Browser Security Guarantees through Formal Shim Verification

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Browsers: Critical Infrastructure

Ubiquitous:

many platforms, sensitive apps

Vulnerable:

Pwn2Own, just a click to exploit

Reactive Defenses:

many ad hoc, bug triage, regressions

Fully Formal Verification

Code in language that eases reasoning

Develop correctness proof in synch

Fully formal, *machine checkable* proof

Fully Formal Verification

Success story: CompCert C compiler

Compiler	*Bugs Found*
GCC	122
LLVM	181
CompCert	**0**

[Yang et al. PLDI 11]

OS (seL4), RDBMS & HTTPD (YNot)

realistic implementations guaranteed bug free

Fully Formal Verification

The Catch

Throw away all your code

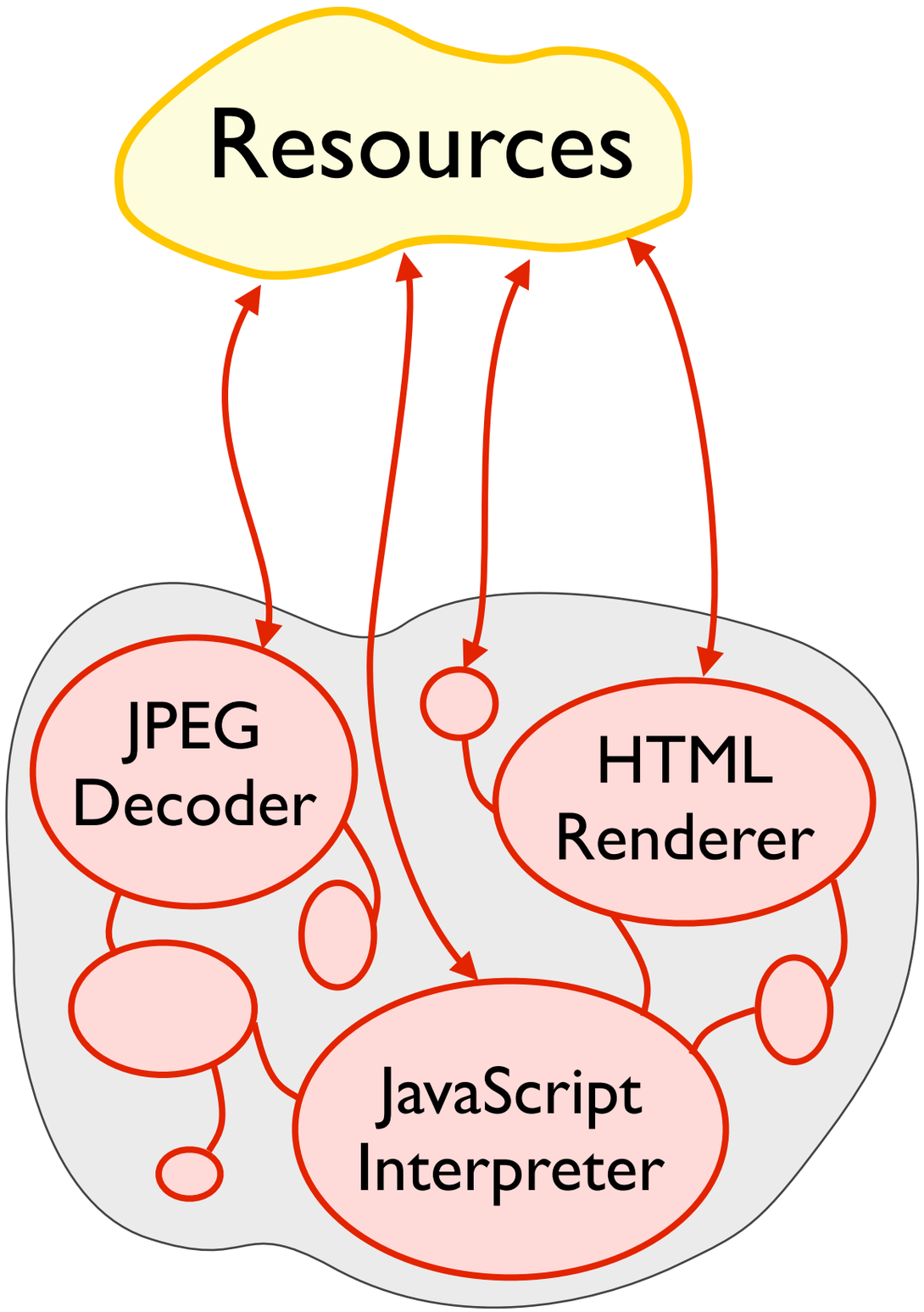
Rewrite in unfamiliar language

Formally specify correctness

Prove every detail correct

Heroic effort

Formally Verify a Browser?!



