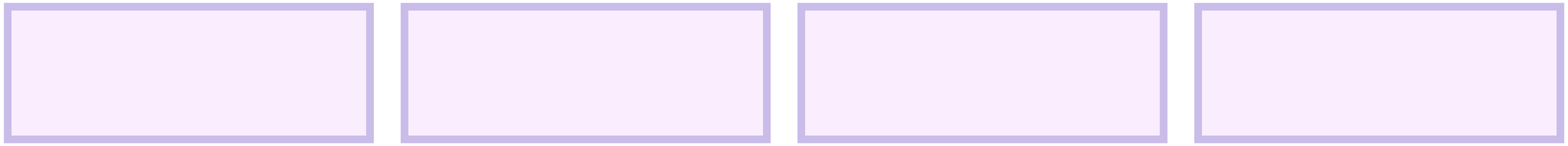
Example: address bar correctness

```
forall trace tab do
  quark_produced(tr
  tab = cur_tab(tra
  domain = addr_ba (trace) ->
  domain = tab_domain(tab)
```

then **domain** is the domain of the focused tab

Quark Kernel: Code, *Spec*, Proof

Specify correct behavior wrt syscall seqs



structure of produceable traces supports spec & proof

Example: address bar correctness

```
forall trace tab domain,
  quark_produced(trace)     ∧
  tab = cur_tab(trace)      ∧
  domain = addr_bar(trace) ->
  domain = tab_domain(tab)
```

Quark Kernel: Code, Spec, Proof

Formal Security Properties

Tab Non-Interference

no tab affects kernel interaction with another tab

Cookie Confidentiality and Integrity

cookies only accessed by tabs of same domain

Address Bar Integrity and Correctness

address bar accurate, only modified by user action

Quark Kernel: Code, *Spec*, Proof

Quark Kernel: Code, Spec, *Proof*

Quark Kernel: Code, Spec, *Proof*

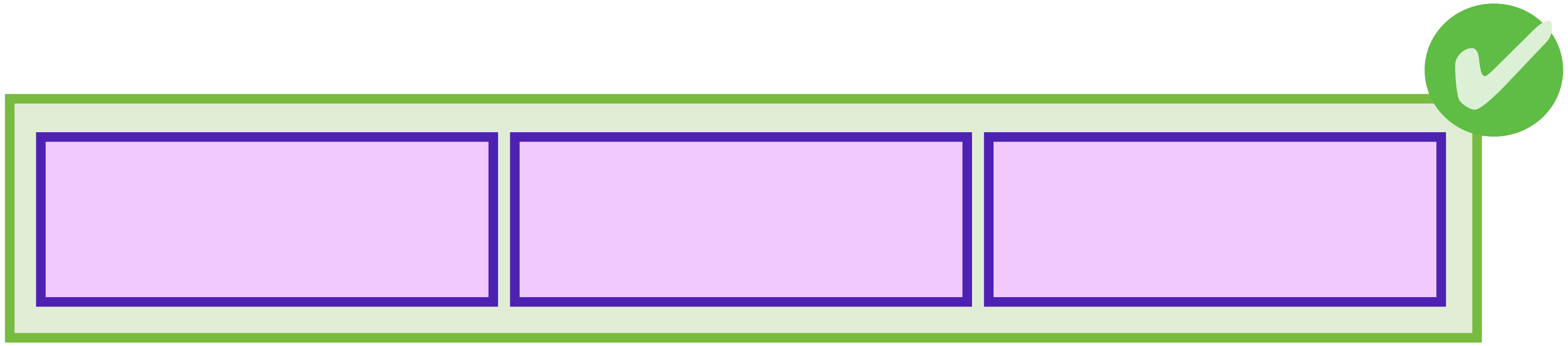
Prove kernel code satisfies sec props

by induction on traces Quark can produce

Quark Kernel: Code, Spec, *Proof*

Prove kernel code satisfies sec props

by induction on traces Quark can produce

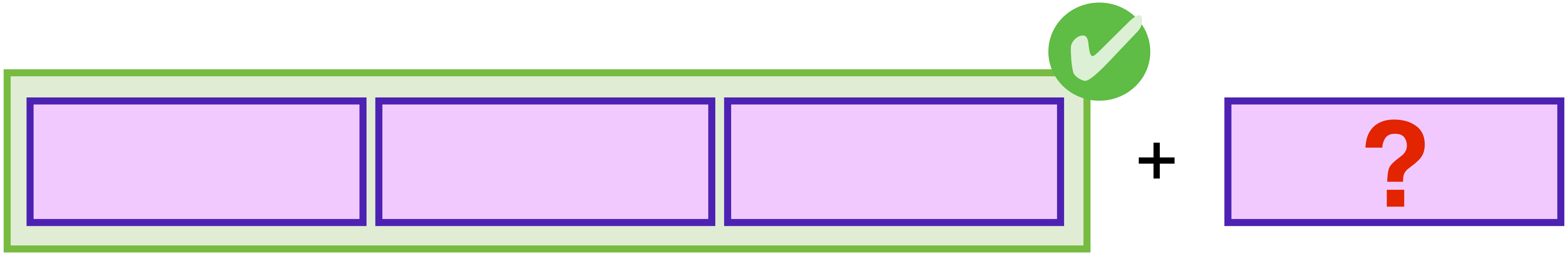


induction hypothesis:
trace valid up to this point

Quark Kernel: Code, Spec, *Proof*

Prove kernel code satisfies sec props

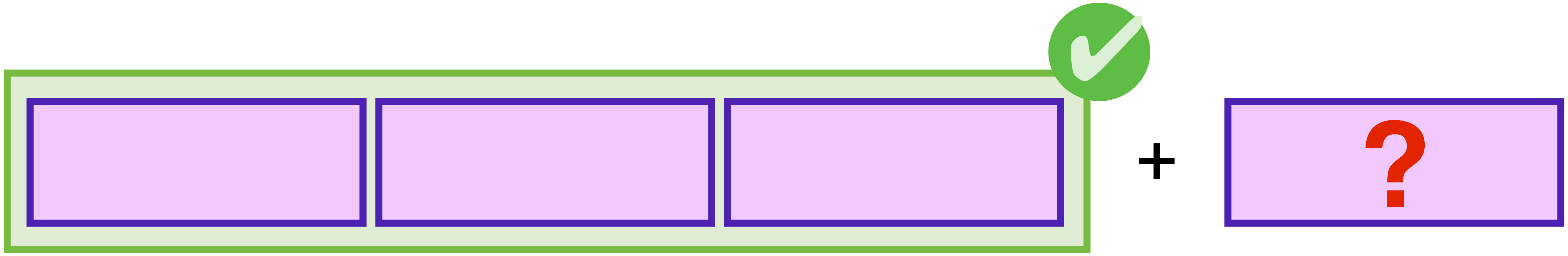
by induction on traces Quark can produce



induction hypothesis:
trace valid up to this point

proof obligation:
still valid after step?

Quark Kernel: Code, Spec, *Proof*



induction hypothesis:
trace valid up to this point

proof obligation:
still valid after step?

Proceed by case analysis on **`kstep()`**

what syscalls can be appended to trace?

will they still satisfy all security properties?

prove each case interactively in proof assistant

Quark Kernel: Code, Spec, *Proof*

Proving required diverse range of tools

monads	*encoding I/O in functional language*
Hoare logic	*reasoning about imperative programs*
op. semantics	*defining correctness of Quark kernel*
linear logic	*proving resources created / destroyed*

YNot

[*Naneveski et al. ICFP 08*]

Quark Kernel: Code, Spec, Proof

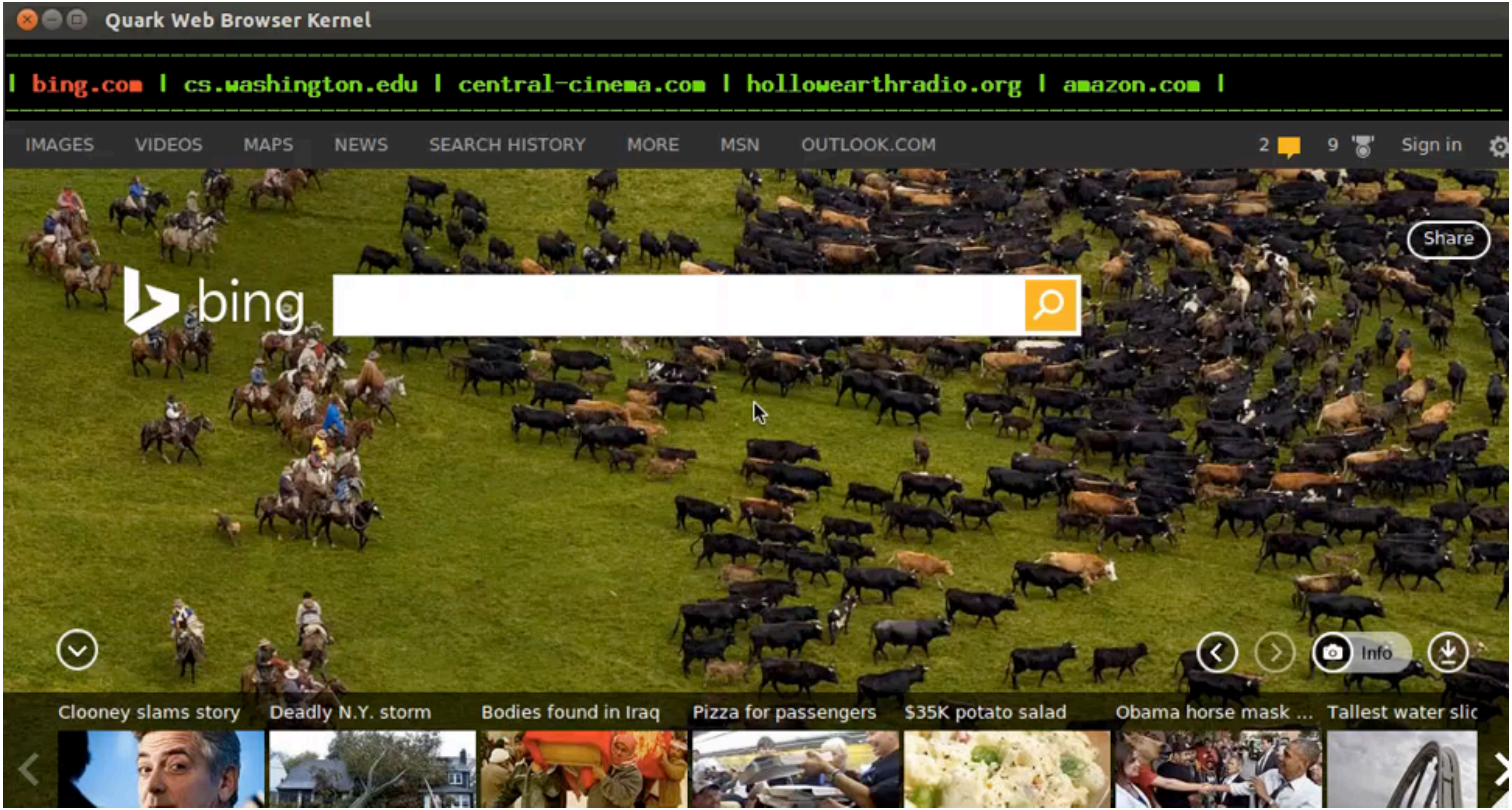
Key Insight: *FSV Effective*

Guarantee sec props for browser

Use state-of-the-art components

Only prove simple browser kernel

Formally Verified Browser!



Extending Quark

Filesystem access, sound, history

could be implemented w/out major redesign

Finer grained resource accesses

support mashups and plugins

Liveness properties

no blocking, kernel eventually services all requests

Trusted Computing Base

Infrastructure we assume correct

bugs here can invalidate our formal guarantees

Fundamental

Statement of security properties

Coq (soundness, proof checker)

Eventually Verified [active research]

OCaml [VeriML]

Tab Sandbox [RockSalt]

Operating System [seL4]

...

Quark Development Effort

150 lines of security props

900 lines of kernel code

4,500 lines of proofs

1,000,000 lines of WebKit

Quark Development Effort

150 lines of secu

week

900 lines of kernel code

4,500 lines of proofs

1,000,000 lines of We

months

Mitigating the Burden of Proof

1: Scaling proofs to critical infrastructure

Formal shim verification for large apps

⇨ *QUARK: browser with security guarantees*

2: Evolving formally verified systems

Reflex DSL exploits domain for proof auto

Mitigating the Burden of Proof

1: Scaling proofs to critical infrastructure

Formal shim verification for large apps

QUARK: browser with security guarantees

2: Evolving formally verified systems

⇨ *Reflex DSL exploits domain for proof auto*

Struggle Against Formality Inertia

Adding cookies to Quark quite difficult

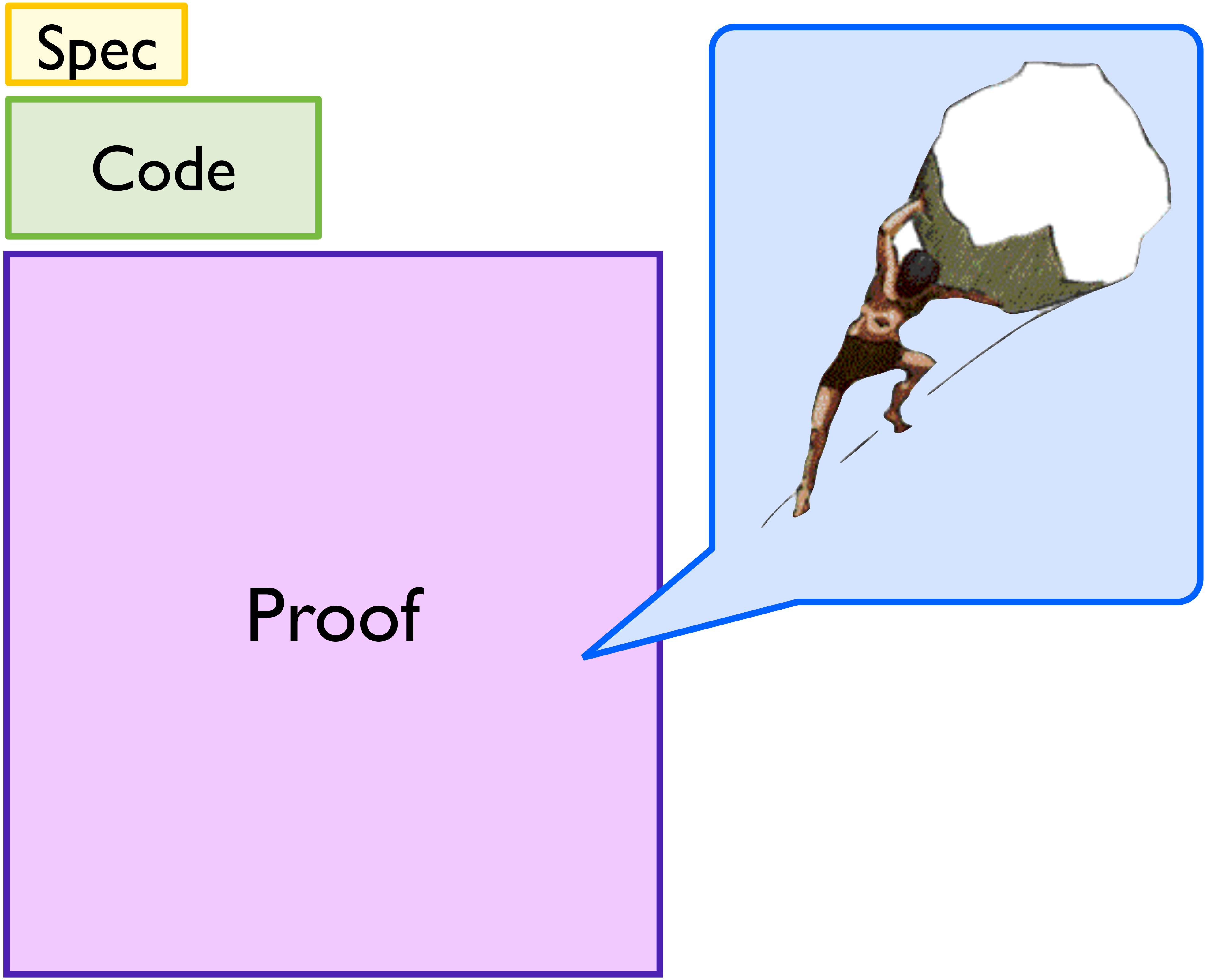
all the pieces already there, still took over a month