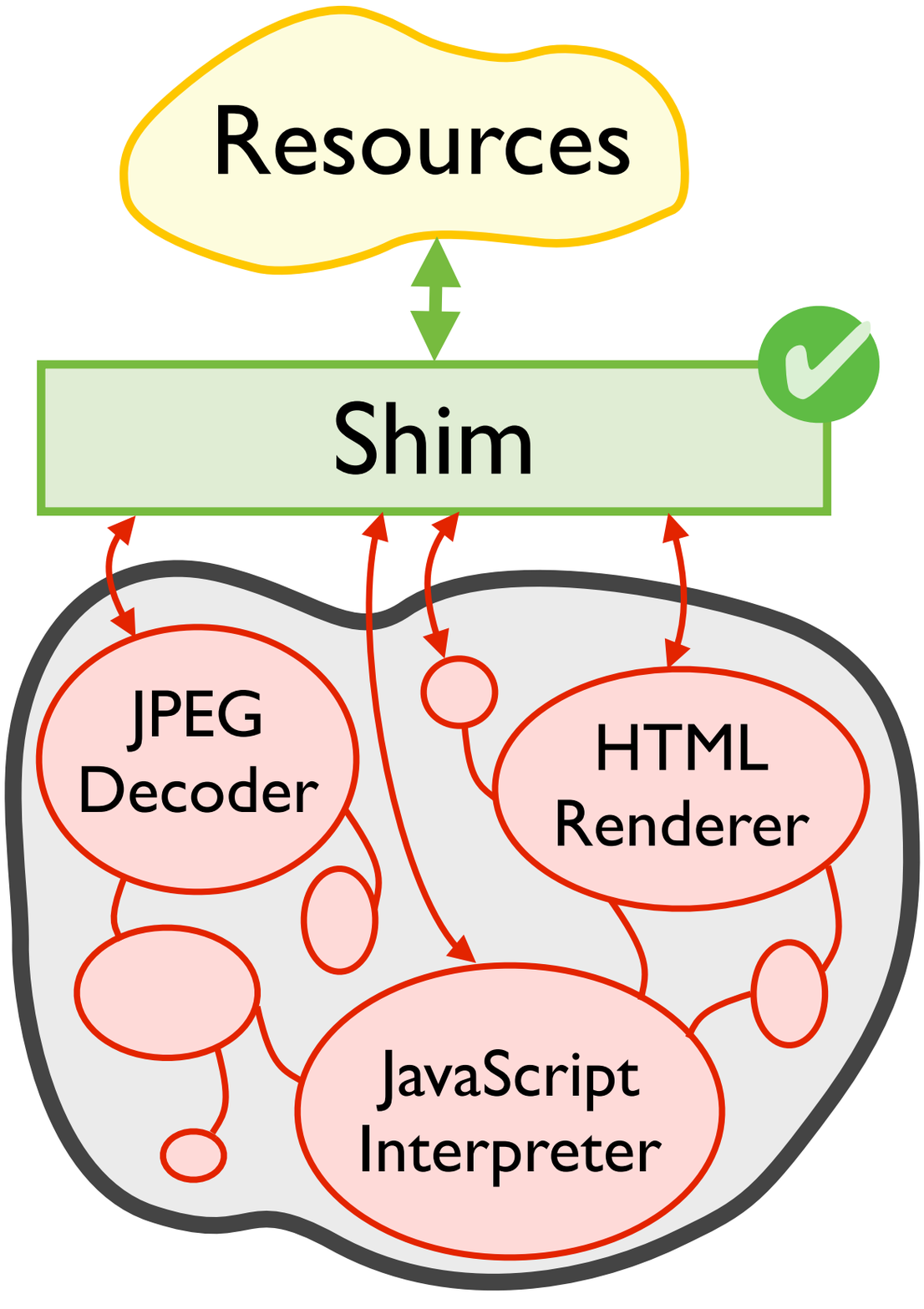
Complex parts

Subtle interactions

Loose access policy

Constant evolution

Formal Shim Verification



Isolate

sandbox untrusted code

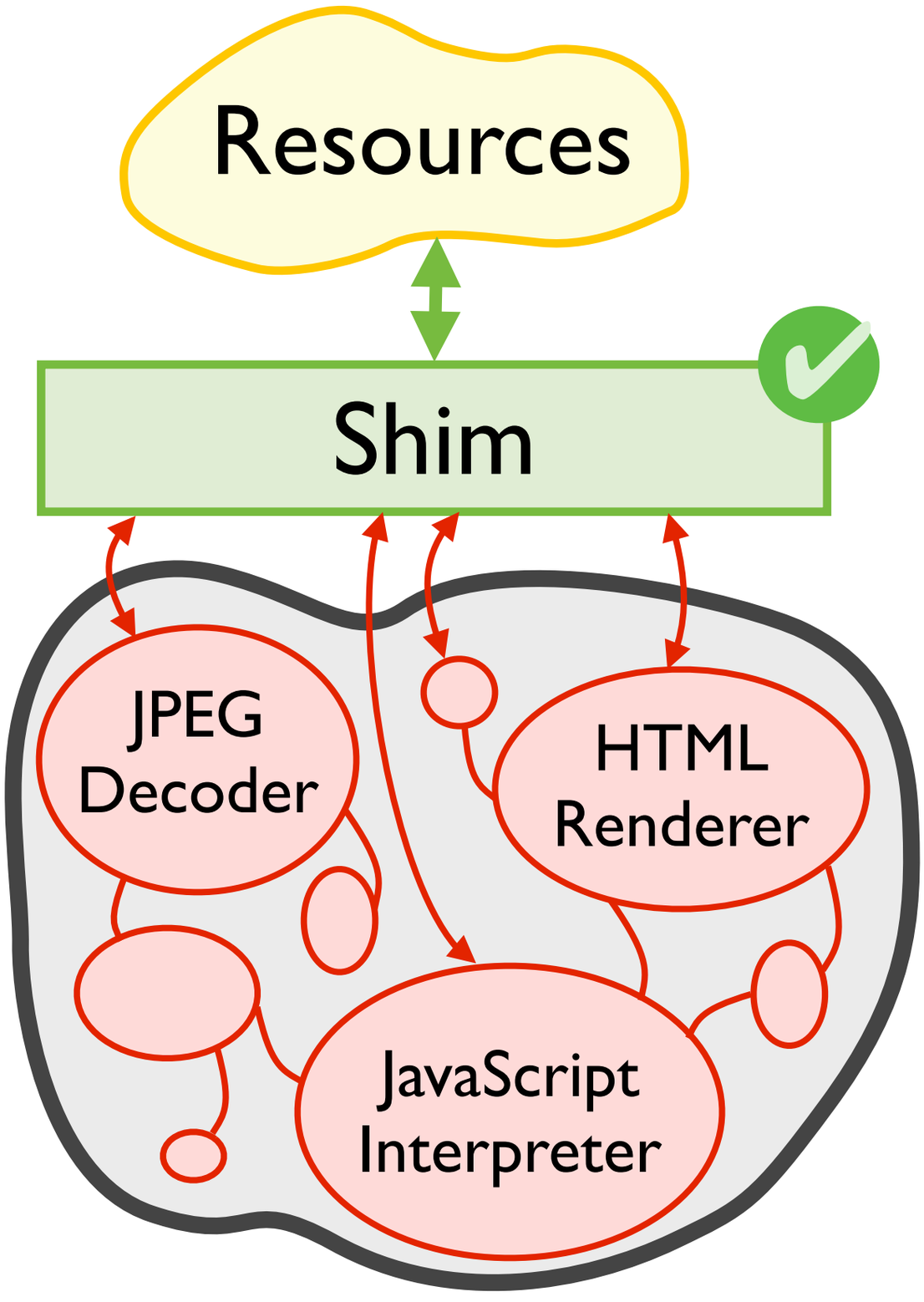
Insert shim

guards resource access

Verify shim

prove security props

Formal Shim Verification



QUARK

formally verified browser