Proof updates repetitive and shallow

sensitive proof scripts, changes not mechanical

```
match svec_ith PAYREST i as _vi return
   forall (EQ: (svec_ith (projT2 (existT vcdesc' ENVD_SIZE PAYREST)) i) = _vi),
   match _vi as __d return (base_term (existT vcdesc' ENVD_SIZE PAYREST) __d -> Prop)
   with
   | Desc d => fun _ => True
   | Comp c => fun b=> FdSet.In
         (comp_fd (projT1 (eval_base_term (envd:=existT _ ENVD_SIZE PAYREST) erest b))) fds end
     match EQ in _ = __vi return base_term _ __vi with Logic.eq_refl =>
       Var (existT vcdesc' ENVD_SIZE PAYREST) i end
   ->
   match _vi as __d return (base_term (existT vcdesc' (S ENVD_SIZE) (PAY0, PAYREST)) __d -> Prop) with
   | Desc d => fun _ => True
   | Comp c => fun b =>
       FdSet.In (comp_fd (projT1 (eval_base_term (envd:=existT _ (S ENVD_SIZE) (PAY0, PAYREST)) (e0, erest) b))) fds end
     match EQ in _ = __vi return base_term _ __vi with Logic.eq_refl =>
       Var (existT vcdesc' (S ENVD_SIZE) (PAY0, PAYREST)) (Some i) end
with
| Desc d => _ | Comp c => _ end (Logic.eq_refl _)
```

Division of Labor *(to scale)*



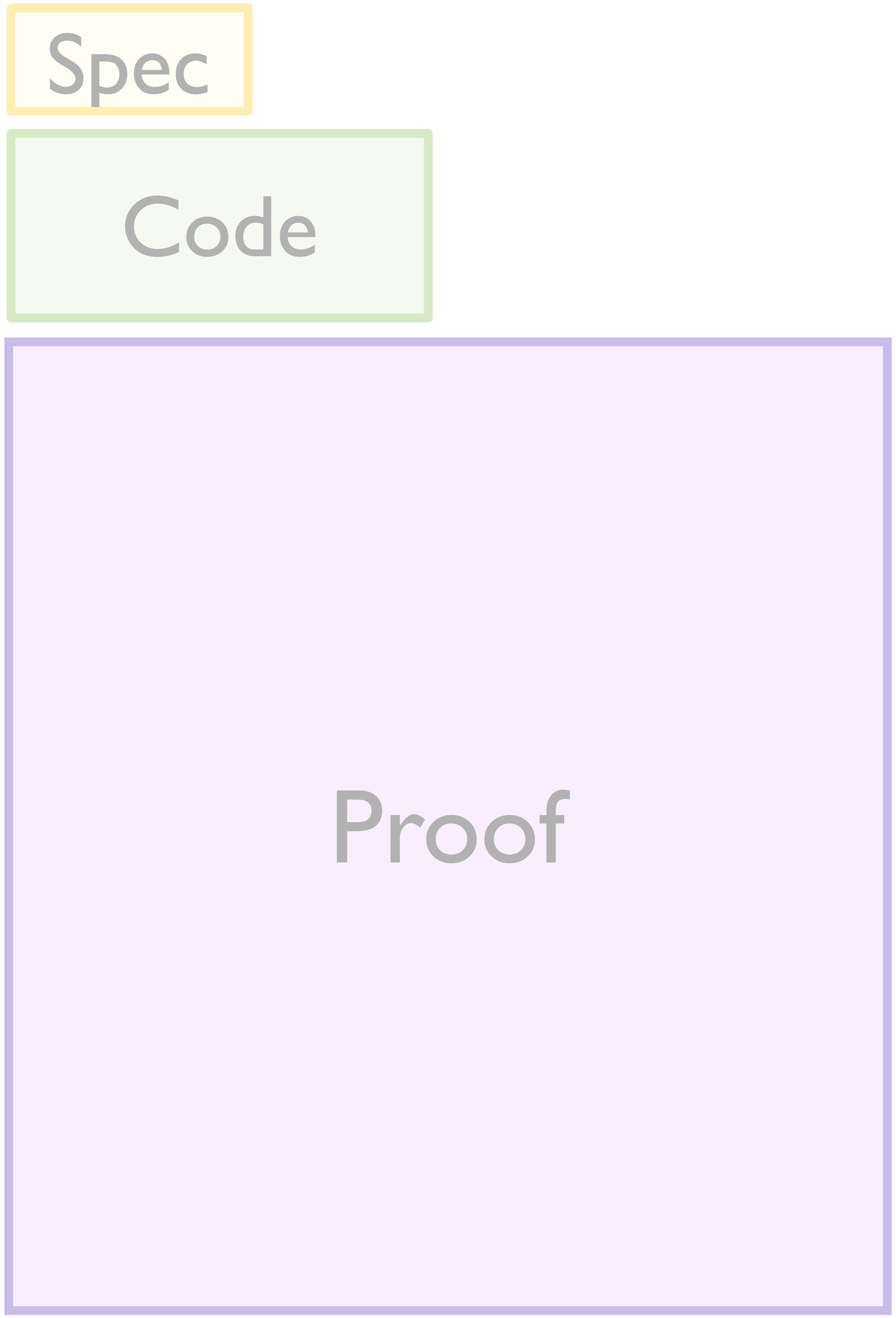
Spec

Code

Proof

Division of Labor

Ideal?