Security Props

1. Tab isolation

2. Cookie integrity

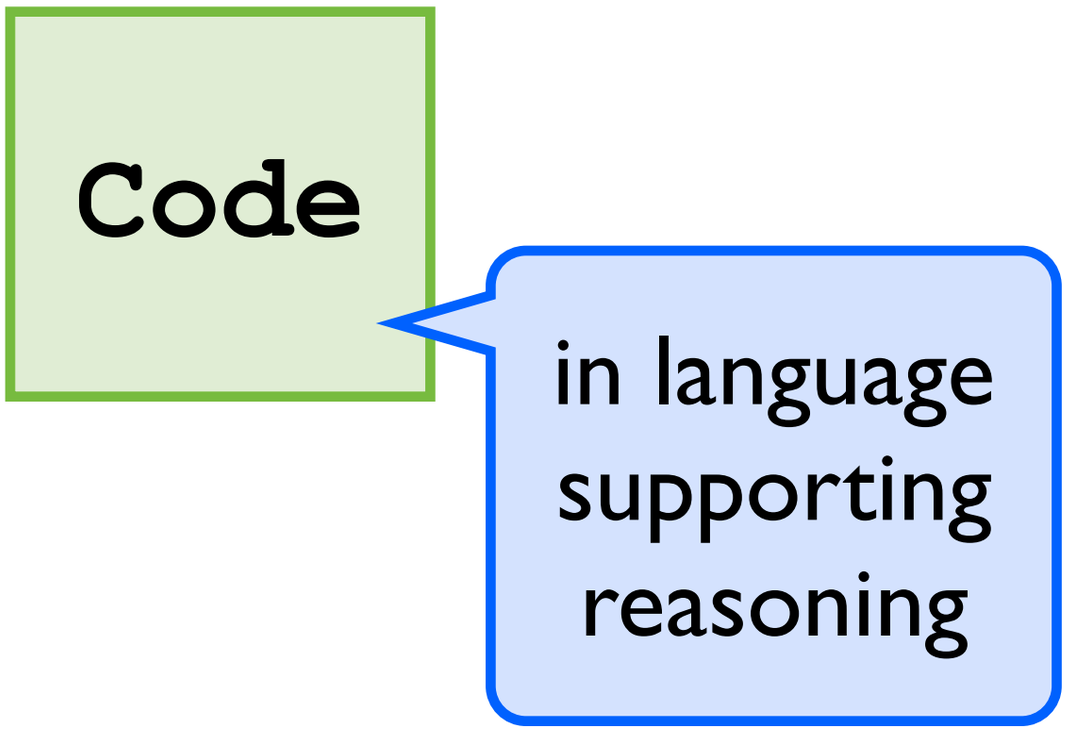
3. Addr bar correctness

Prove code correct

machine checkable proof

Fully Formal Verification

Fully Formal Verification



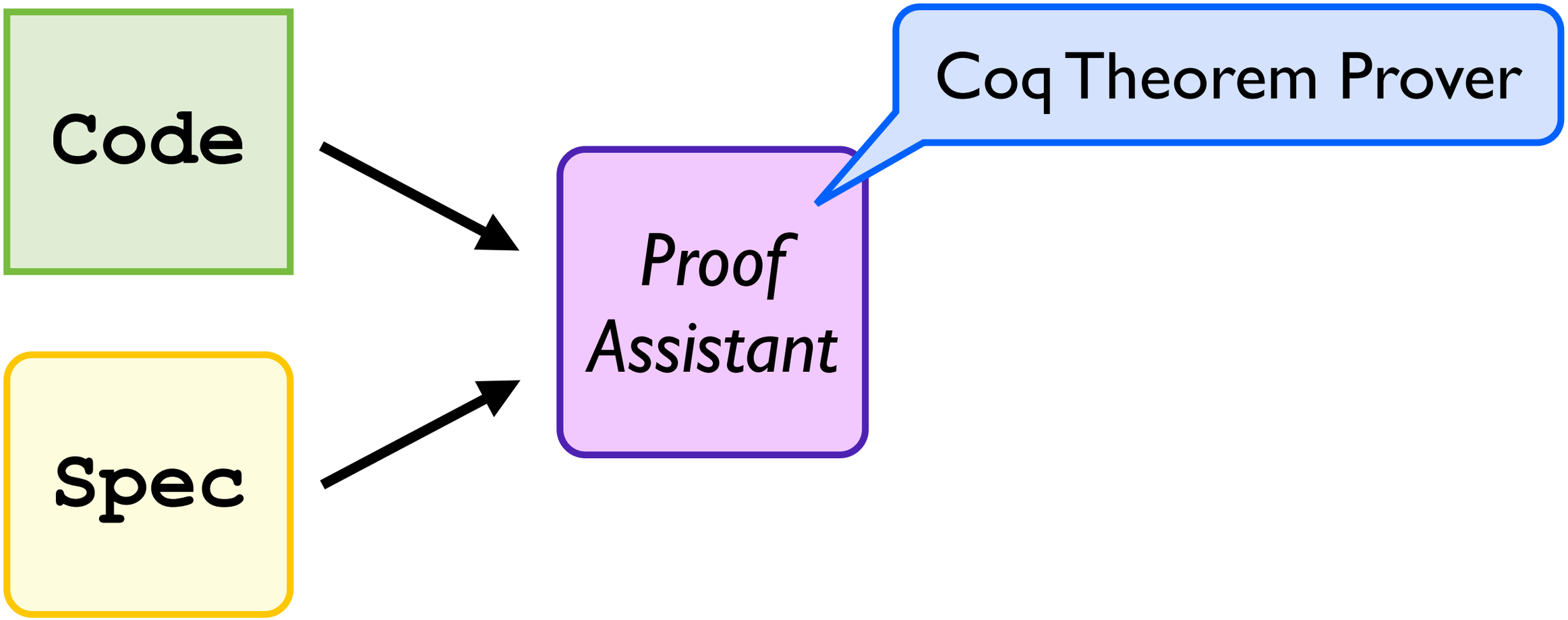
Fully Formal Verification

Code

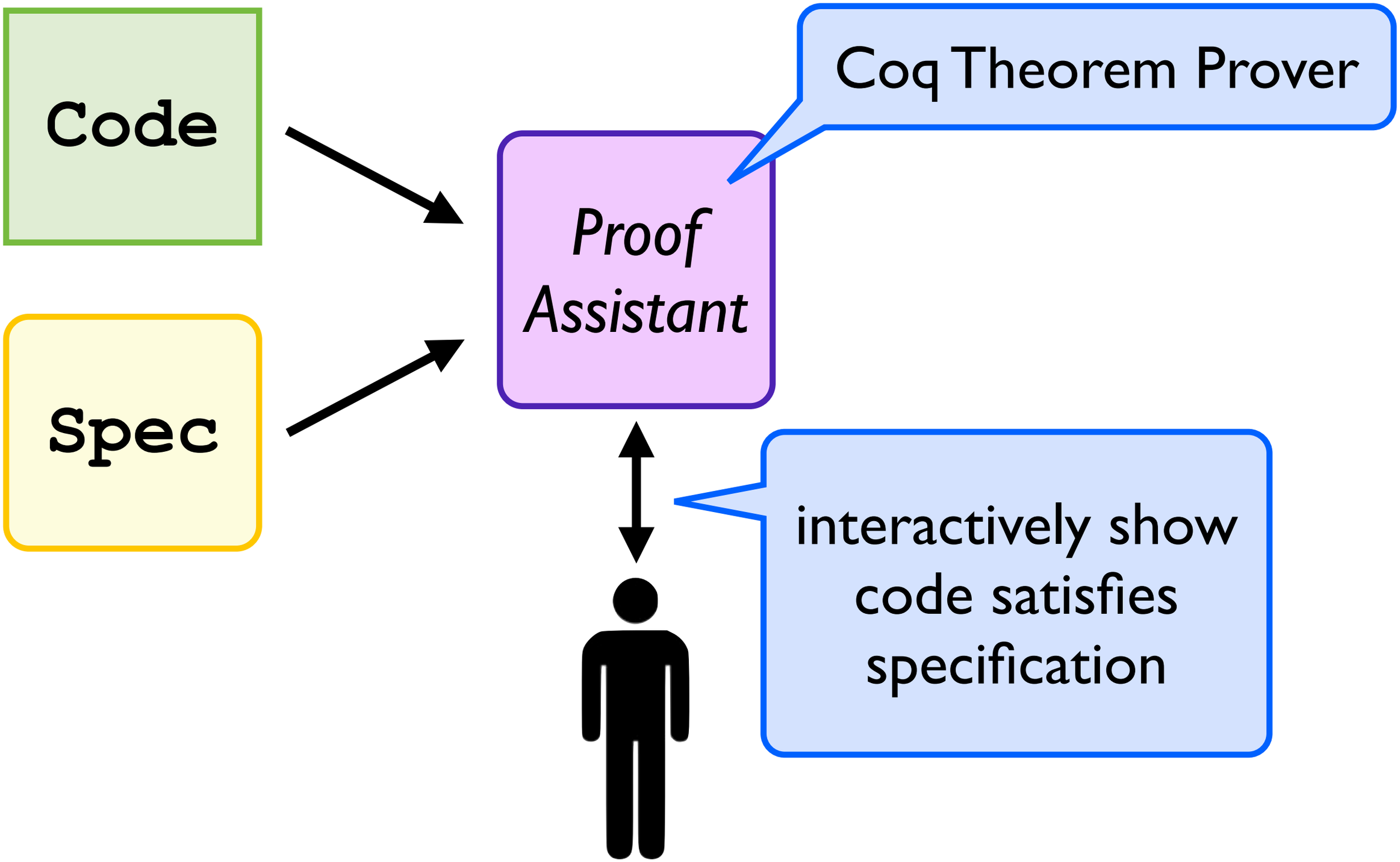
Spec

logical properties
characterizing correctness

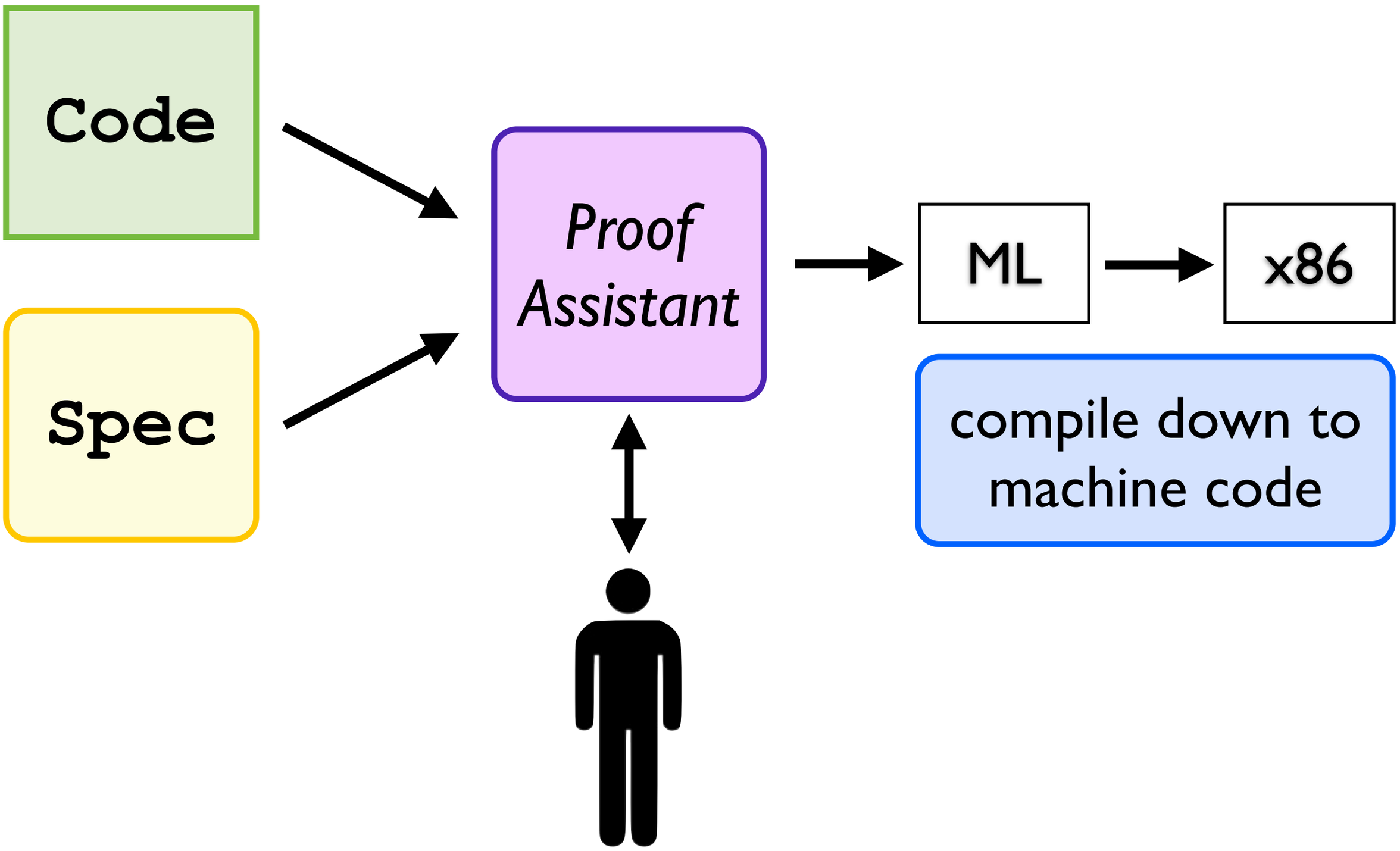
Fully Formal Verification



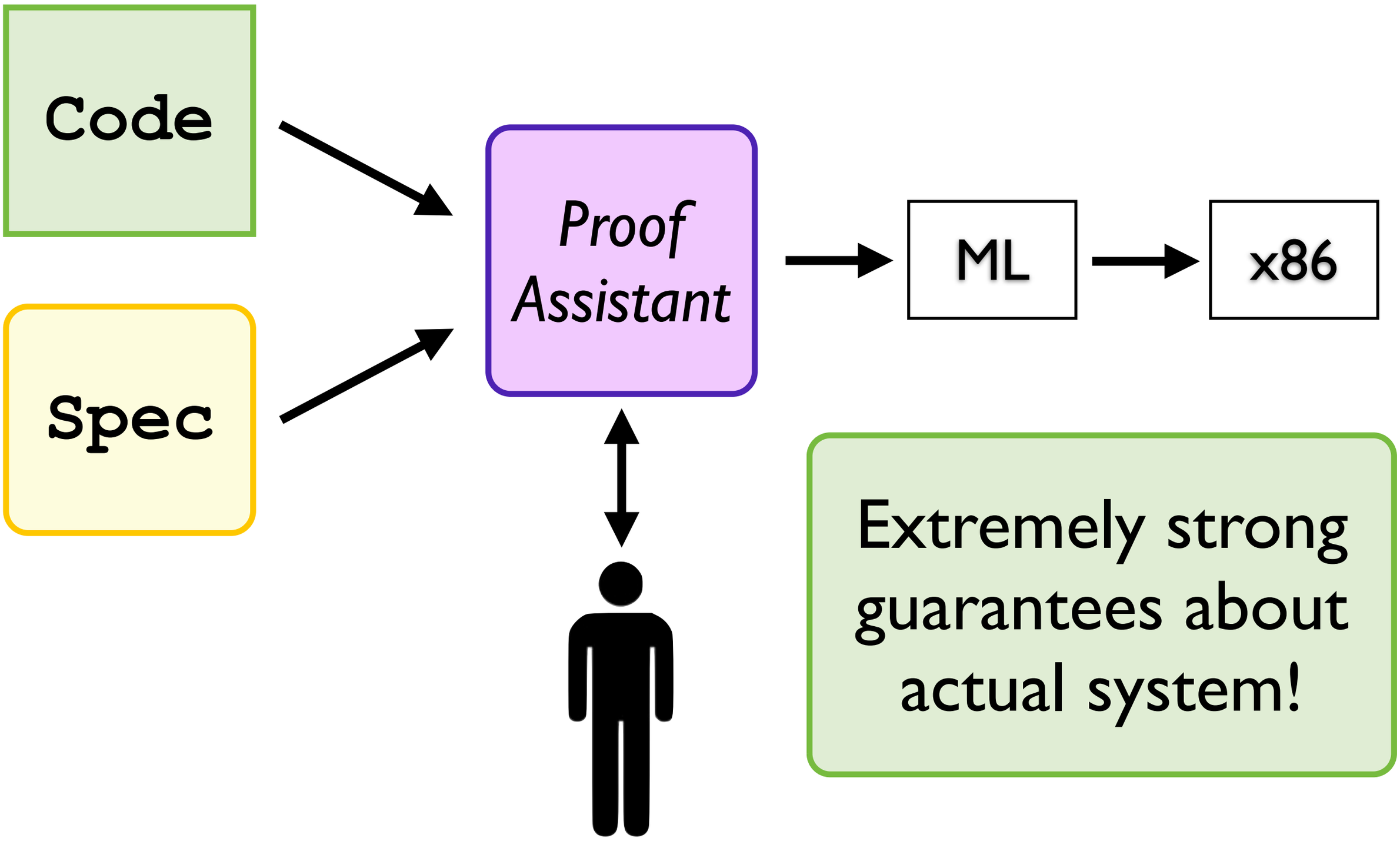
Fully Formal Verification



Fully Formal Verification

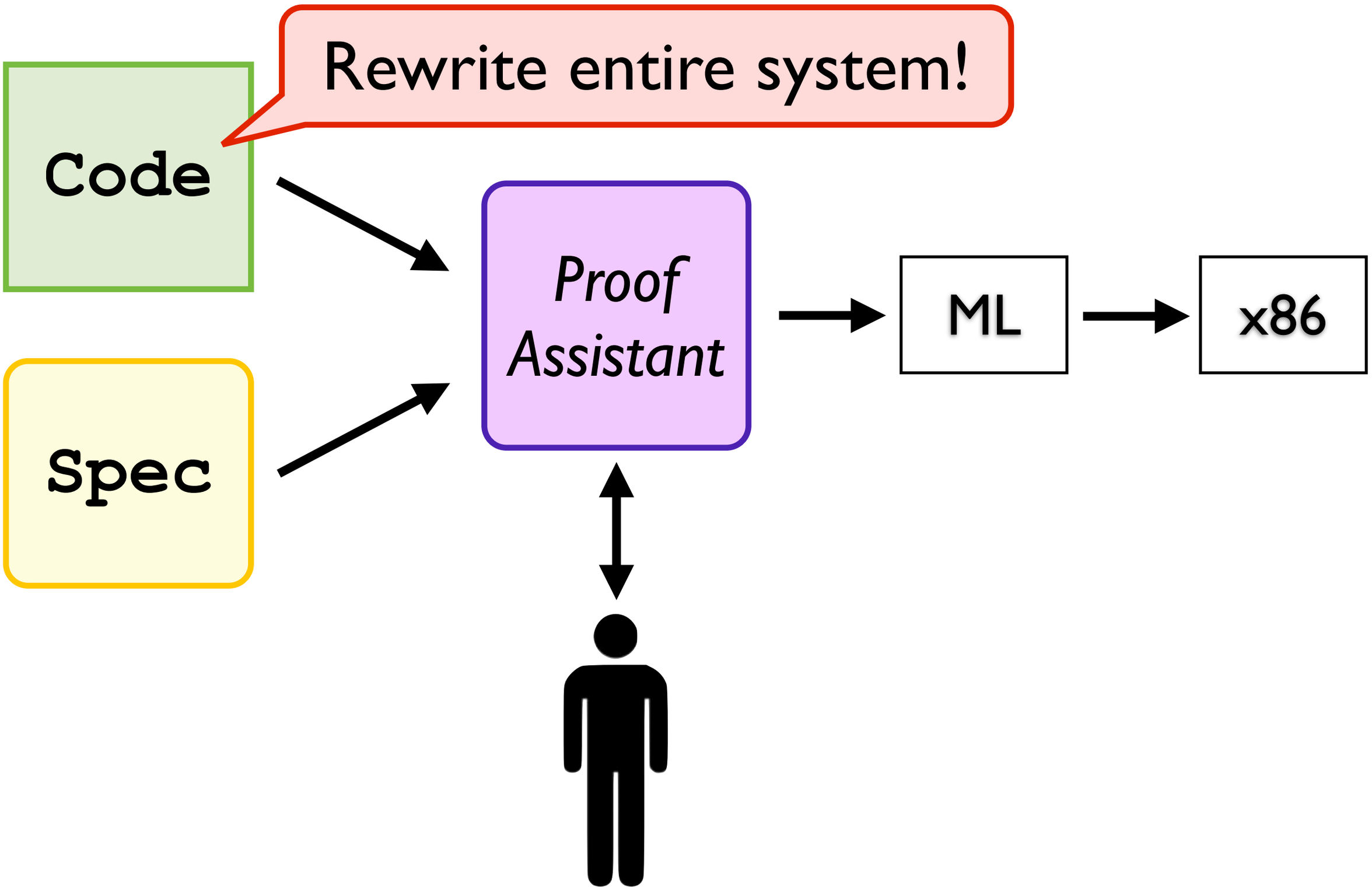


Fully Formal Verification

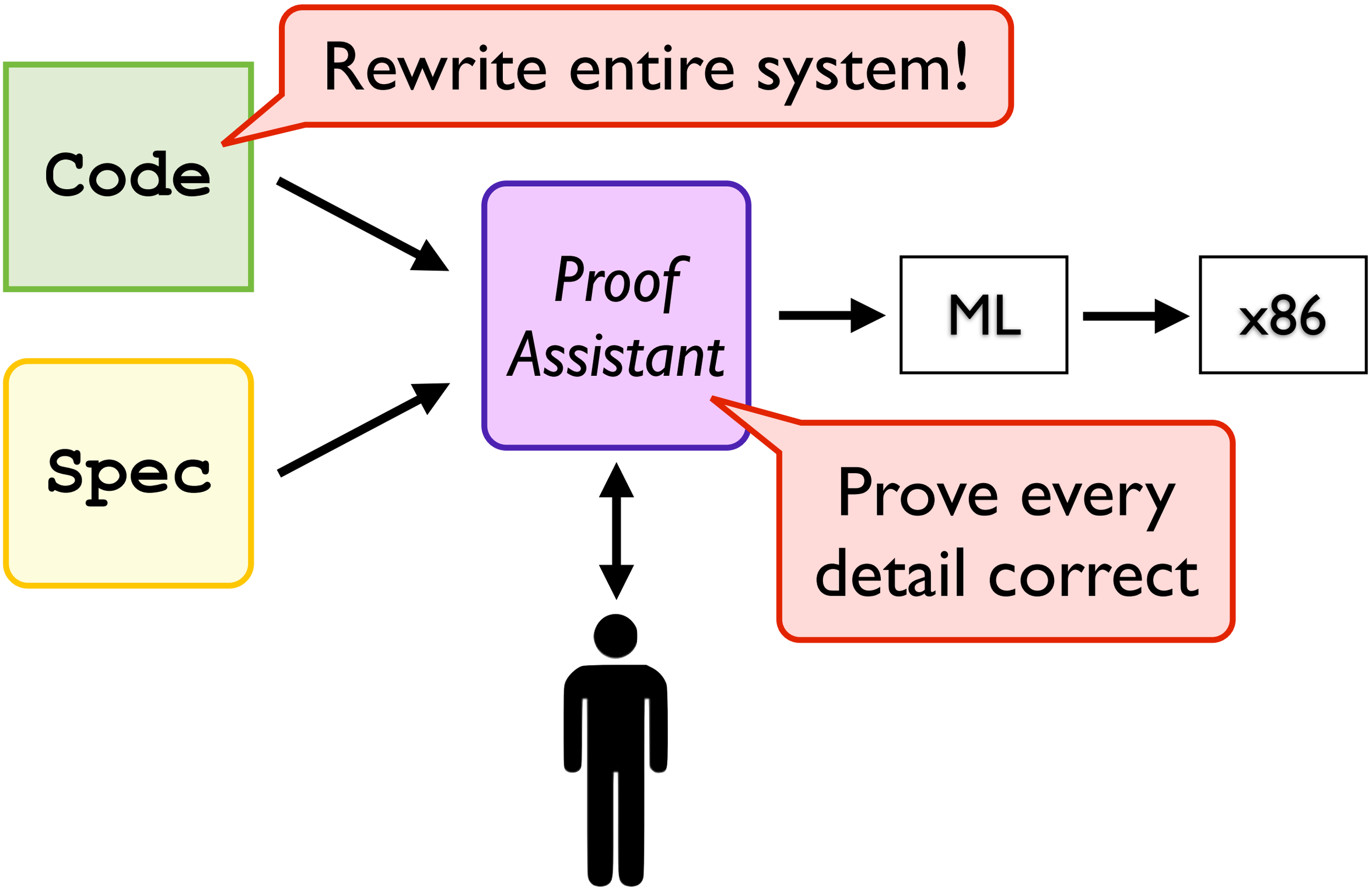


Extremely strong guarantees about actual system!