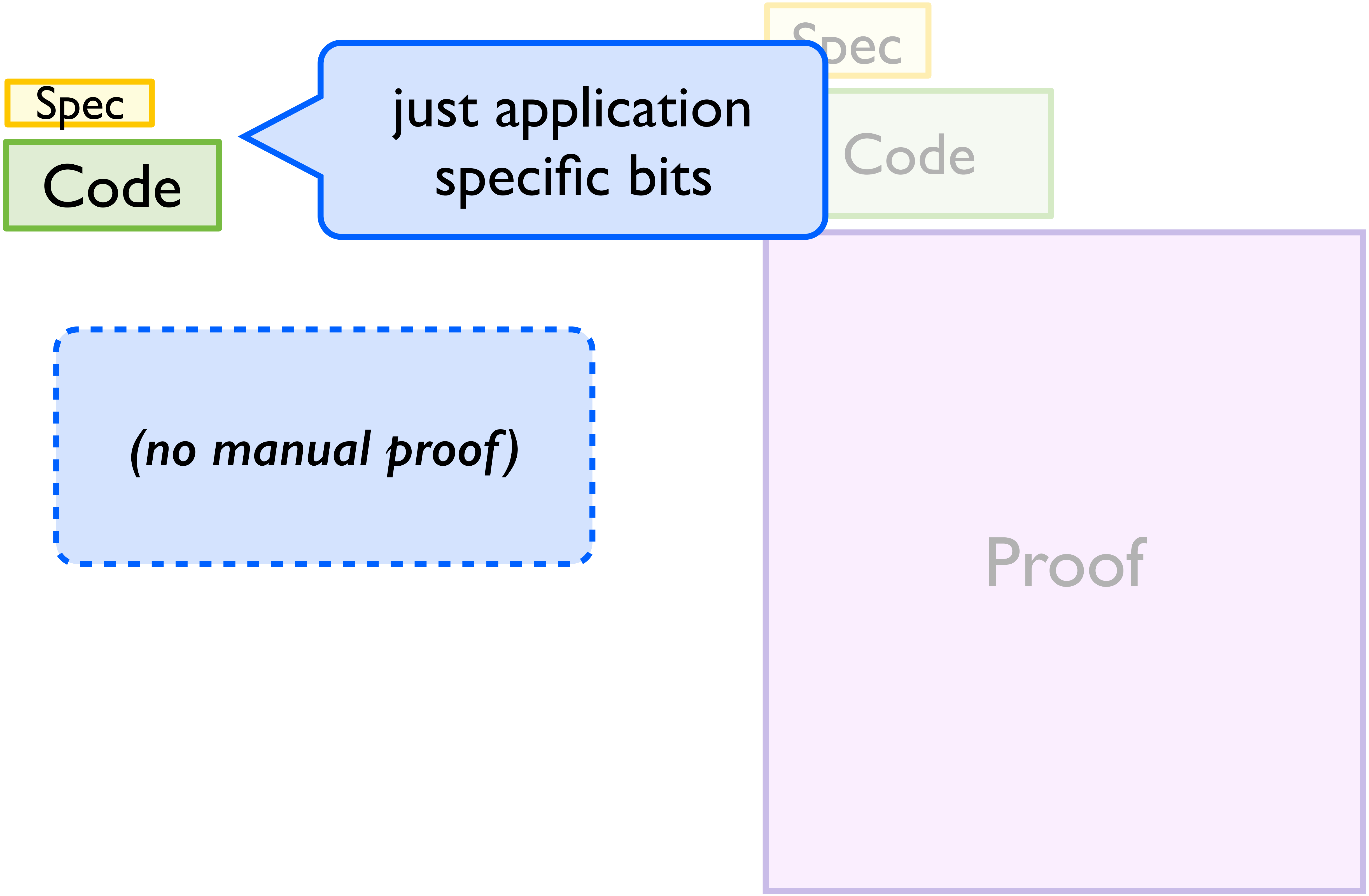


Spec

Code

Proof

Division of Labor



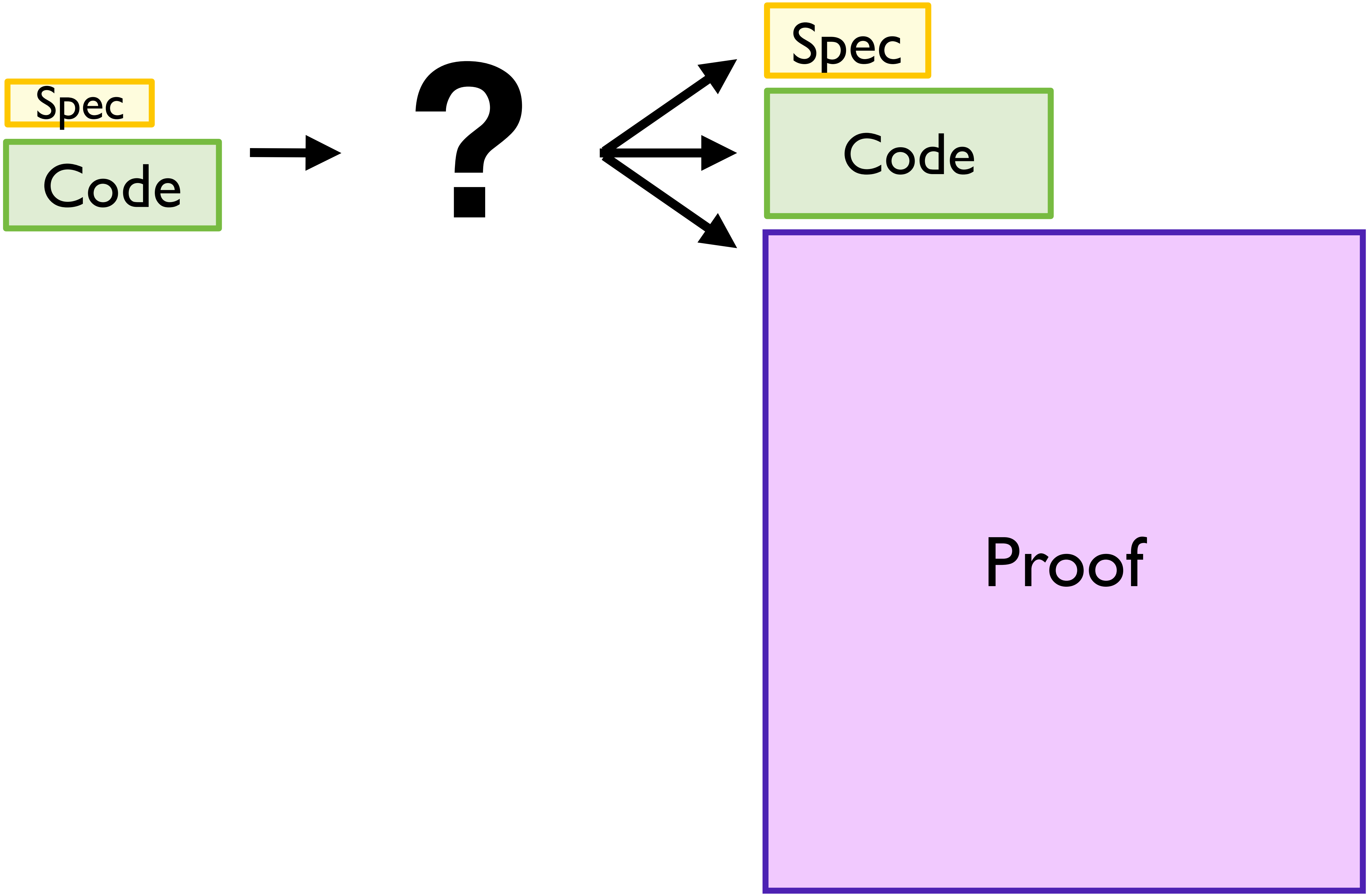
Spec

Code

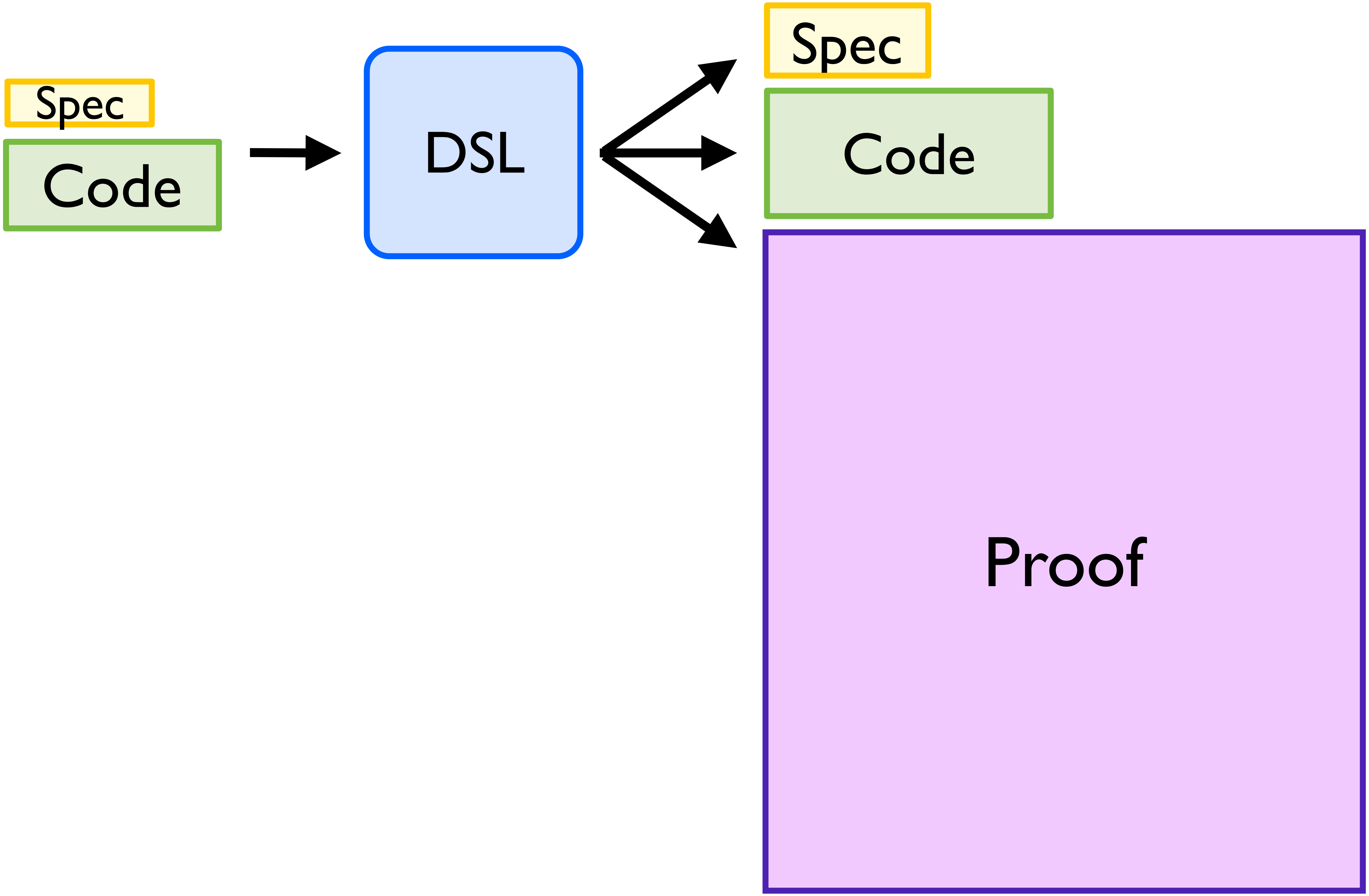
just application specific bits

(no manual proof)

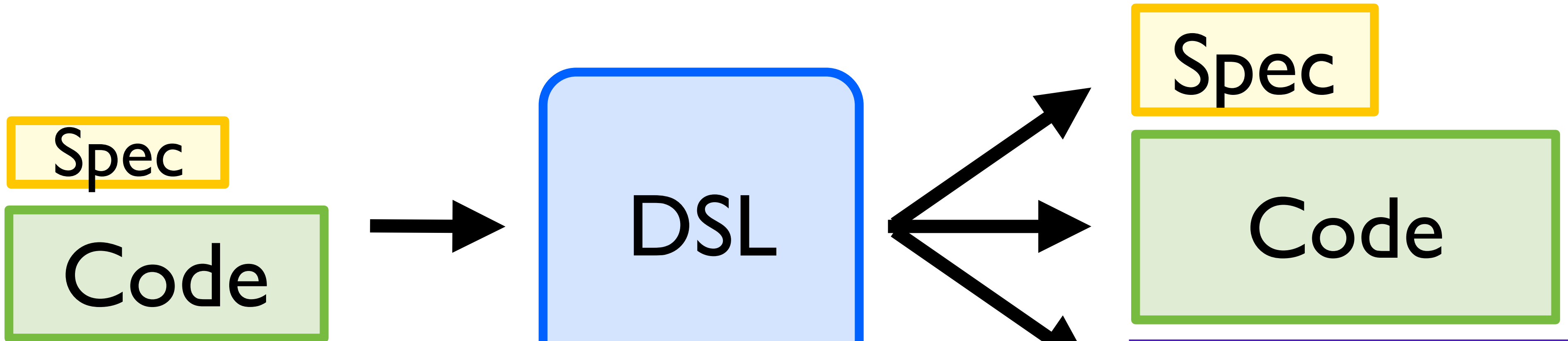
Division of Labor

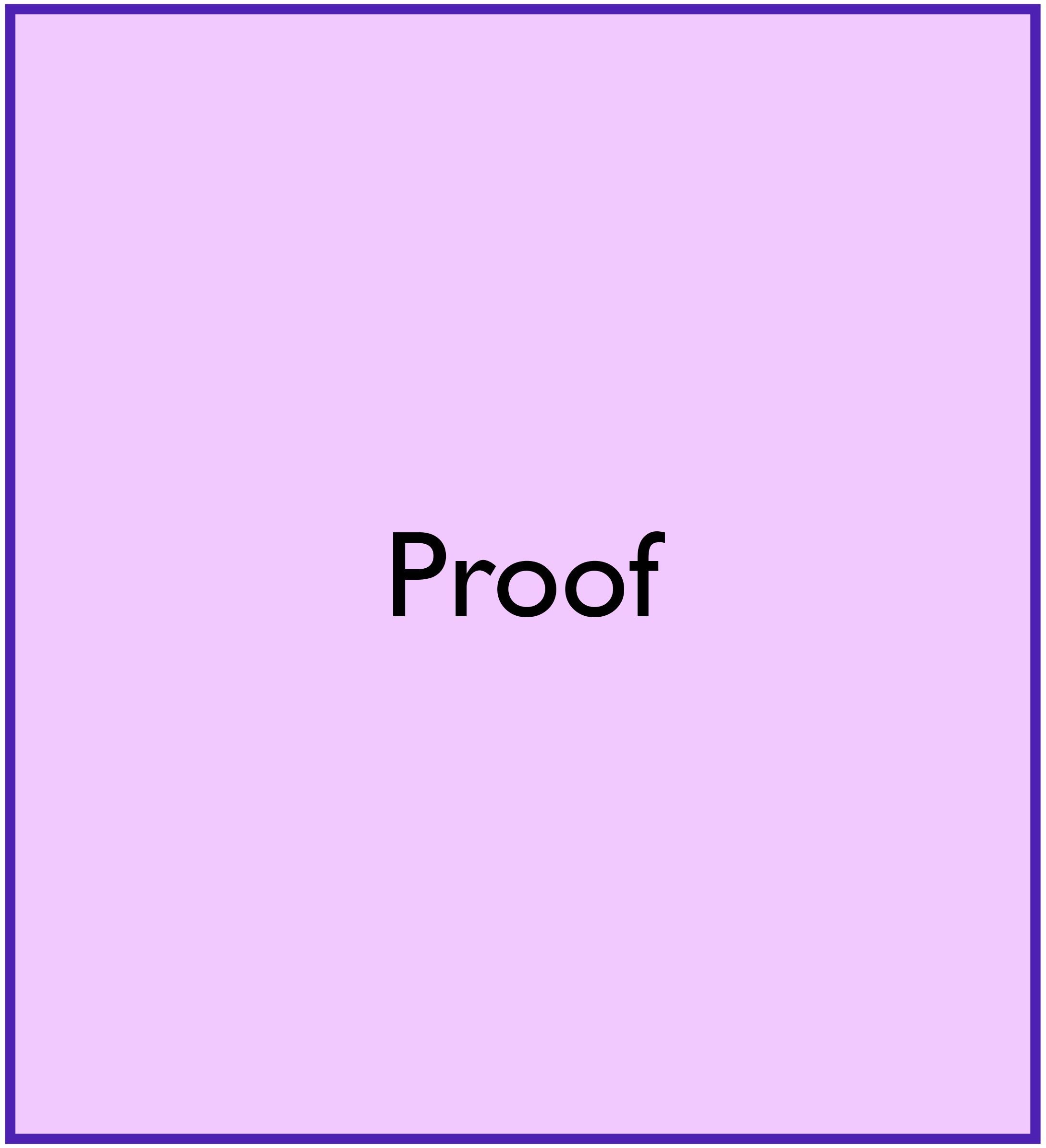


Division of Labor



Division of Labor





Easier to implement, verify, and maintain

Does not demand verification expertise

Reflex: a DSL for Reactive Systems

[PLDI *14*]

Exploit structure of app domain

kernel based archs, well suited to FSV design

```
Components = ...
Messages   = ...
```

e.g. *tabs, cookie managers*

e.g. *GetCookie, MouseClick*

Reflex: a DSL for Reactive Systems

[PLDI *14*]

Exploit structure of app domain

kernel based archs, well suited to FSV design

```
Components = ...
Messages   = ...

Handlers:
  When C sends M:
   ...

  When C′ s
    ...
```

when component **C** sends message **M** ...

... react by:

updating state

accessing resources

sending messages

loop free!

Reflex: a DSL for Reactive Systems

[PLDI 14]

Exploit structure of app domain

kernel based archs, well suited to FSV design

Provide expressive spec language

subset of LTL and non-interference properties

```
forall d c,
  [Recv(Tab(d), CookieSet(c))]
  Enables
  [Send(CookieMgr(d), CookieSet(c))]
```

cookie integrity

Reflex: a DSL for Reactive Systems

[PLDI *14*]

Exploit structure of app domain

kernel based archs, well suited to FSV design

Provide expressive spec language

subset of LTL and non-interference properties

Auto prove user-provided specs

exploit domain, ensure all traces match spec

Counterexample-driven search discovers invariants.

Reflex: a DSL for Reactive Systems

[PLDI 14]

Ex

Reflex Effective:

n

Prototype sshd, browser, httpd

Pr

Specify basic access controls

es

A

Auto prove user-provided specs

c

Reflex: Evaluation

auto prove non-interference

Web browser	Domains do not interfere, Cookie integrity, …
SSH server	No PTY access before authentication, At most 3 authentication attempts, …
Web server	Clients only spawned after successful login, File requests guarded by access control, …

auto prove non-local props

Auto verified 33 properties (80% in < 2 minutes)

Reflex: Development Effort

Reflex :

Many reactive systems

7500 lines of Coq

Web browser	**SSH server**	**Web server**

Quark Web browser :

5500 lines of Coq

Single reactive system

Mitigating the Burden of Proof

1: Scaling proofs to critical infrastructure

Formal shim verification for large apps

QUARK: browser with security guarantees

2: Evolving formally verified systems

⇨ *Reflex DSL exploits domain for proof auto*

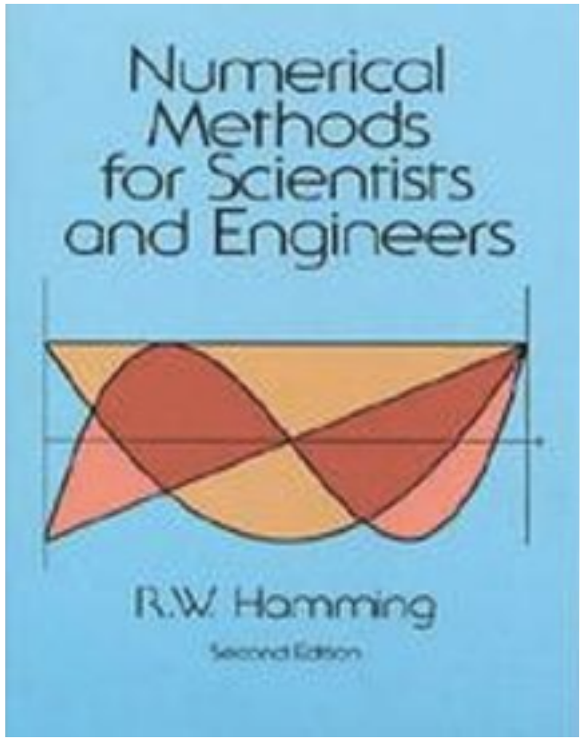
AND NOW FOR
SOMETHING
COMPLETELY
DIFFERENT

Double Trouble

```
x = 0.1 + 0.2;
if (x != 0.3)
  printf(“wat.\n”);
```

$$\frac{(-b)-\sqrt{b^2-4\cdot(a\cdot c)}}{2\cdot a}$$

Futz



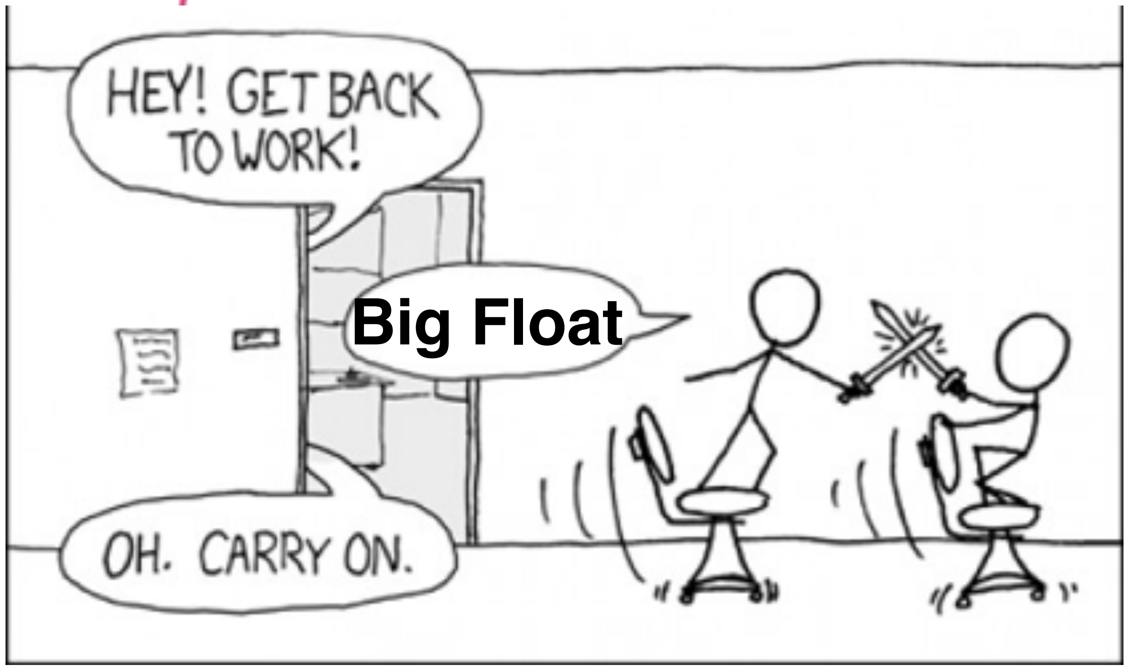
Numerical Methods for Scientists and Engineers