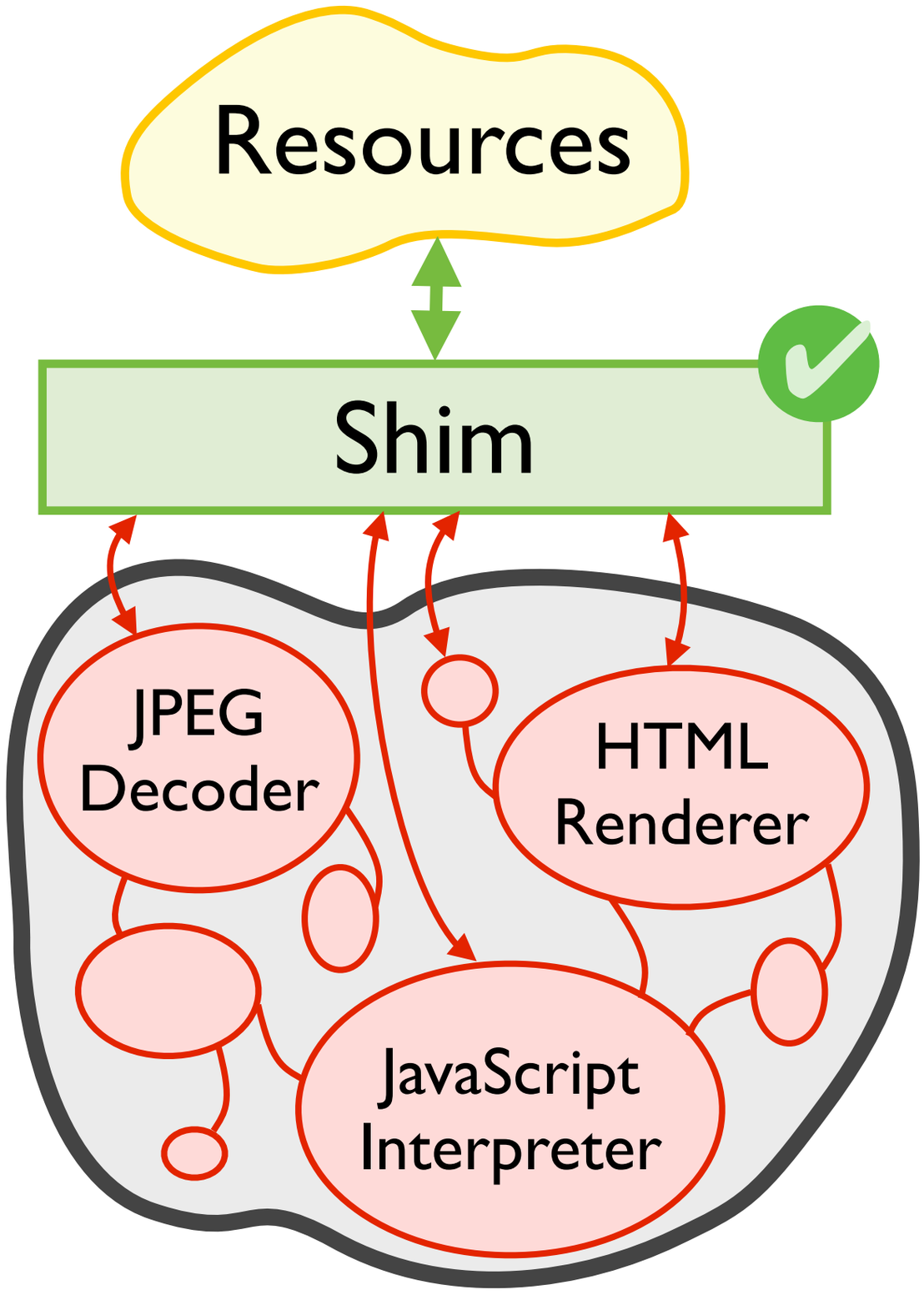
Fully Formal Verification



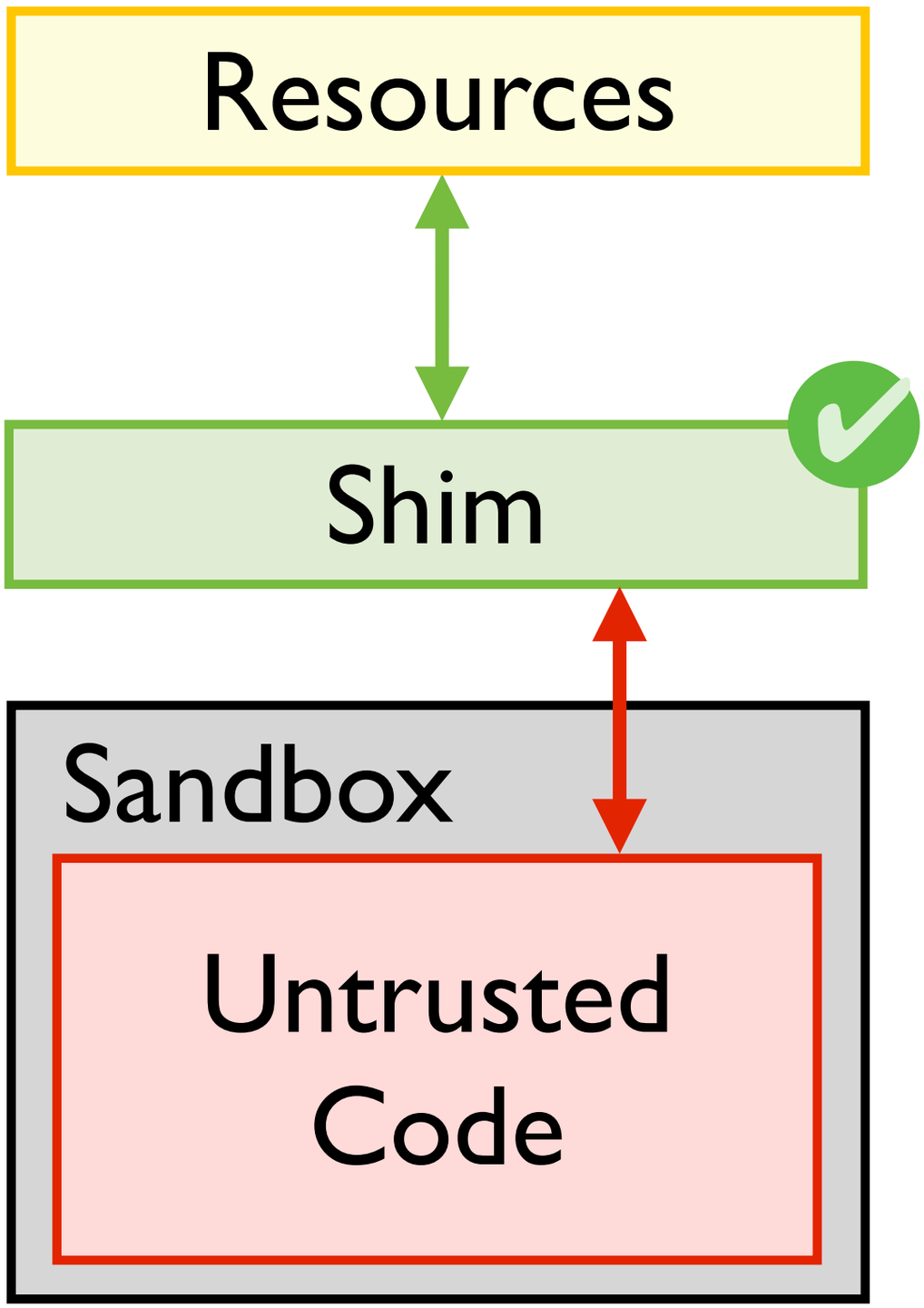
Fully Formal Verification



Formal Shim Verification



Formal Shim Verification



Adapt to sandbox

request access via shim

Write shim

design effective interface

Formally verify shim

ensure accesses secure

Formal Shim Verification

Key Insight

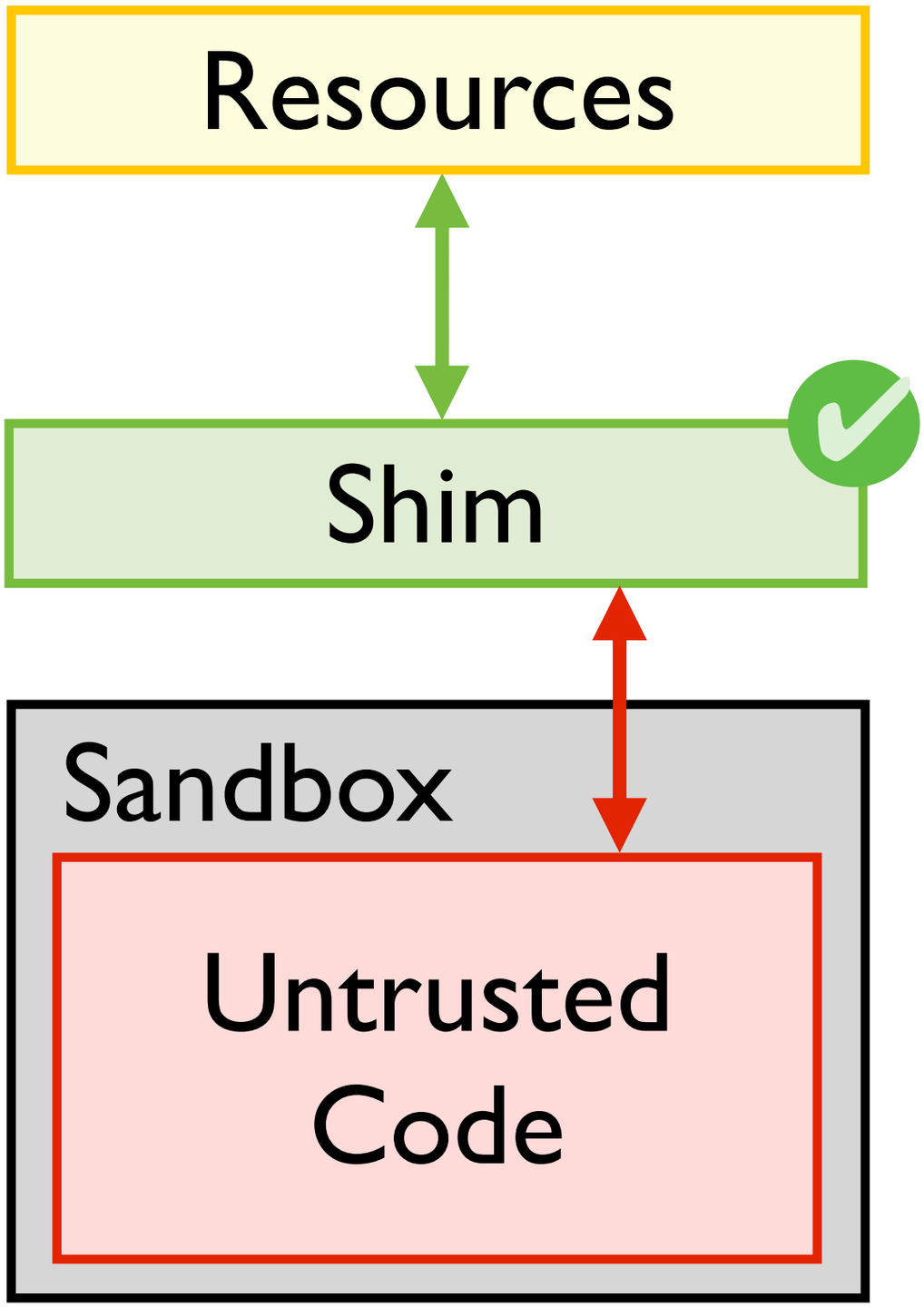
Guarantee sec props for entire system

Only reason about small shim

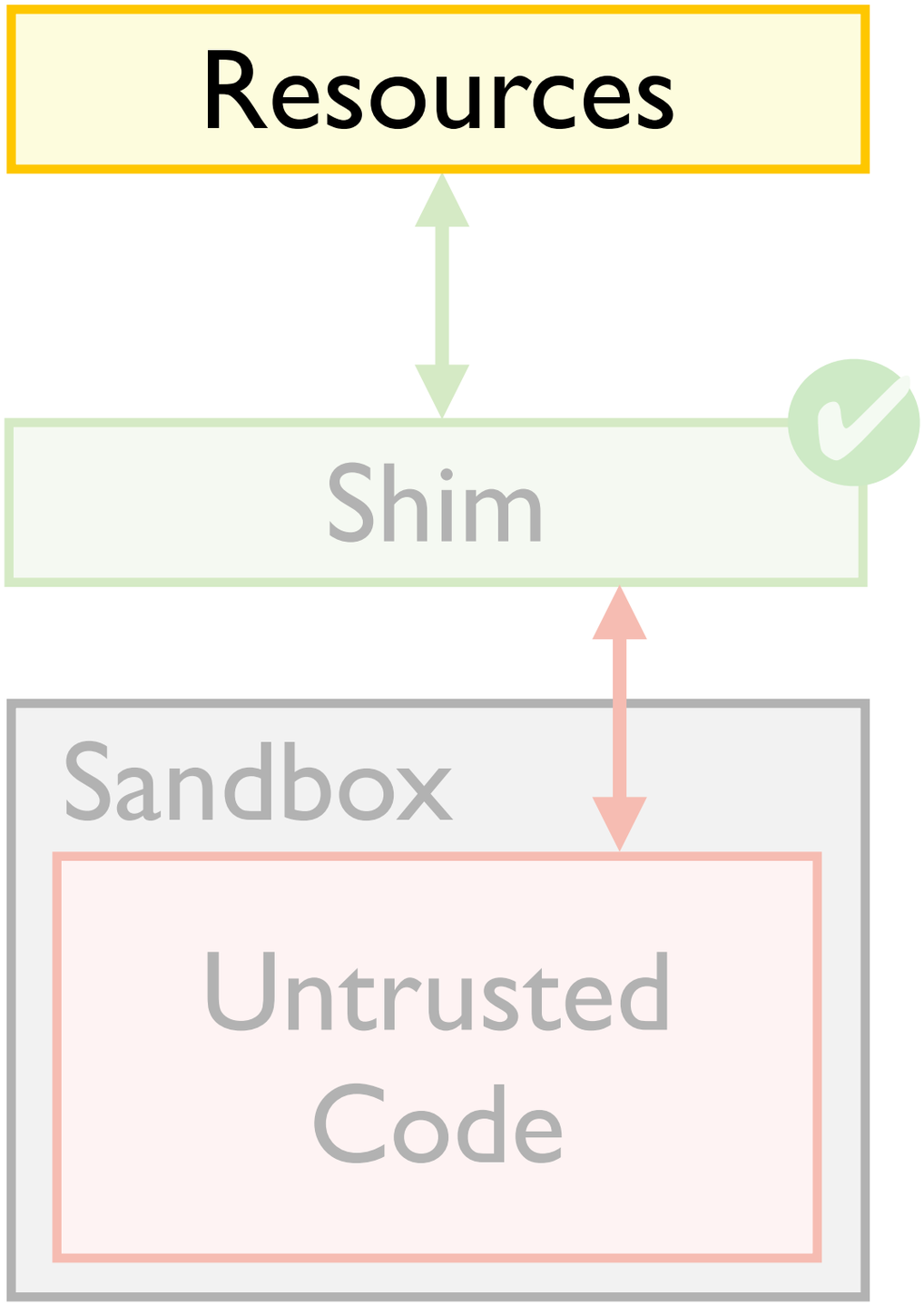
Radically ease verification burden

Prove *actual code* correct

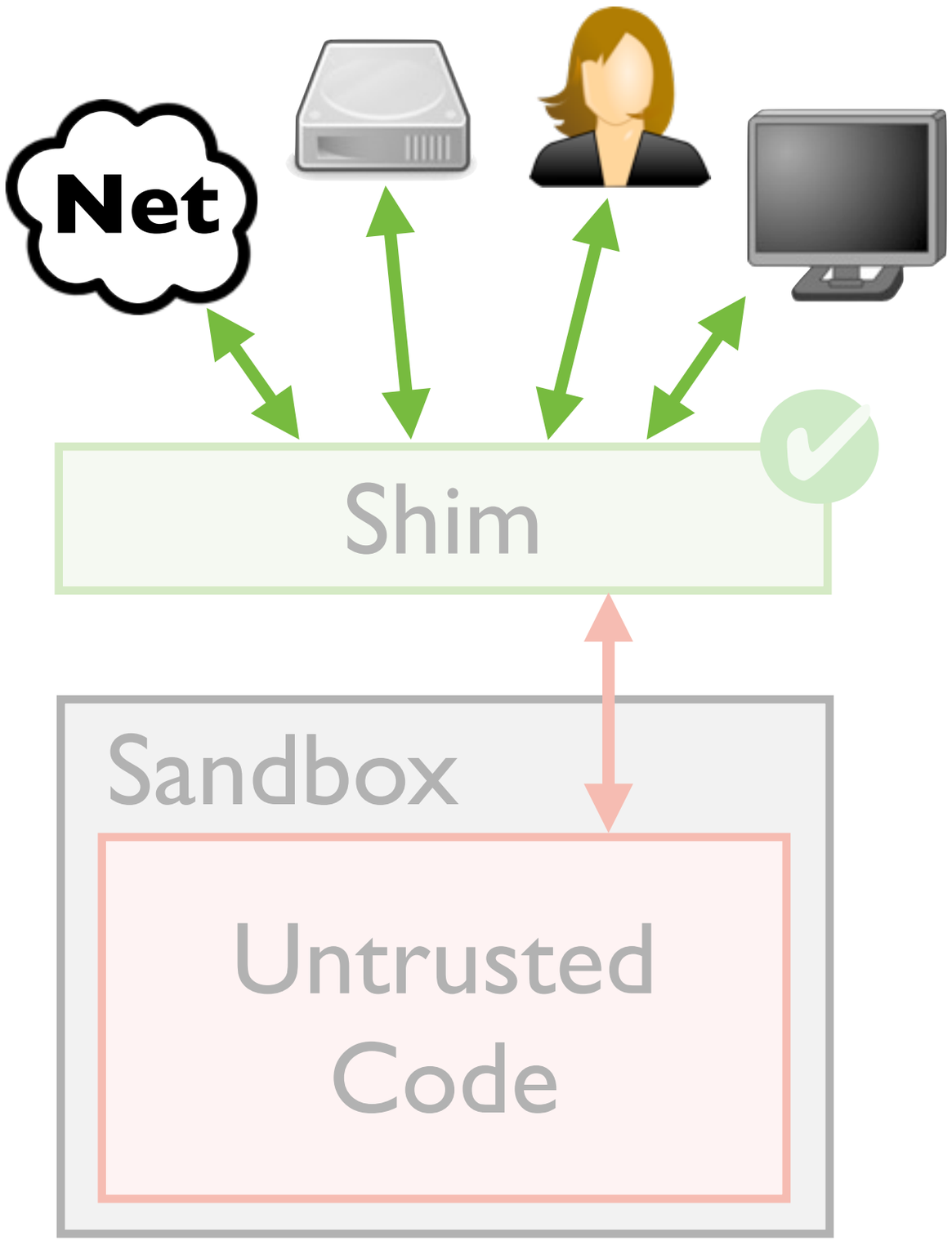
Quark: Verified Browser



Quark: Verified Browser



Quark: Verified Browser



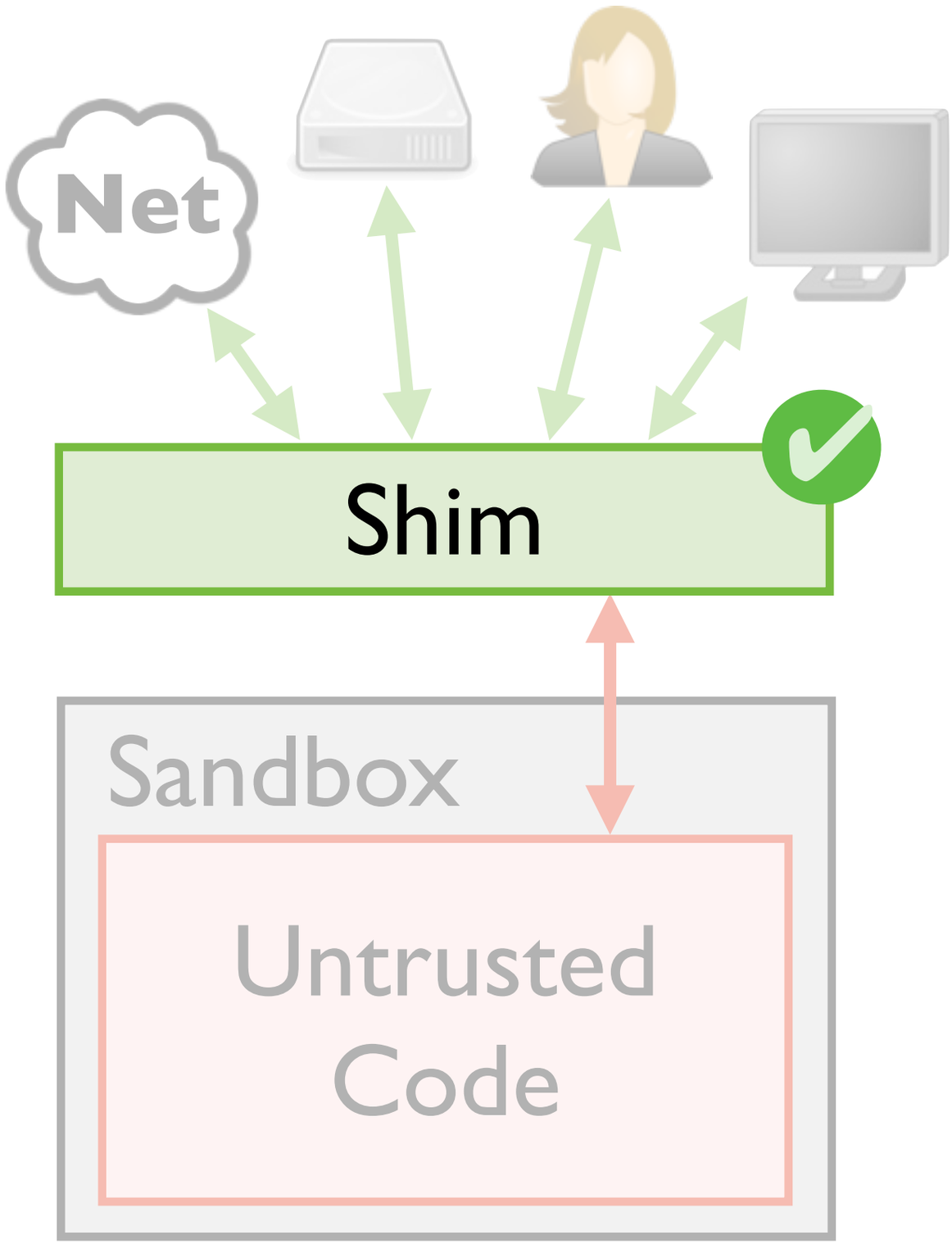
Resources

network

persistent storage

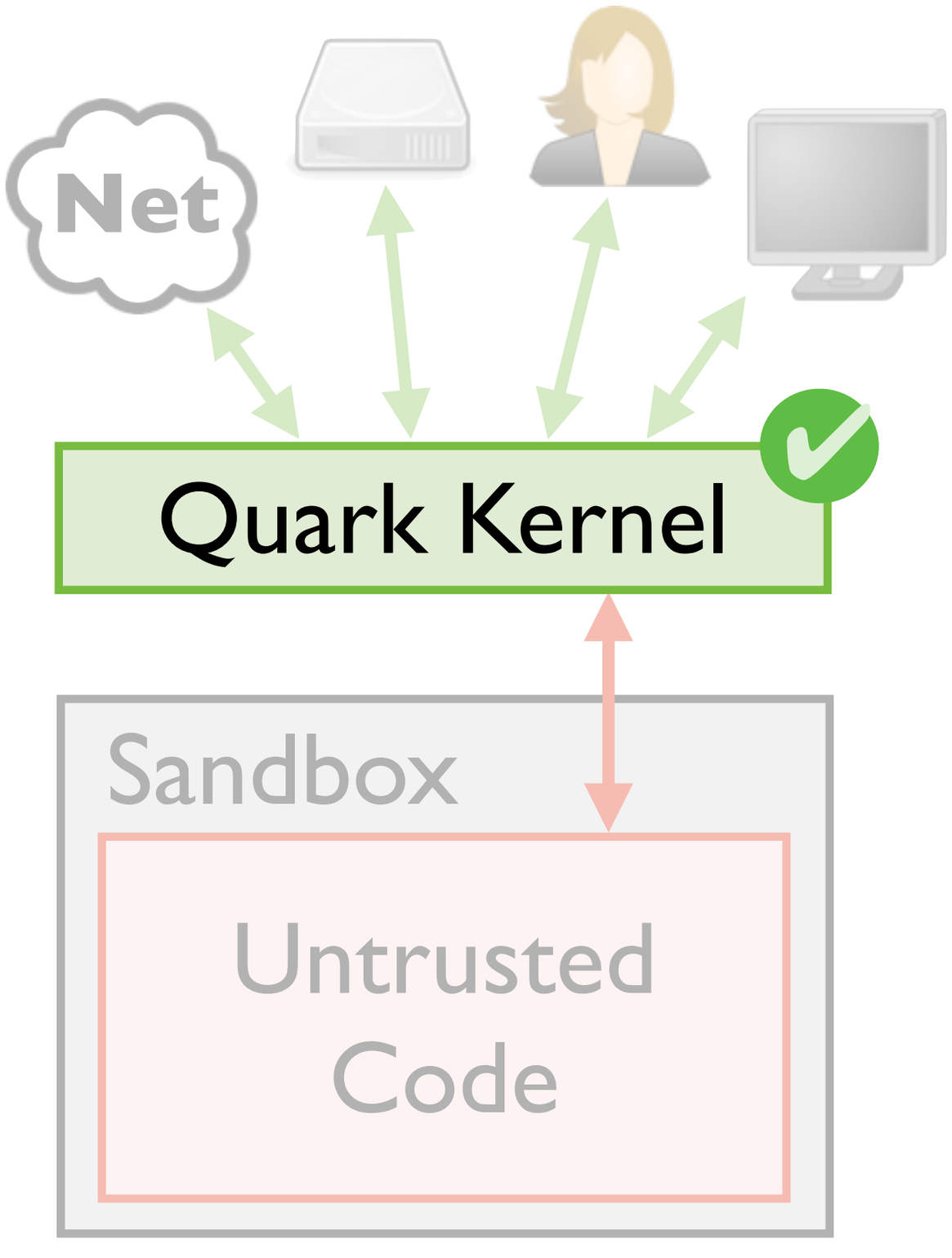
user interface

Quark: Verified Browser



Resources

Quark: Verified Browser