R.W. Hamming

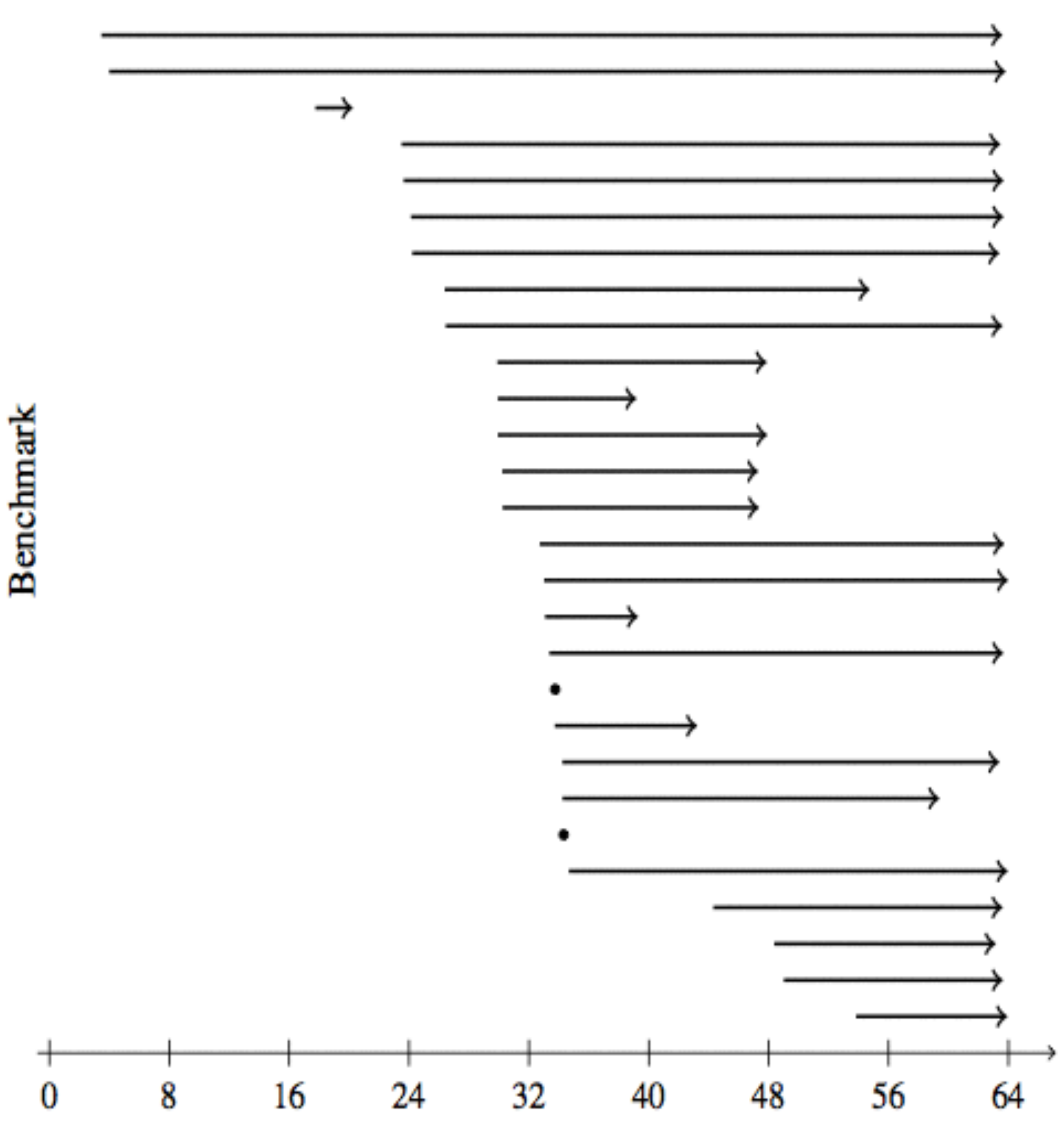
Second Edition

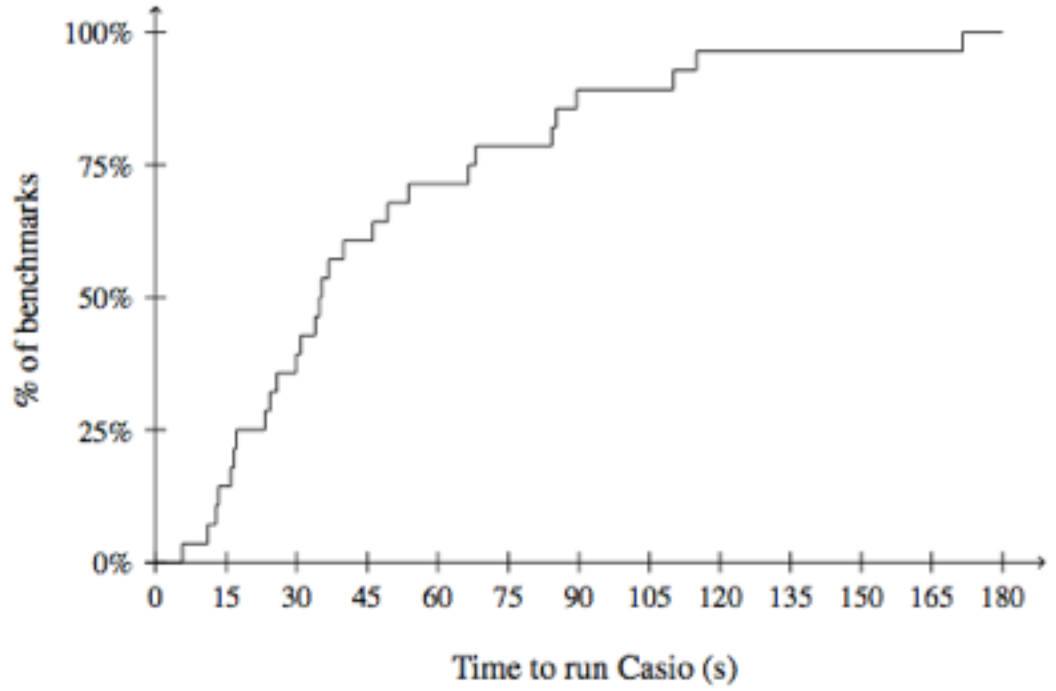
Analyze

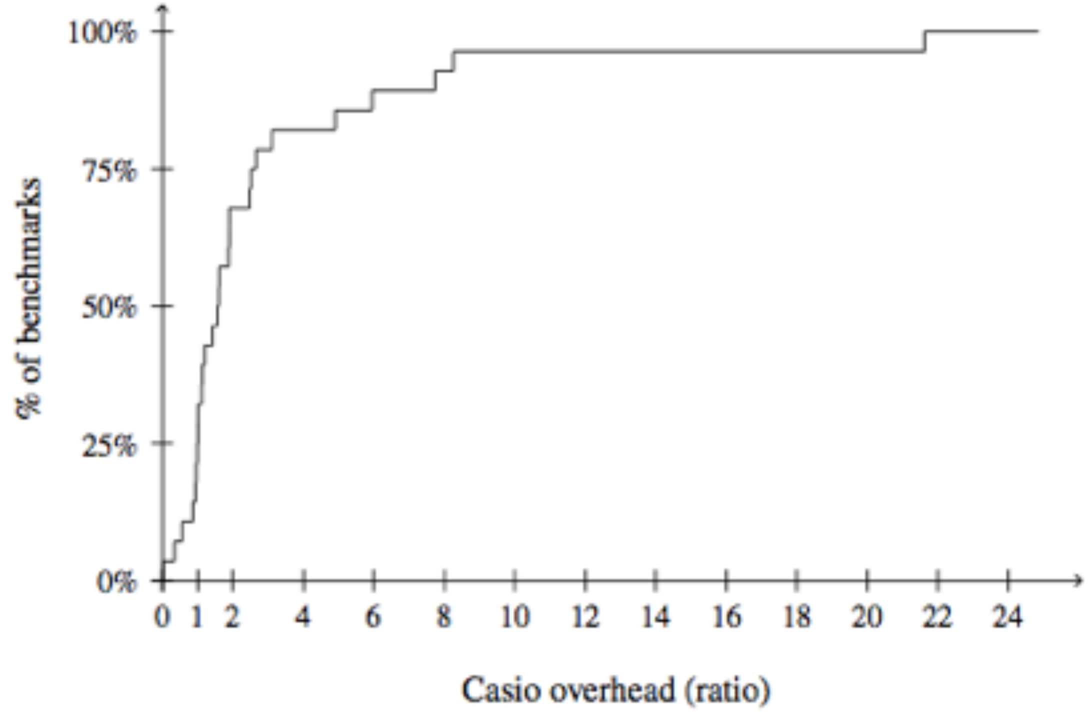
MPFR



Less Double Trouble







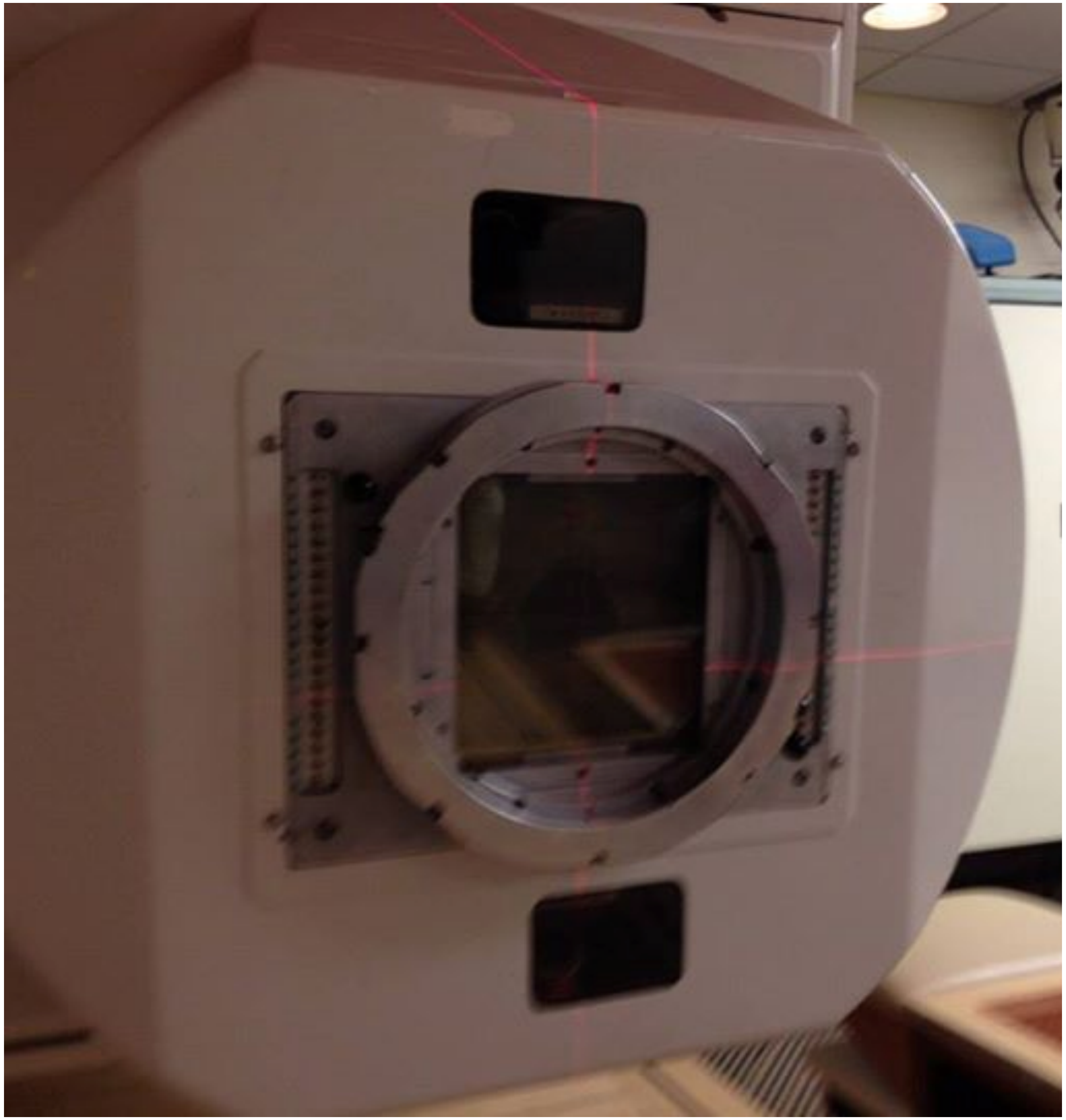
Neutron Beams

UW Medicine
SCHOOL OF MEDICINE

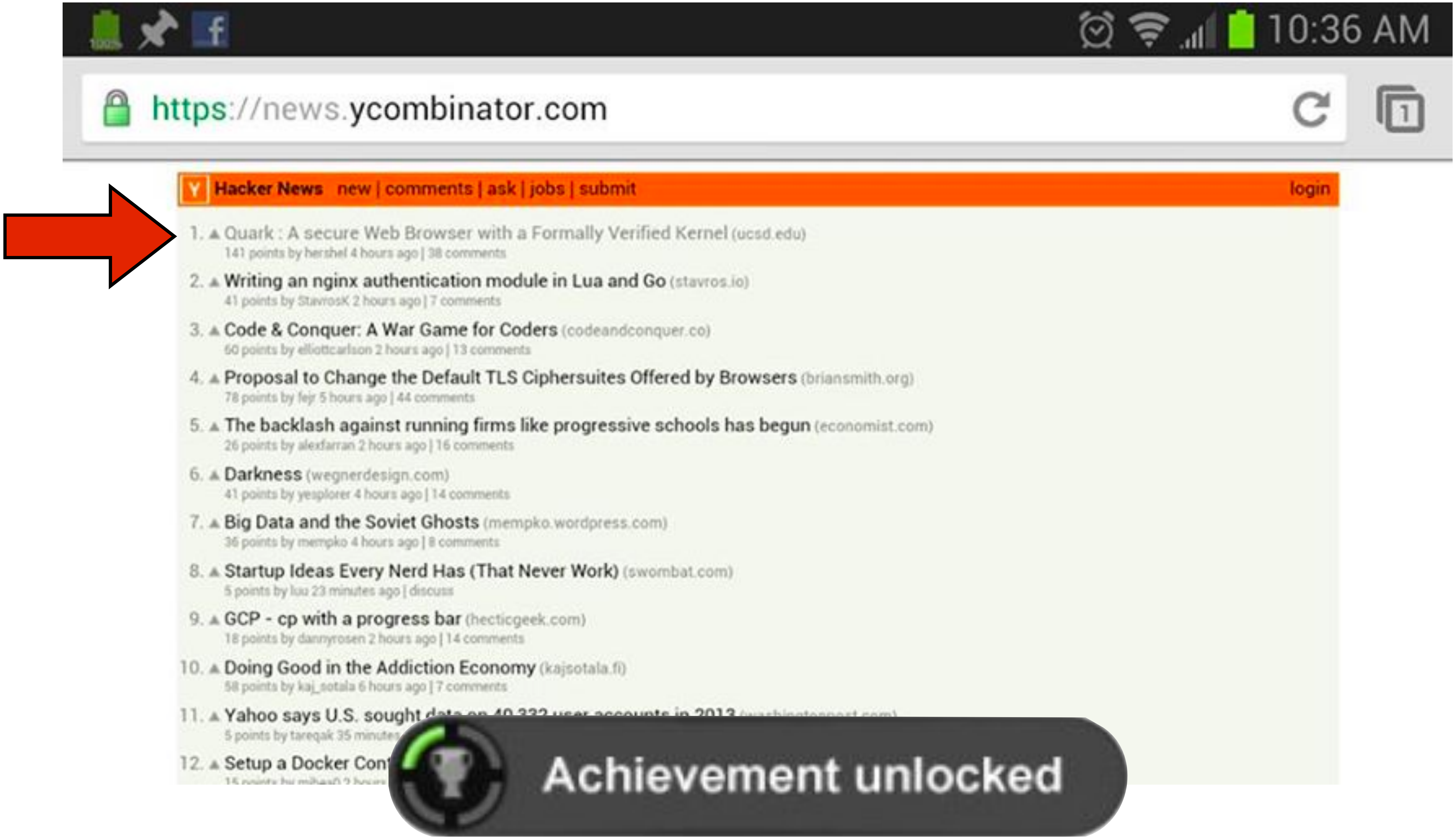
RADIATION AREA
IF YOU NEED ACCESS, SEE ENGINEERING STAFF IN NN143E
CAUTION
RADIOACTIVE MATERIALS
PRE-ACTION SPRINKLER VALVE INSIDE ROOM NN-141B

Neutron Beams

UW Medicine
SCHOOL OF MEDICINE



EPICS


10:36 AM
https://news.ycombinator.com
Y
Hacker News new | comments | ask | jobs | submit
login
Achievement unlocked

1. ▲ Quark : A secure Web Browser with a Formally Verified Kernel (ucsd.edu)
141 points by hershel 4 hours ago | 38 comments

2. ▲ Writing an nginx authentication module in Lua and Go (stavros.io)
41 points by StavrosK 2 hours ago | 7 comments

3. ▲ Code & Conquer: A War Game for Coders (codeandconquer.co)
60 points by elliottcarlson 2 hours ago | 13 comments

4. ▲ Proposal to Change the Default TLS Ciphersuites Offered by Browsers (briansmith.org)
78 points by fejr 5 hours ago | 44 comments

5. ▲ The backlash against running firms like progressive schools has begun (economist.com)
26 points by alexfarran 2 hours ago | 16 comments

6. ▲ Darkness (wegnerdesign.com)
41 points by yesplorer 4 hours ago | 14 comments

7. ▲ Big Data and the Soviet Ghosts (mempko.wordpress.com)
36 points by mempko 4 hours ago | 8 comments

8. ▲ Startup Ideas Every Nerd Has (That Never Work) (swombat.com)
5 points by luu 23 minutes ago | discuss

9. ▲ GCP - cp with a progress bar (hecticgeek.com)
18 points by dannyrosen 2 hours ago | 14 comments

10. ▲ Doing Good in the Addiction Economy (kajsotala.fi)
58 points by kaj_sotala 6 hours ago | 7 comments

11. ▲ Yahoo says U.S. sought data on 40,332 user accounts in 2013 (washingtonpost.com)
5 points by tareqak 35 minutes

12. ▲ Setup a Docker Con
15 points by mihea0 2 hours

Notkinfest
Notkinfest

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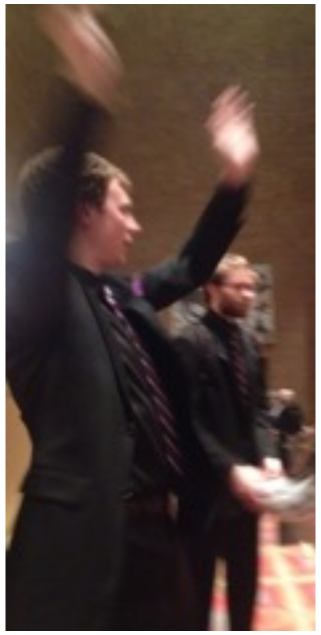
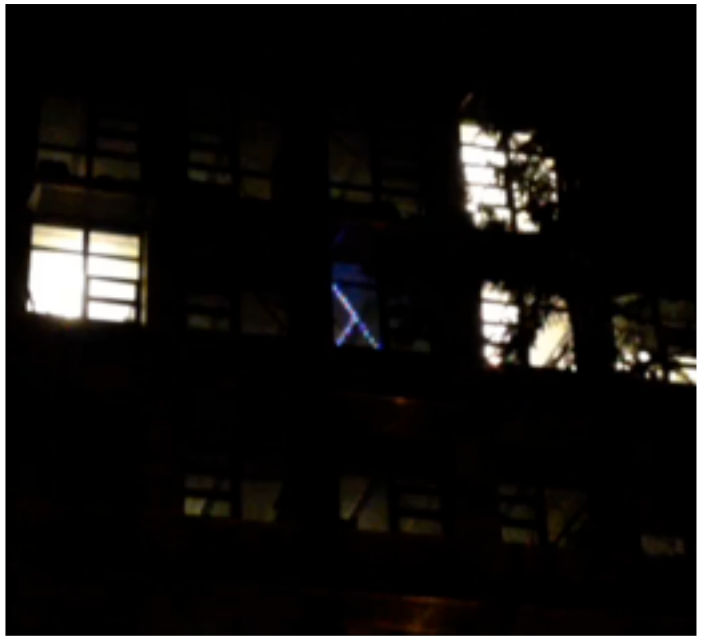
MONAD





Thank You!

Goal: mitigate formality inertia

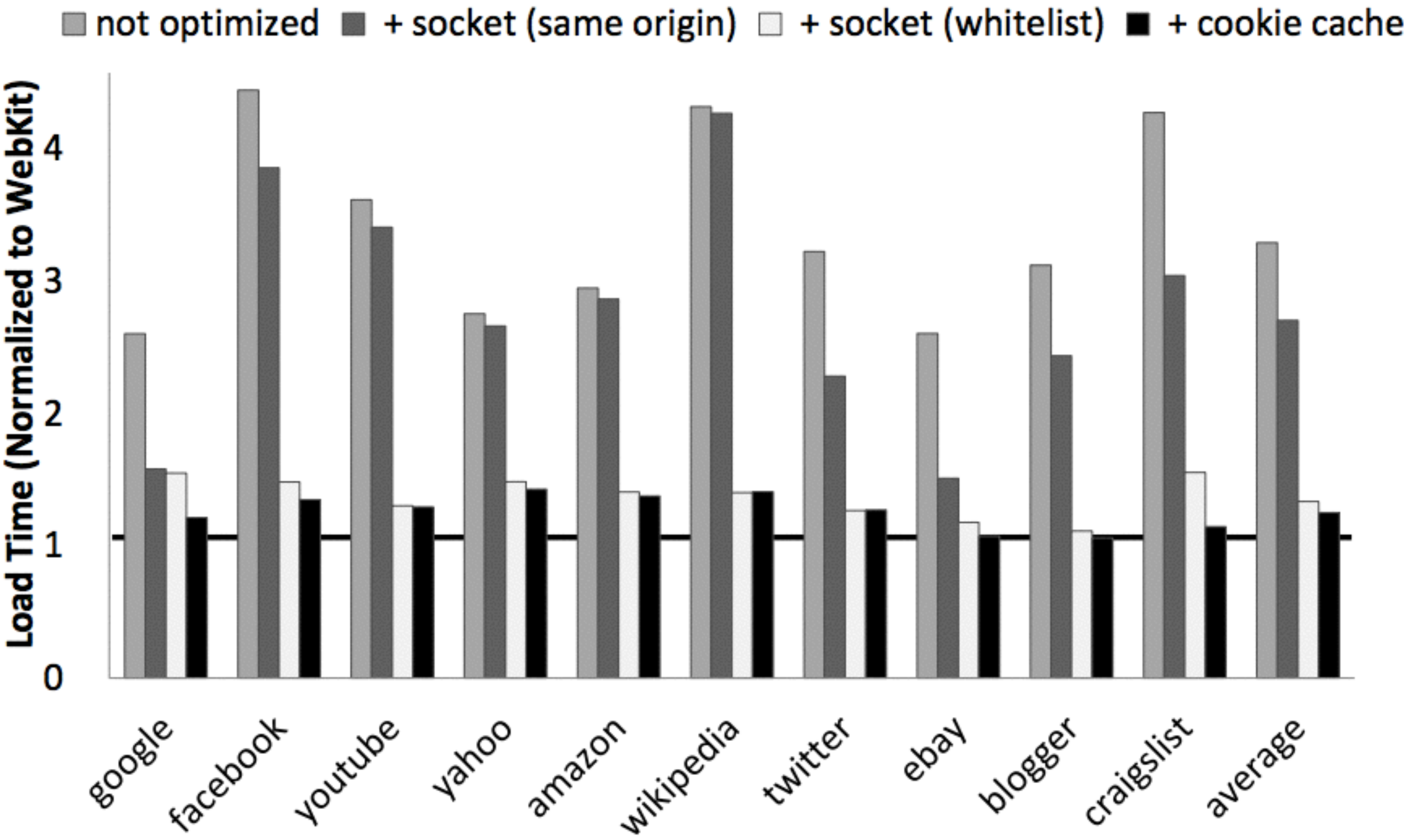
address scaling and evolving formally verified systems

1. Extend verification frontier

develop techniques to verify critical "pinch points"

2. Make verification accessible

equip domain experts with effective tools


not optimized
+ socket (same origin)
+ socket (whitelist)
+ cookie cache
Load Time (Normalized to WebKit)
0
1
2
3
4
google
facebook
youtube
yahoo
amazon
wikipedia
twitter
ebay
blogger
craigslist
average

Verifying Optimizations

Rich compiler correctness history:

McCarthy 67, Samet 75, Cousot 77, …

Already solved?

Compiler	*Bugs Found*
GCC	122
LLVM	181
CompCert	0

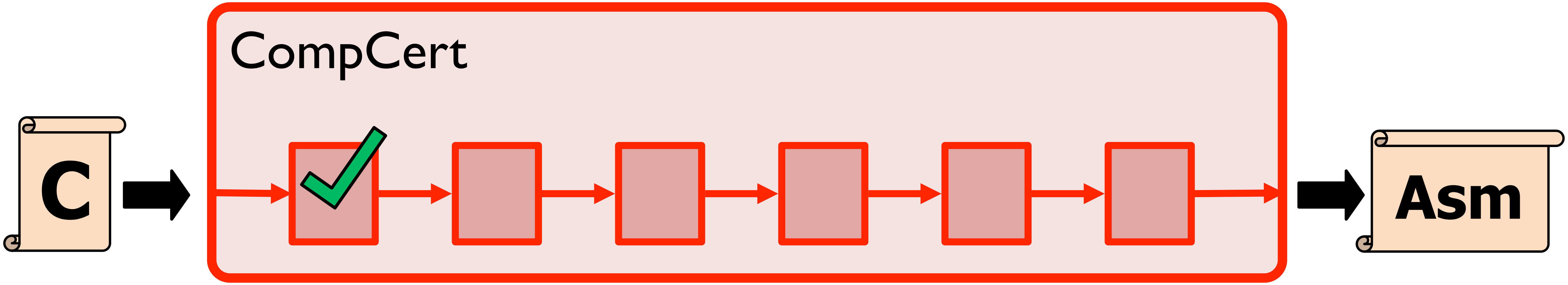
[*Yang et al. PLDI 11*]

many optimization bugs

lacks many optimizations

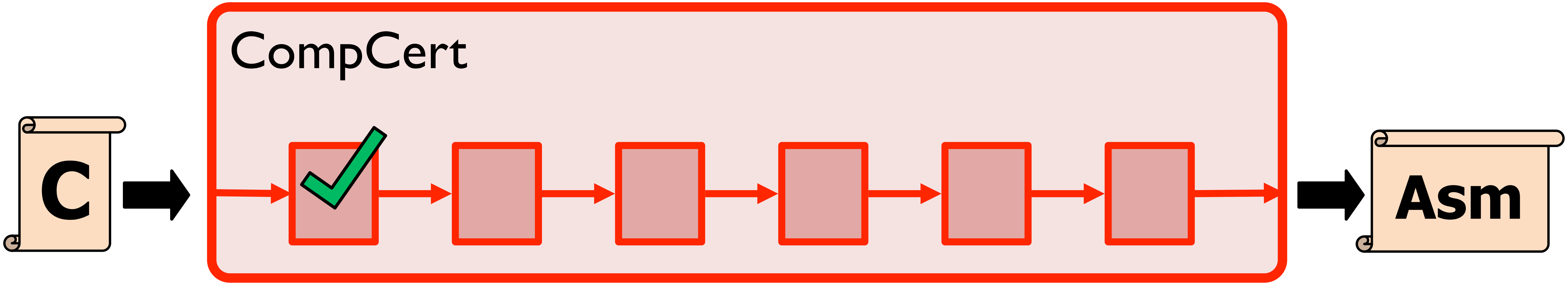
Verifying Optimizations

Verifying Optimizations



Verifying Optimizations

✓ = Proof original and opt code equivalent.

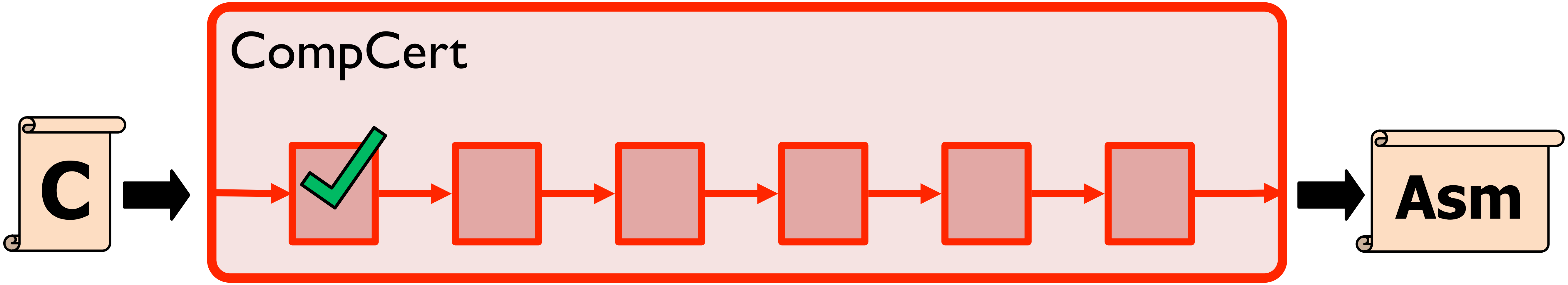


Verifying Optimizations

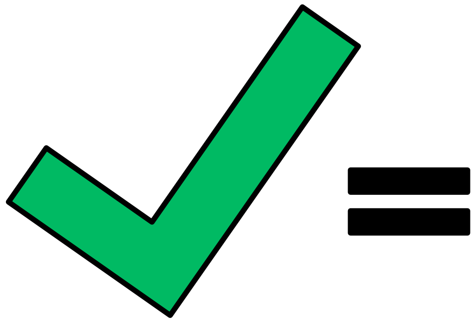
✓ =

Proof original and opt code equivalent.