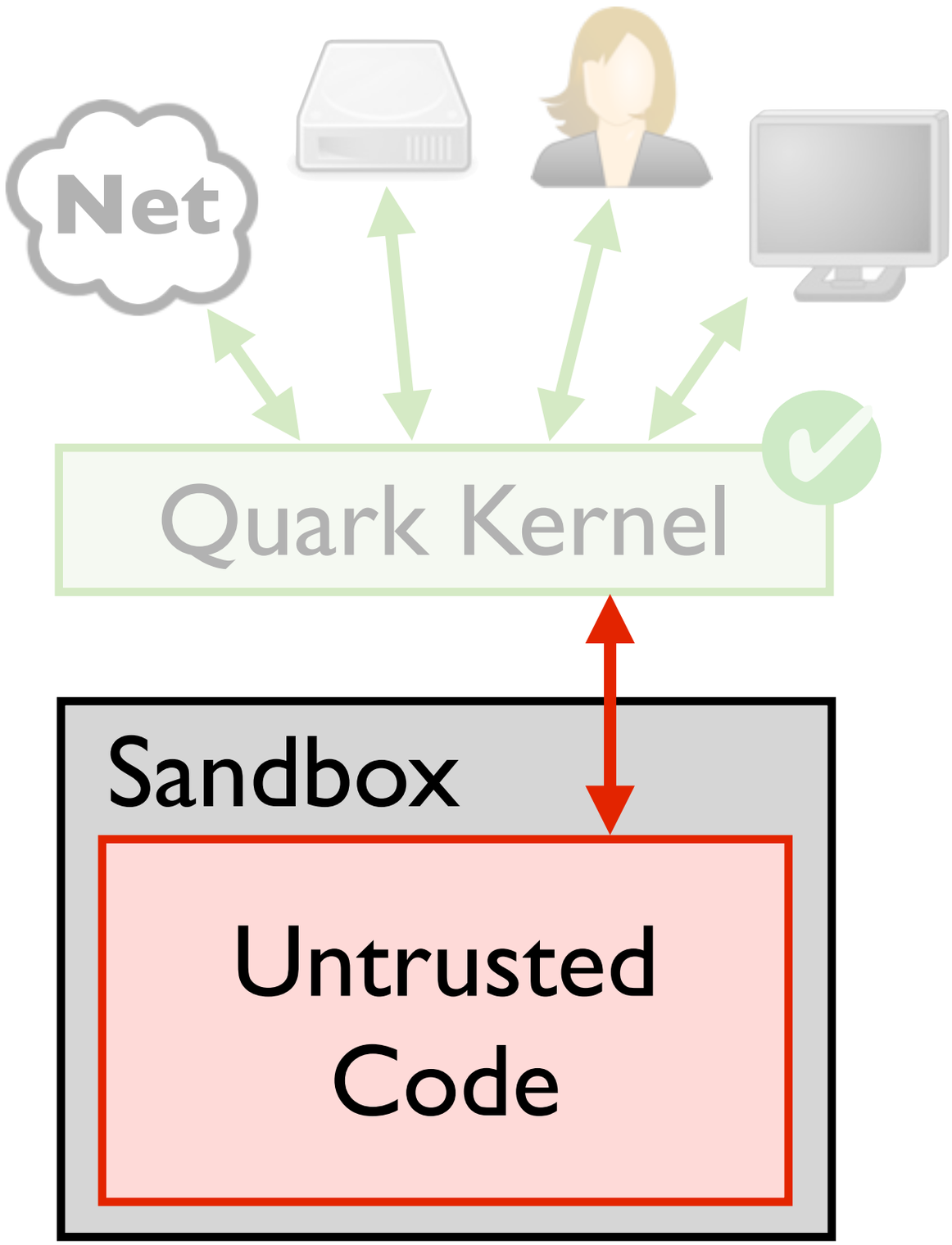
Resources

Shim

Quark browser kernel

code, spec, proof in Coq

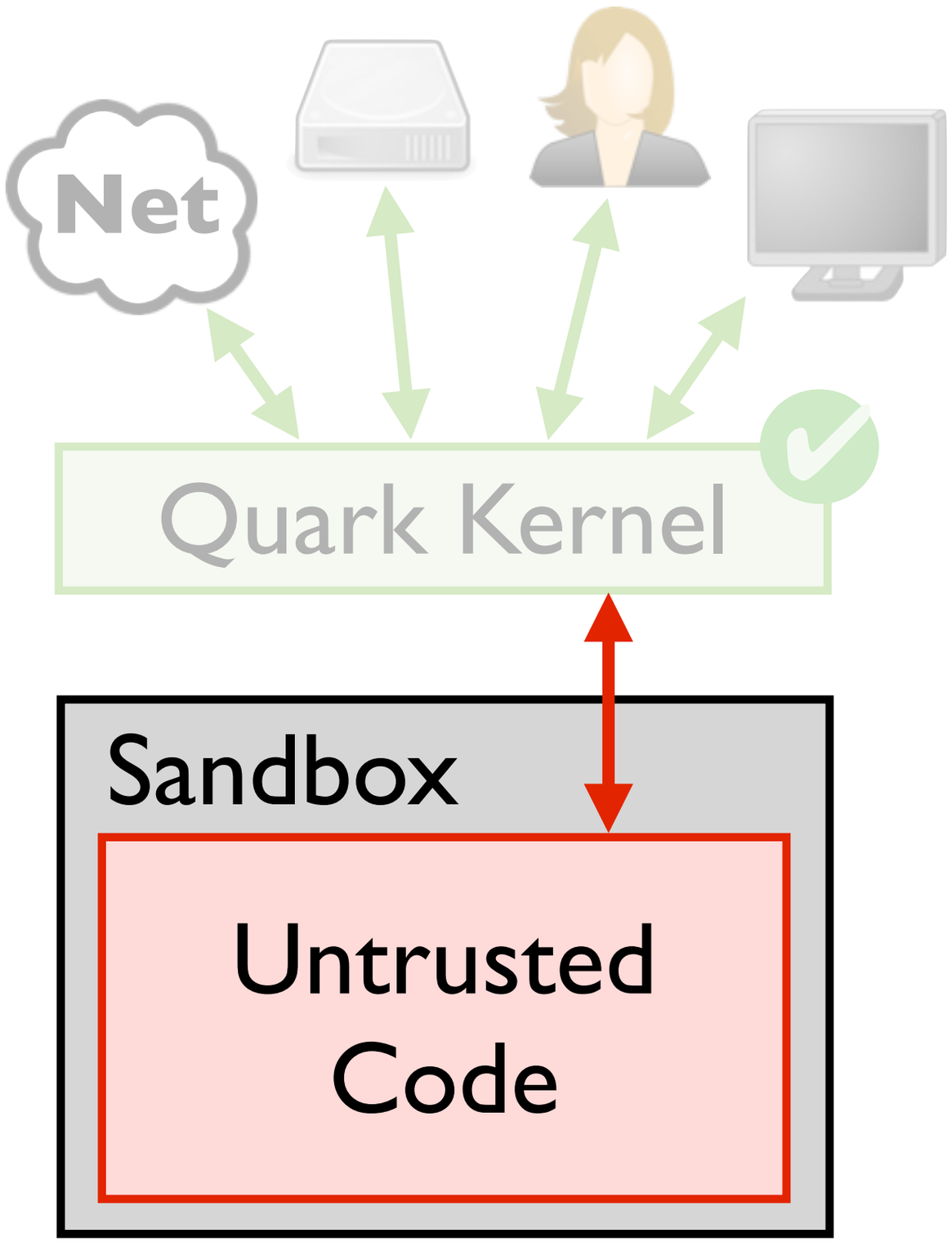
Quark: Verified Browser



Resources

Shim

Quark: Verified Browser



Resources

Shim

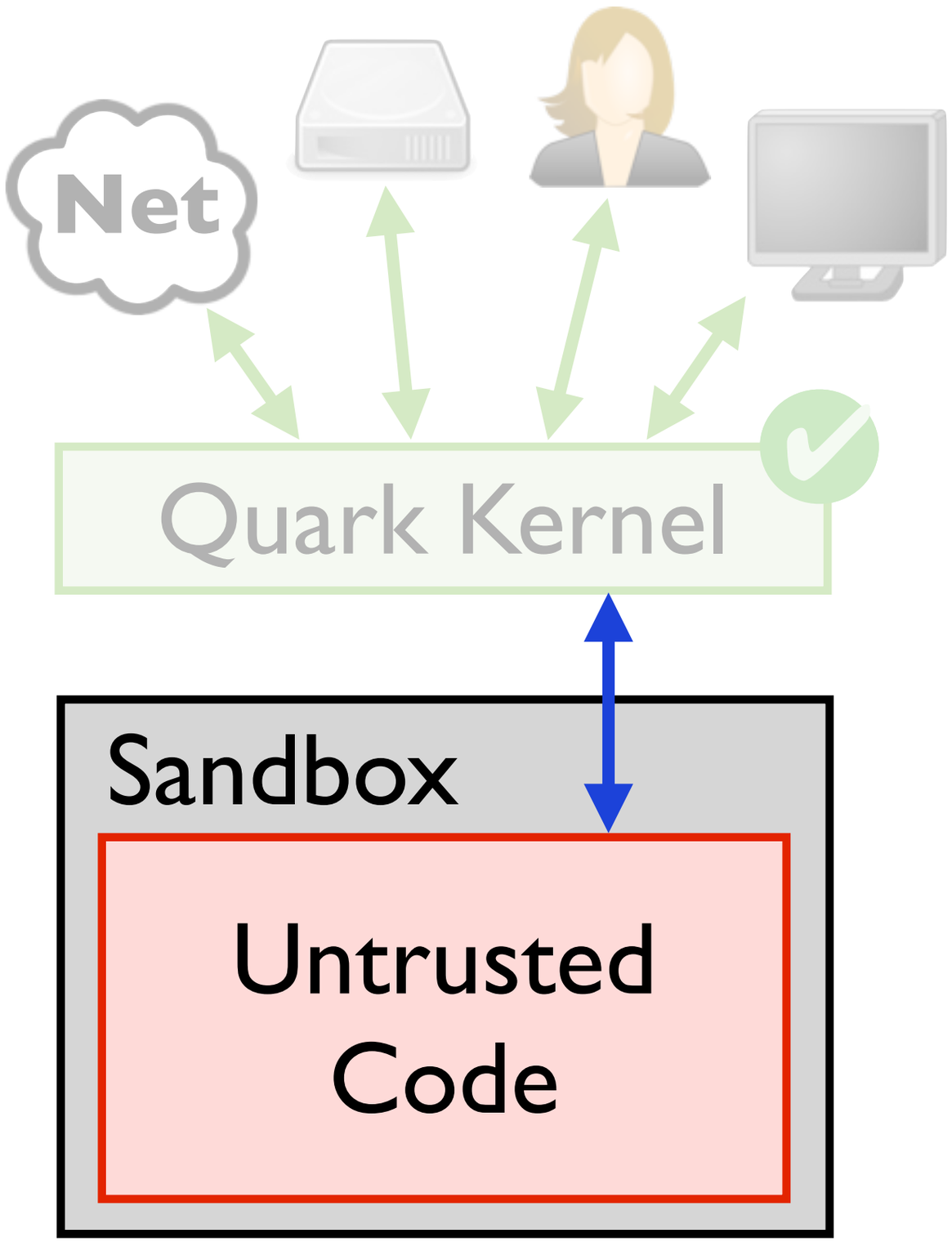
Untrusted Code

browser components

run as separate procs

strictly sandboxed

Quark: Verified Browser



Resources

Shim

Untrusted Code

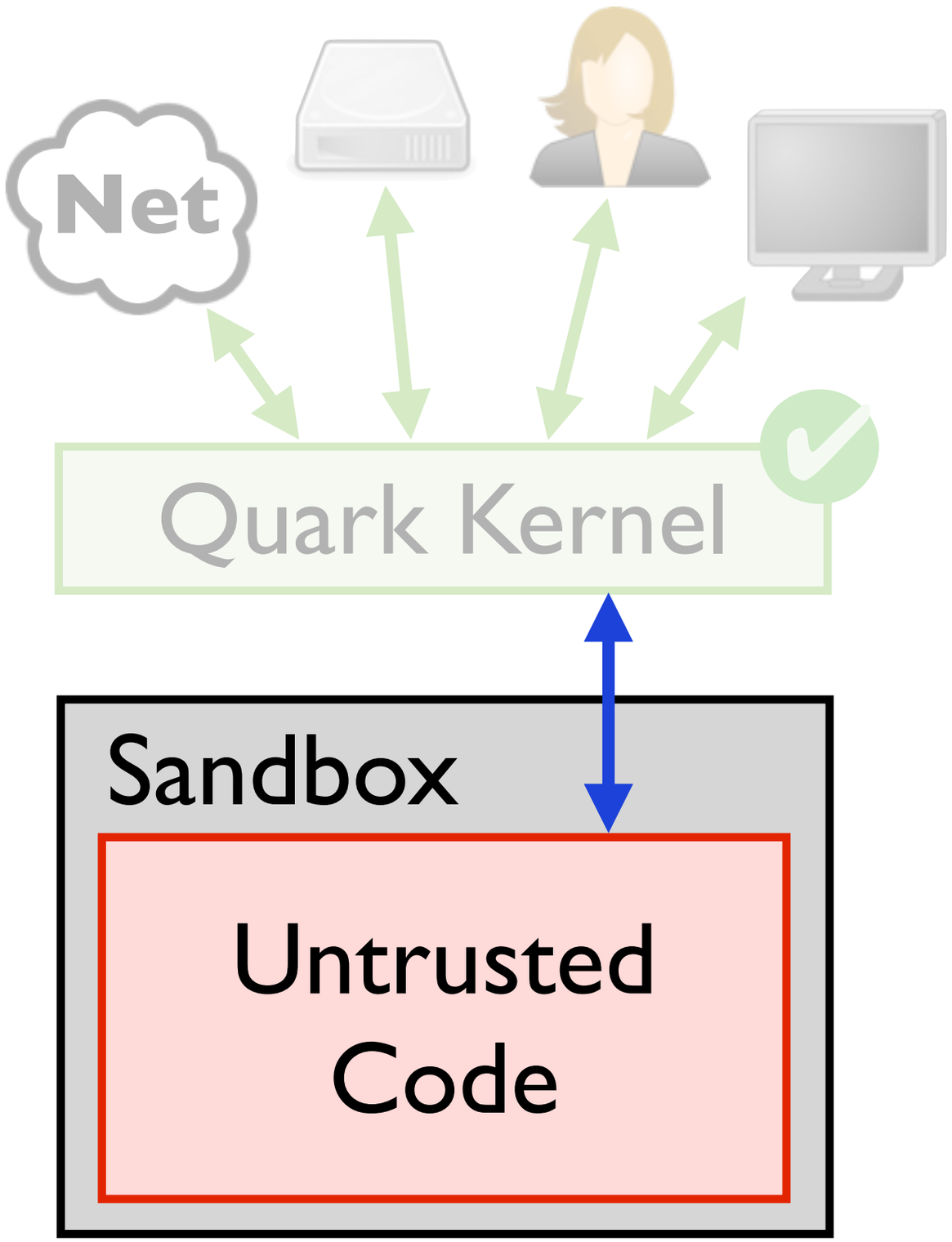
browser components