Construct *bisimulation relation:*



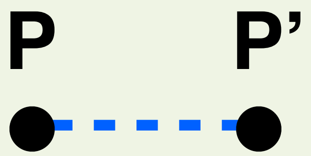
Verifying Optimizations

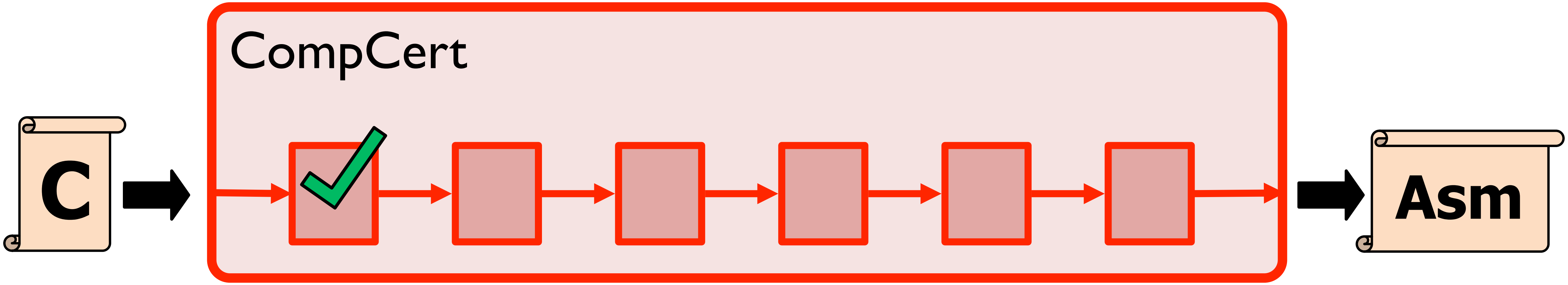


Proof original and opt code equivalent.

Constru *ation:*

if orig and opt in equal states



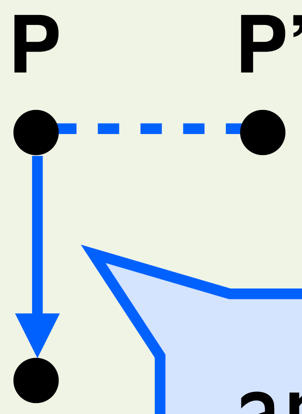


Verifying Optimizations

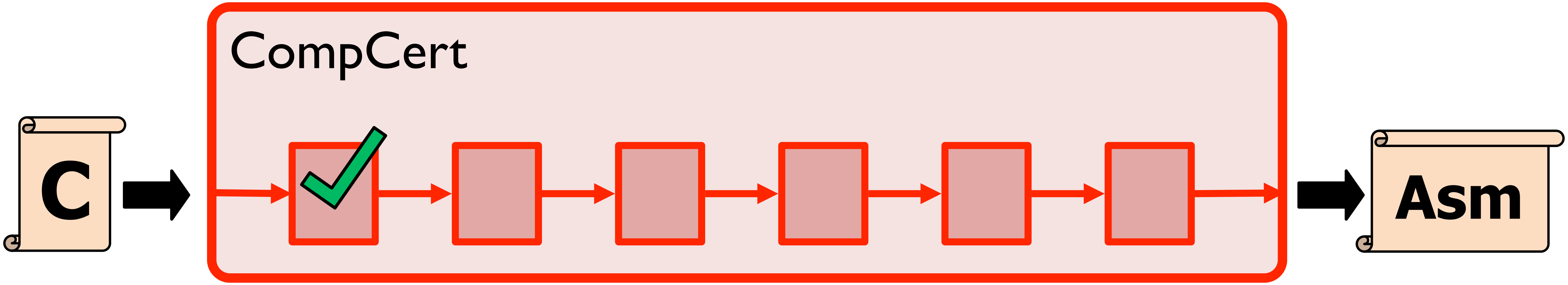
Proof original and opt code equivalent.

Constru *ation:*

if orig and opt in equal states



and orig prog can take some action

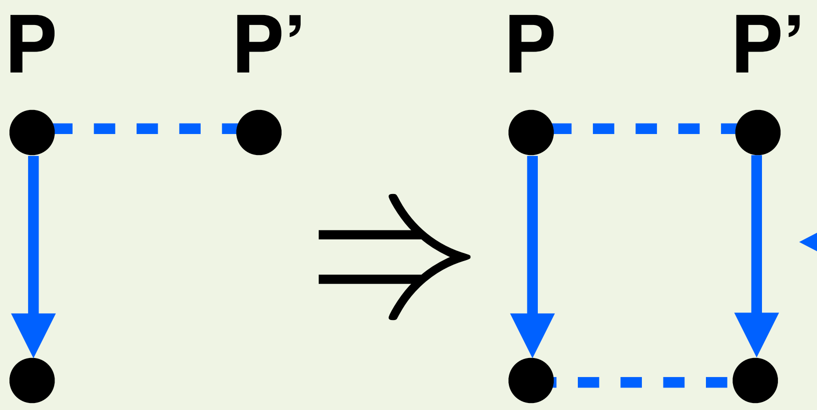


Verifying Optimizations

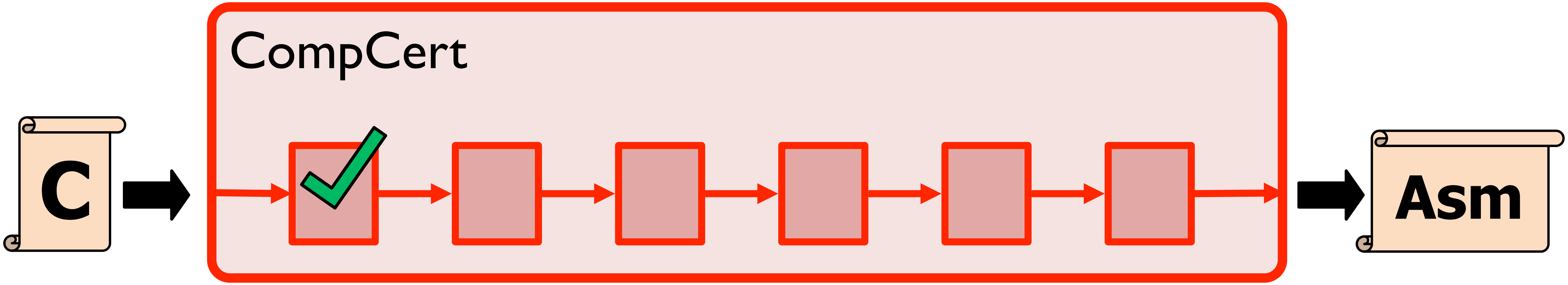
✓ =

Proof original and opt code equivalent.

Construct *bisimulation relation:*



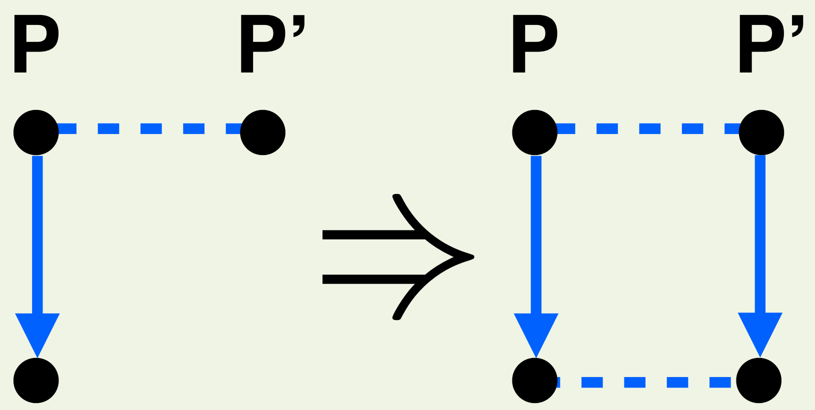
then opt prog can take same action to another equal state



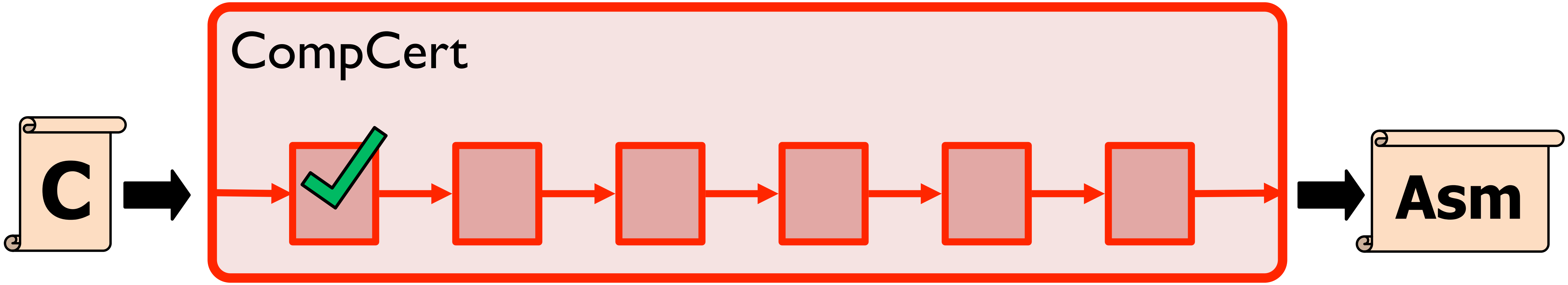
Verifying Optimizations

Proof original and opt code equivalent.

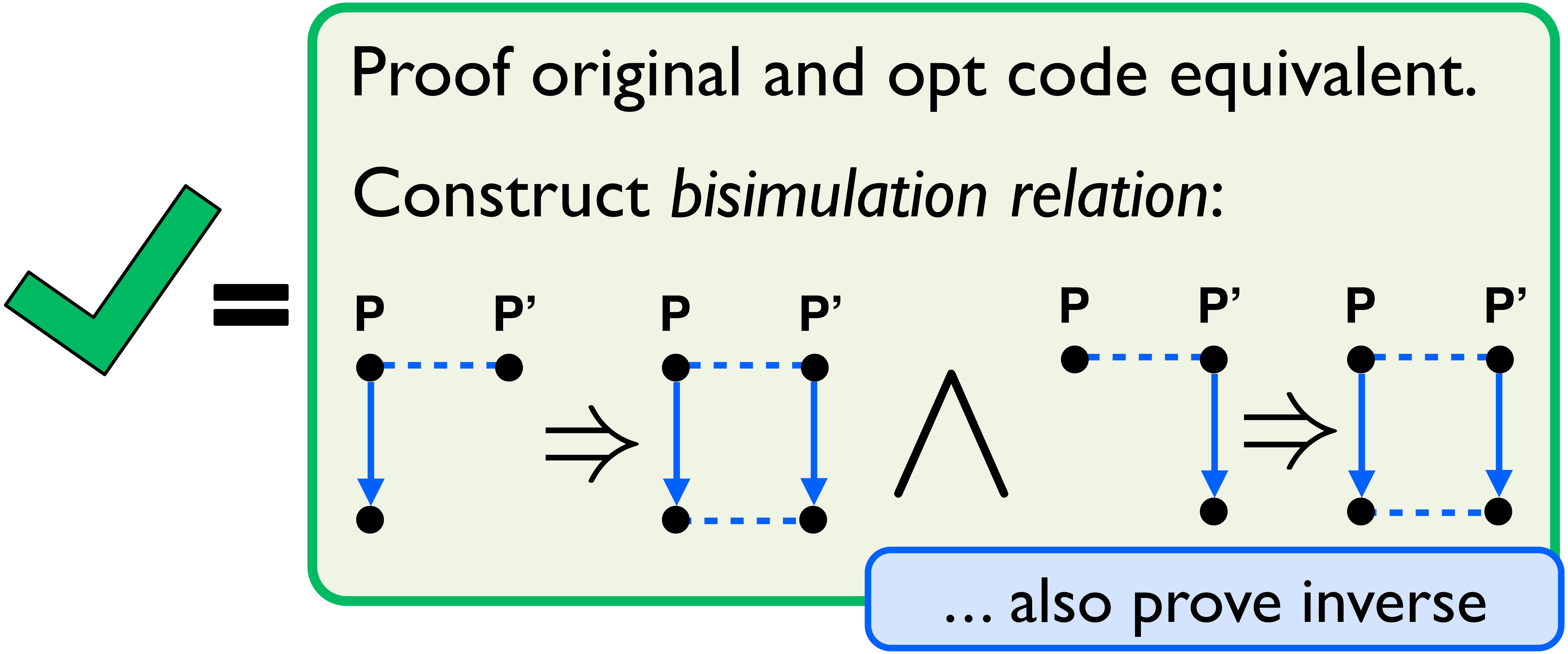
Construct *bisimulation relation*:



implies: *anything orig can do, opt can do too*



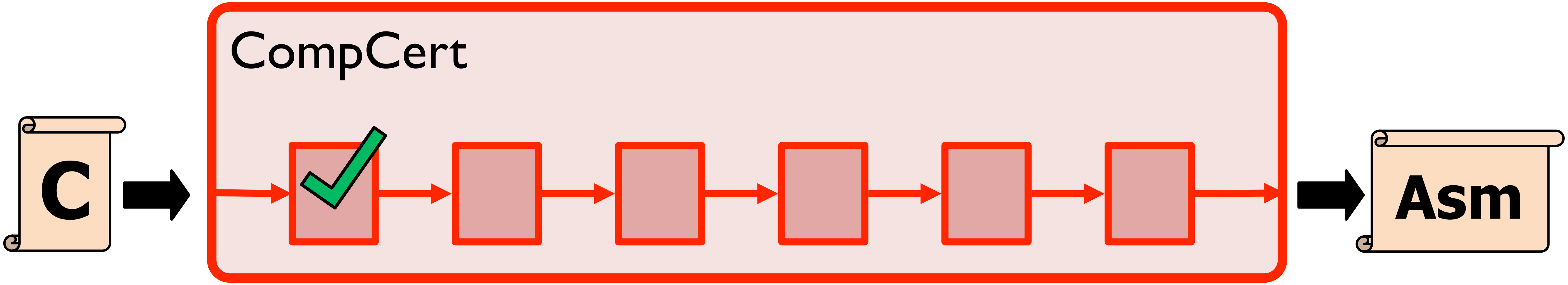
Verifying Optimizations



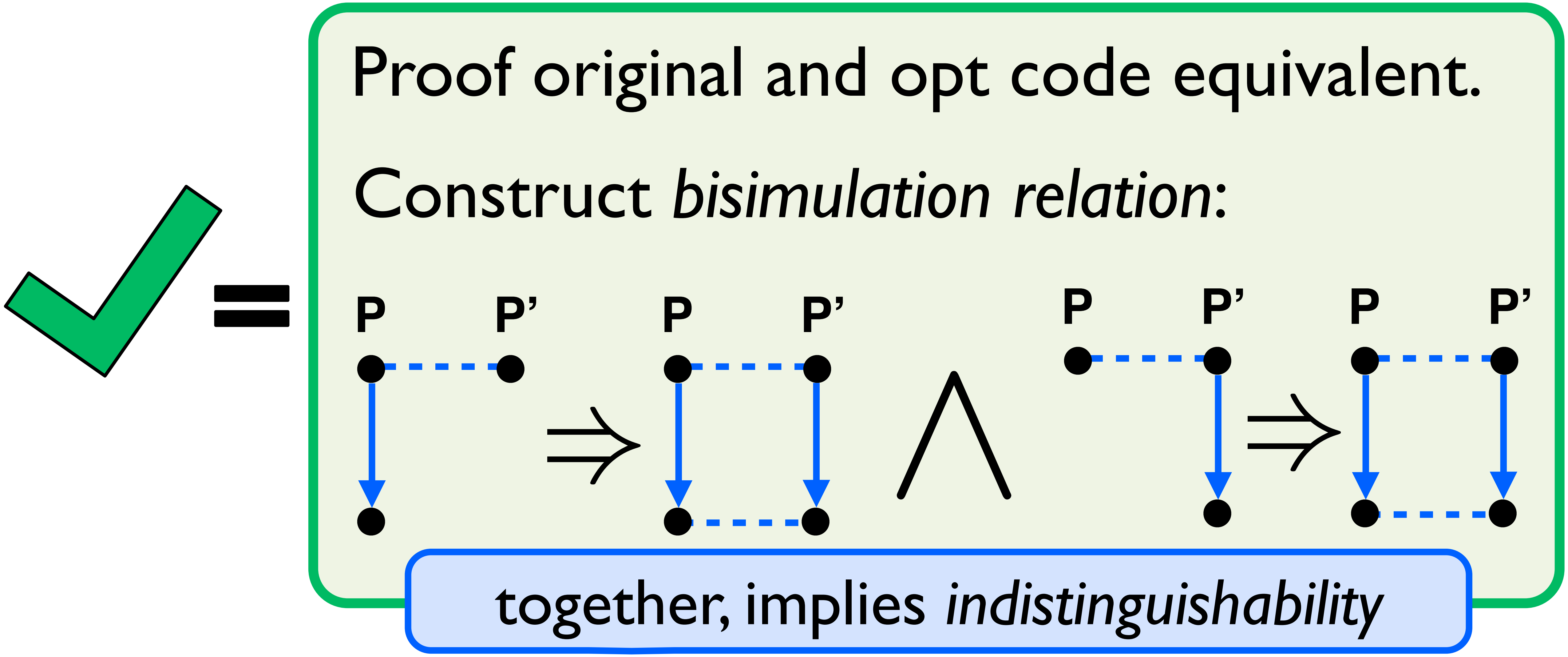
Proof original and opt code equivalent.

Construct *bisimulation relation:*

… also prove inverse



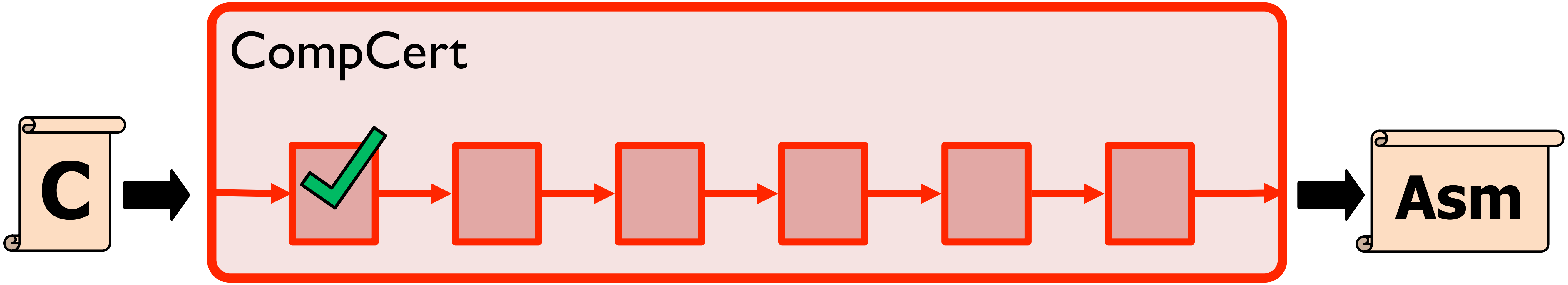
Verifying Optimizations



Proof original and opt code equivalent.

Construct *bisimulation relation*:

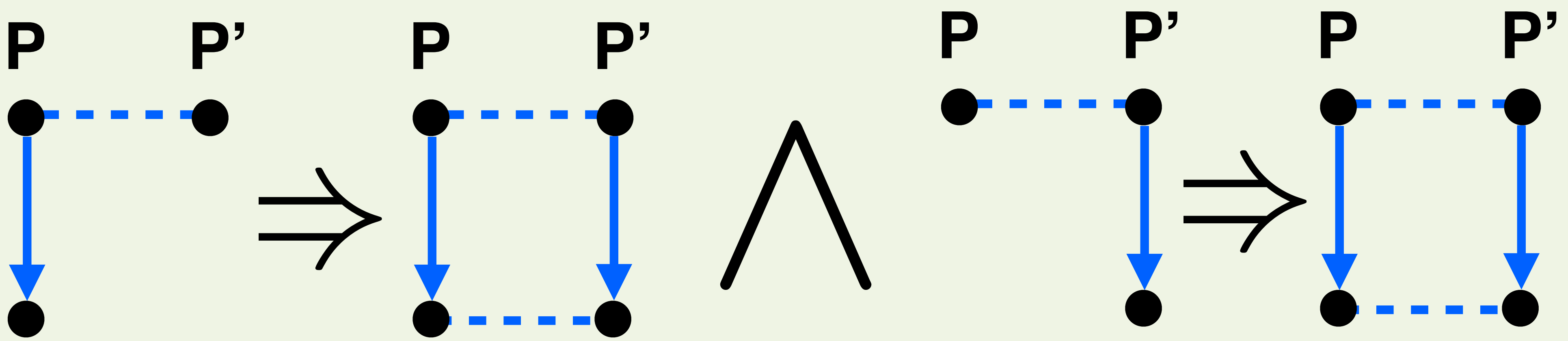
together, implies *indistinguishability*

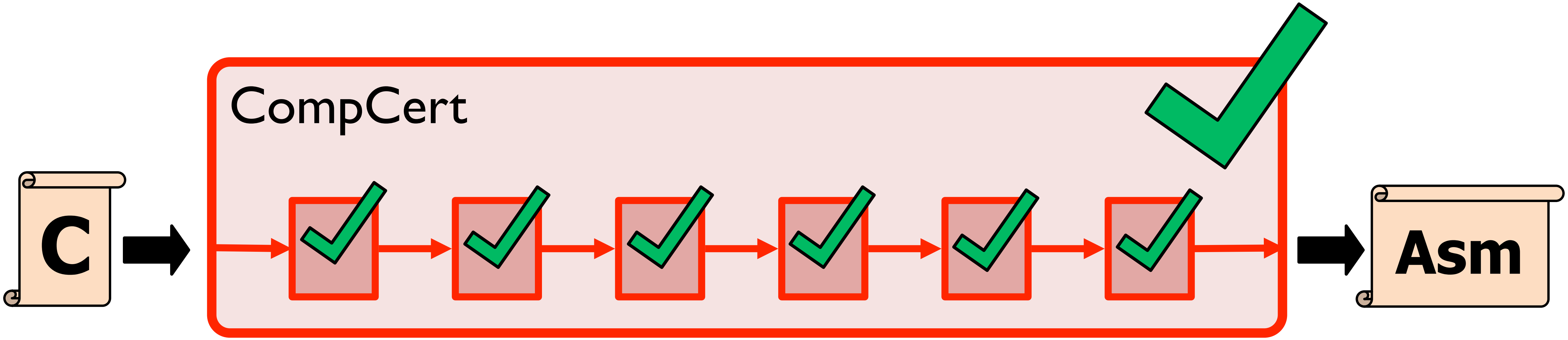


Verifying Optimizations

Proof original and opt code equivalent.

Construct *bisimulation relation*:



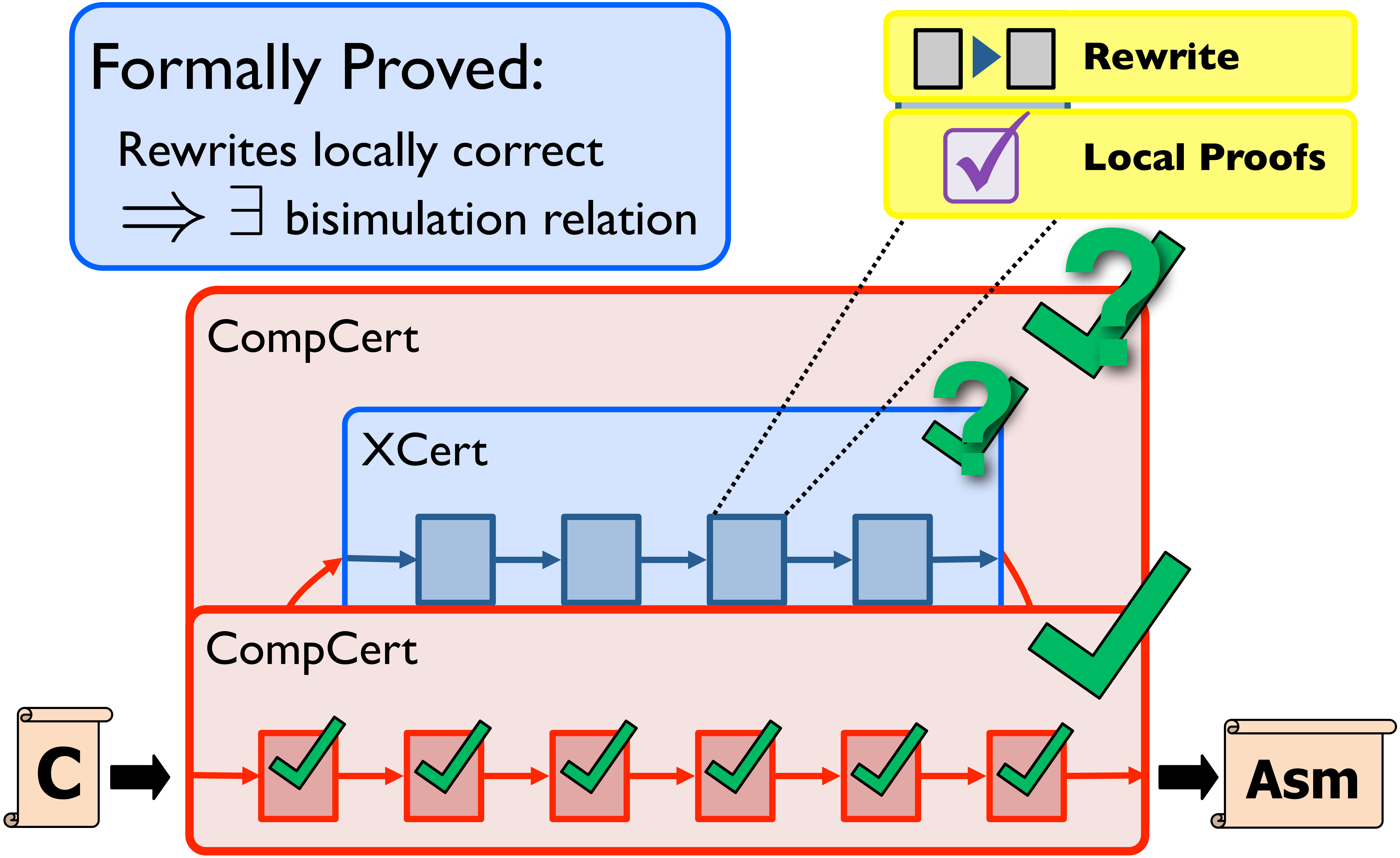


Verifying Optimizations

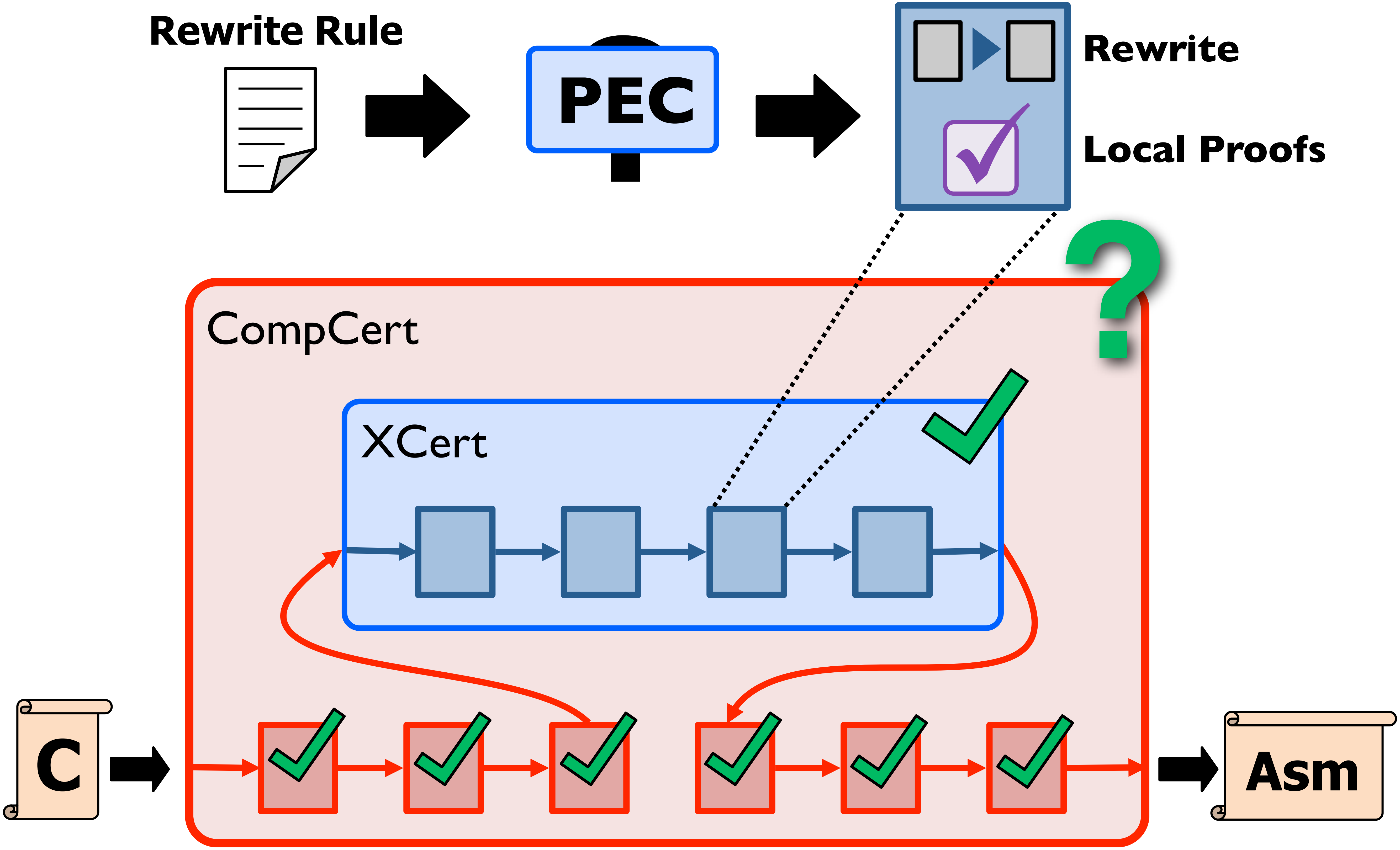
Formally Proved:

Rewrites locally correct

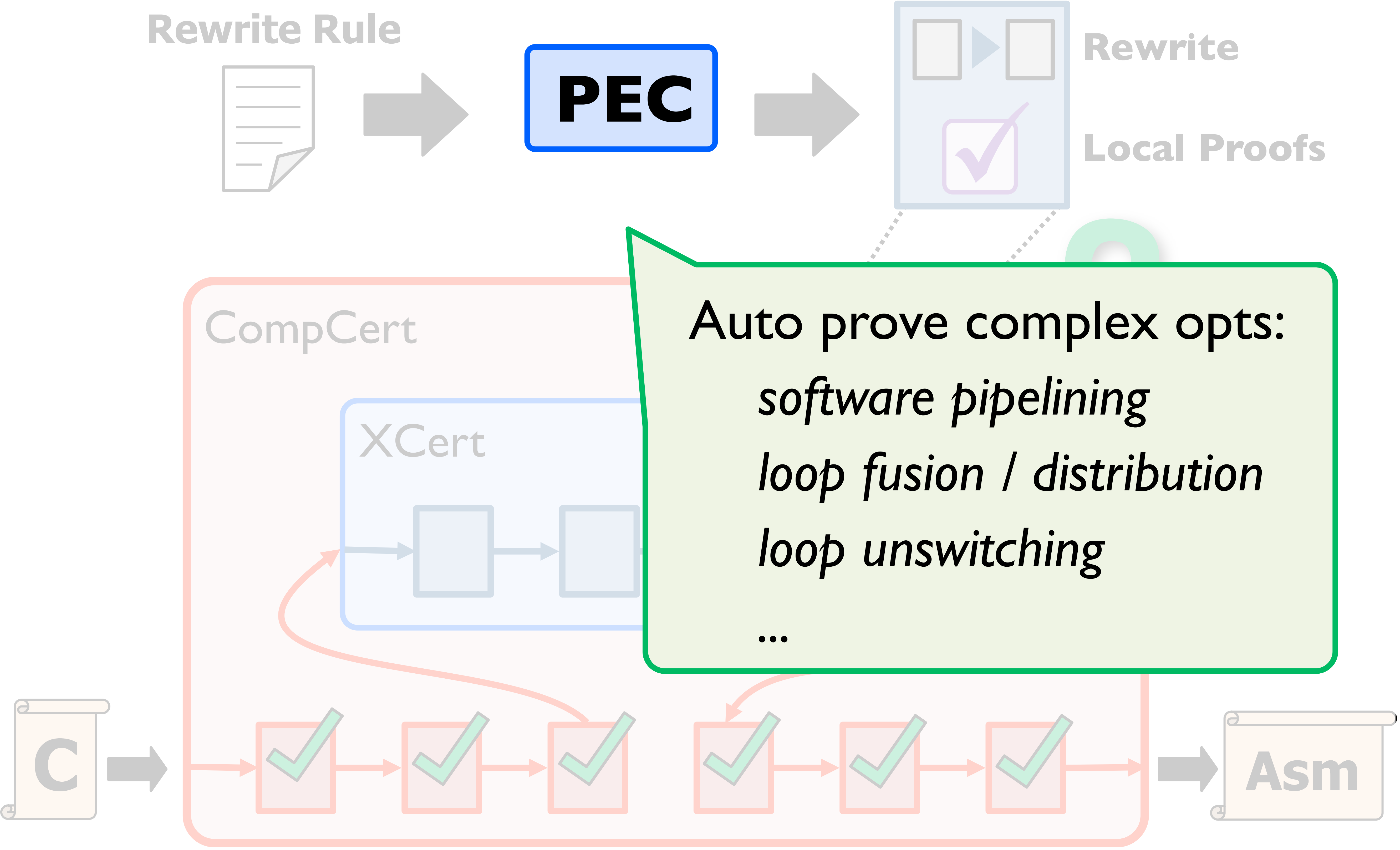
$\Longrightarrow \exists$ bisimulation relation



Verifying Optimizations



Verifying Optimizations



Auto prove complex opts:

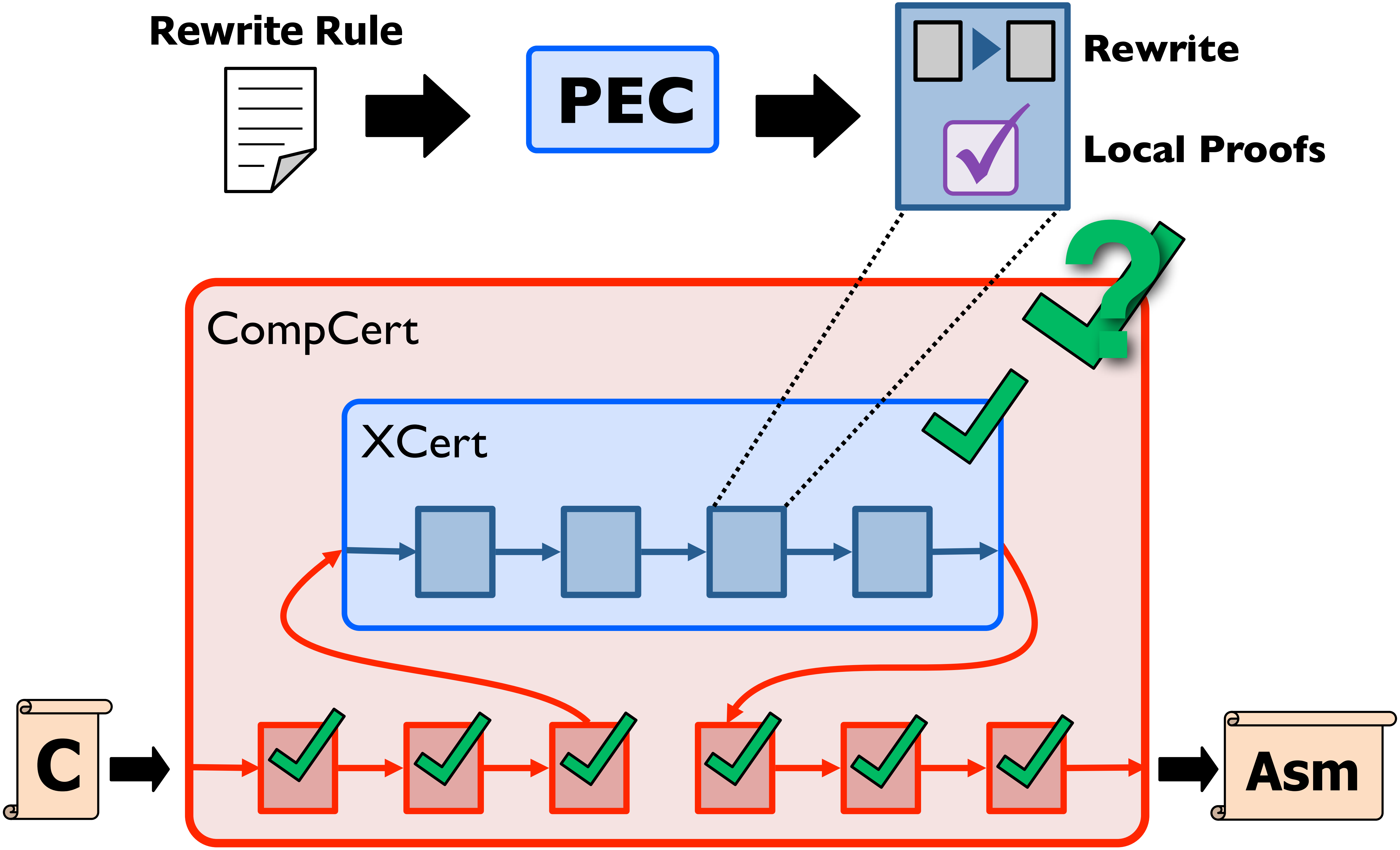
software pipelining

loop fusion / distribution

loop unswitching

...

Verifying Optimizations



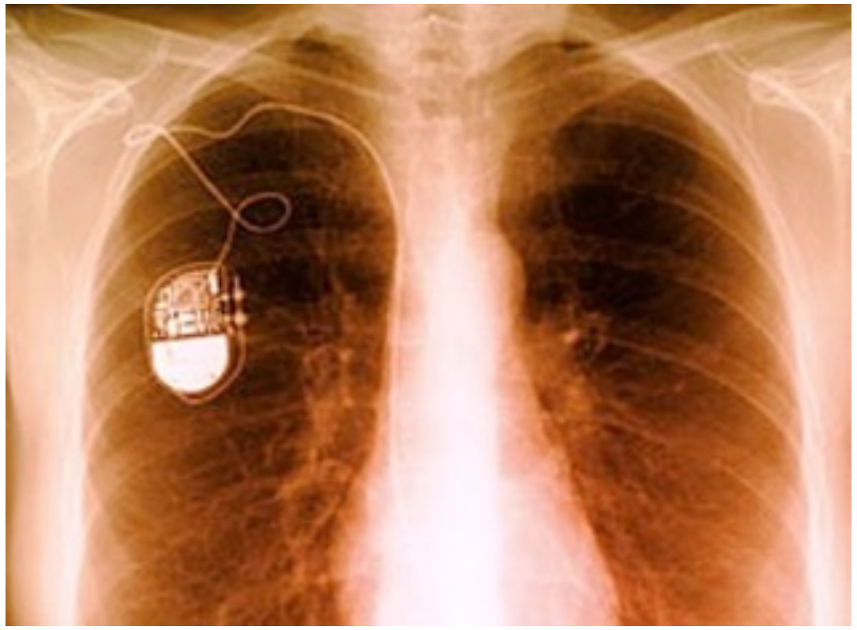
Future Work

Generating and evaluating specs

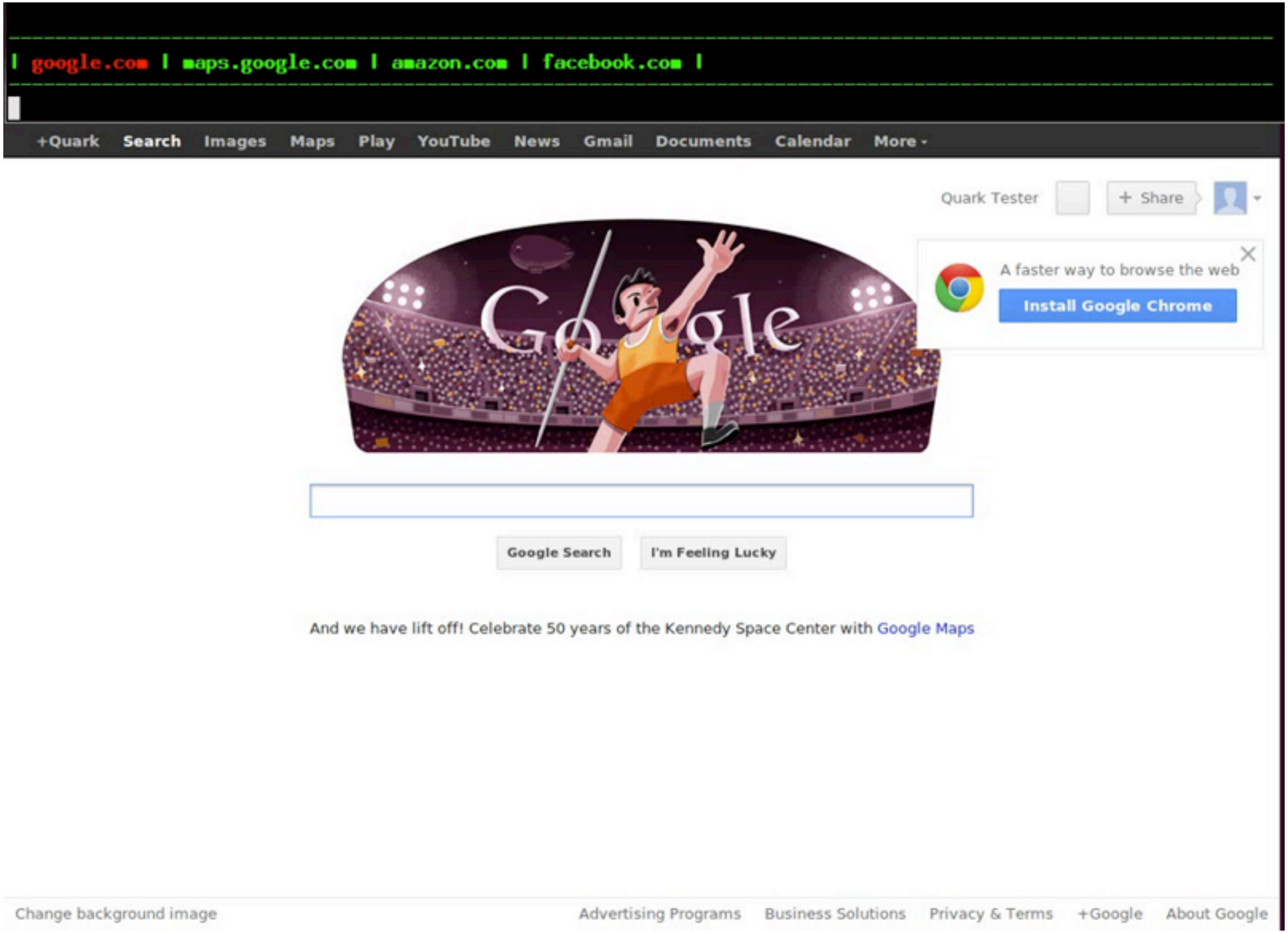
techniques to ensure spec matches intuition

> *Even perfect program verification can only establish that a program meets its specification... Much of the essence of building a program is in fact the debugging of the specification.*
>
> **Frederick P. Brooks, Jr.**
> *No Silver Bullet*

Software Infrastructure



Quark Usability



```
| google.com | maps.google.com | amazon.com | facebook.com |
```

And we have lift off! Celebrate 50 years of the Kennedy Space Center with Google Maps

Browsers: Critical Infrastructure

Browsers: Critical Infrastructure

Browsers: Critical Infrastructure

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VISA

WELLS FARGO

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Conference Submissions