run as separate procs

strictly sandboxed

talk to kernel over pipe

Quark: Verified Browser



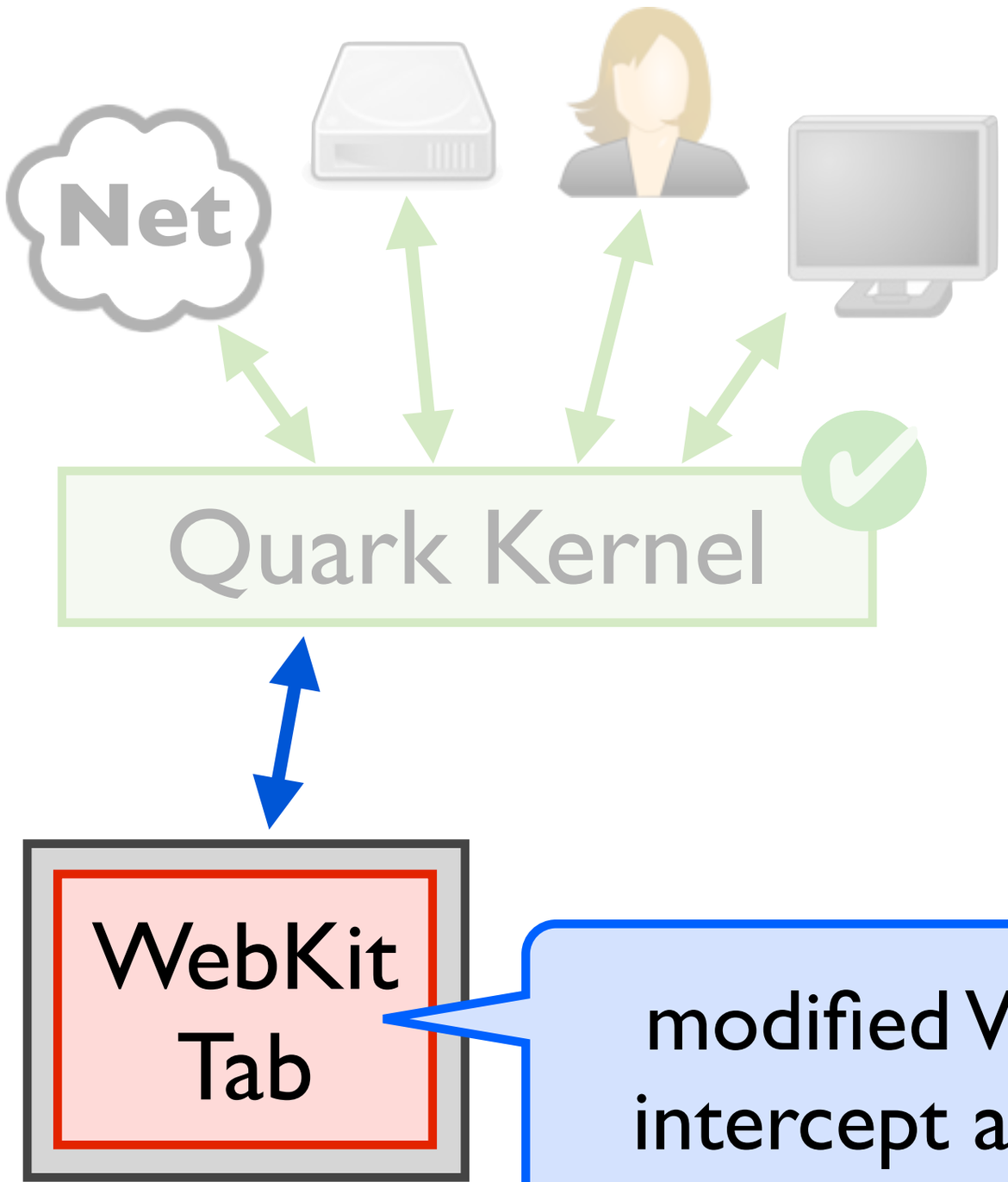
Resources

Shim

Untrusted Code

two component types

Quark: Verified Browser



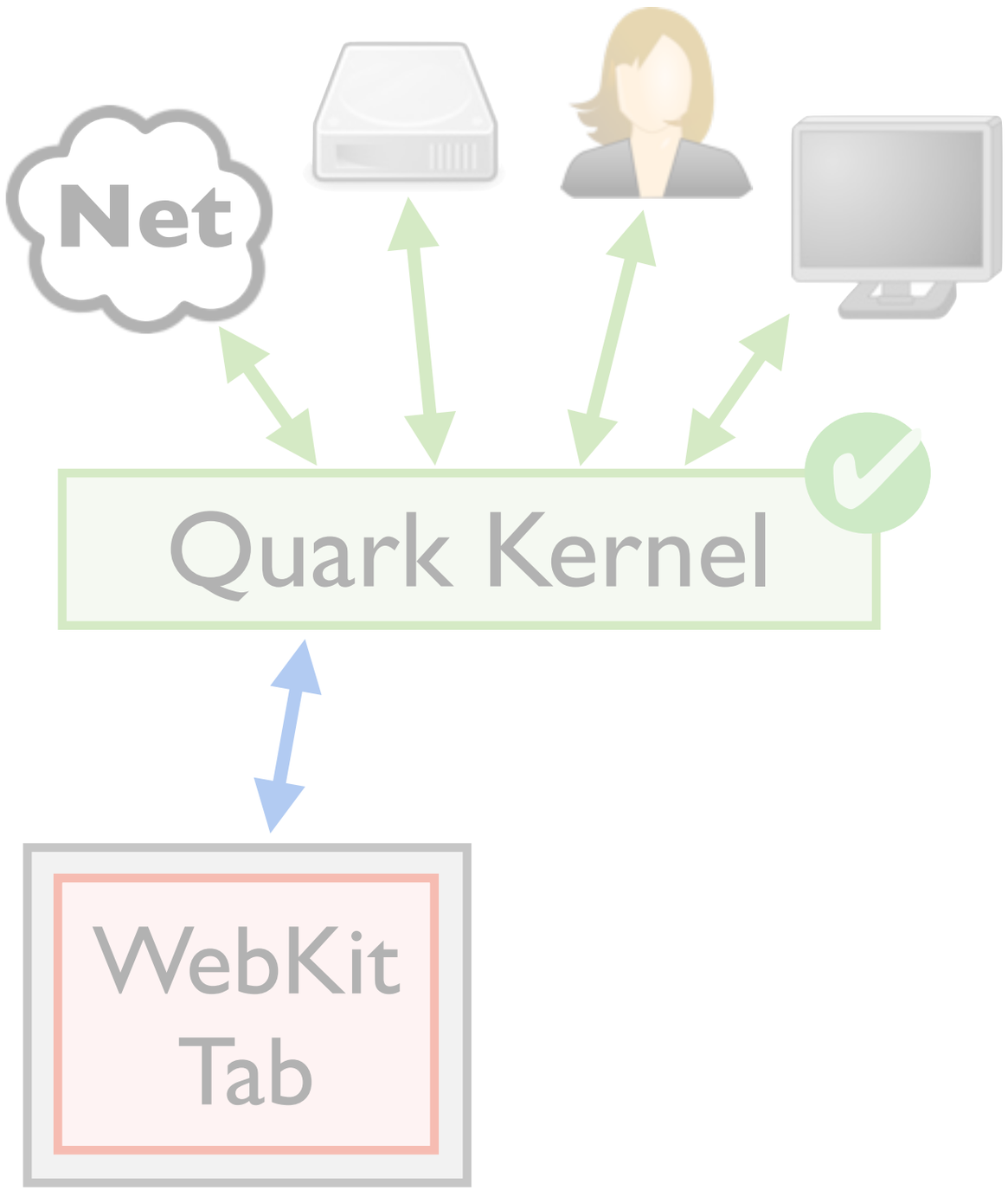
Resources

Shim

Untrusted Code

two component types

Quark: Verified Browser



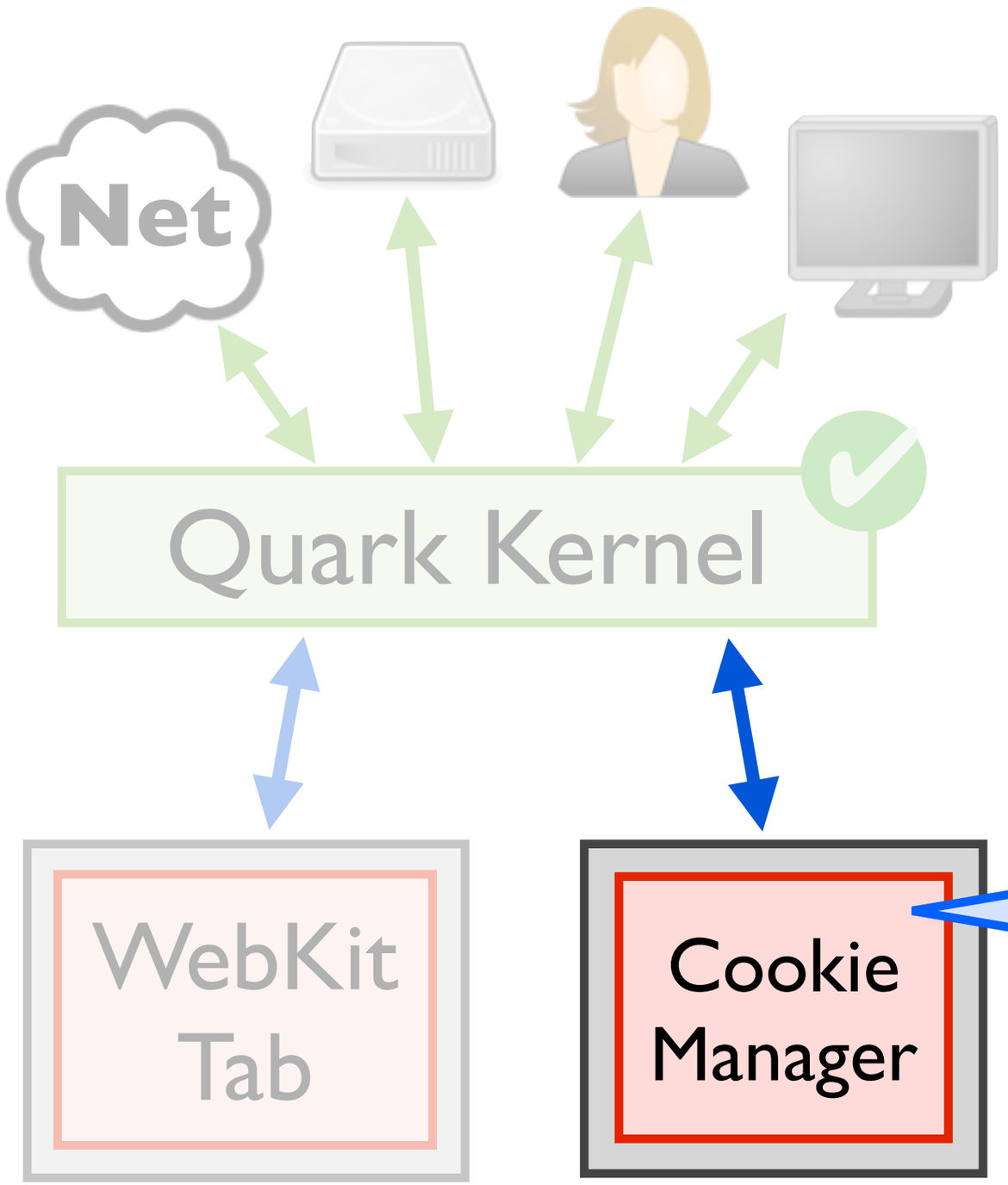
Resources

Shim

Untrusted Code

two component types

Quark: Verified Browser



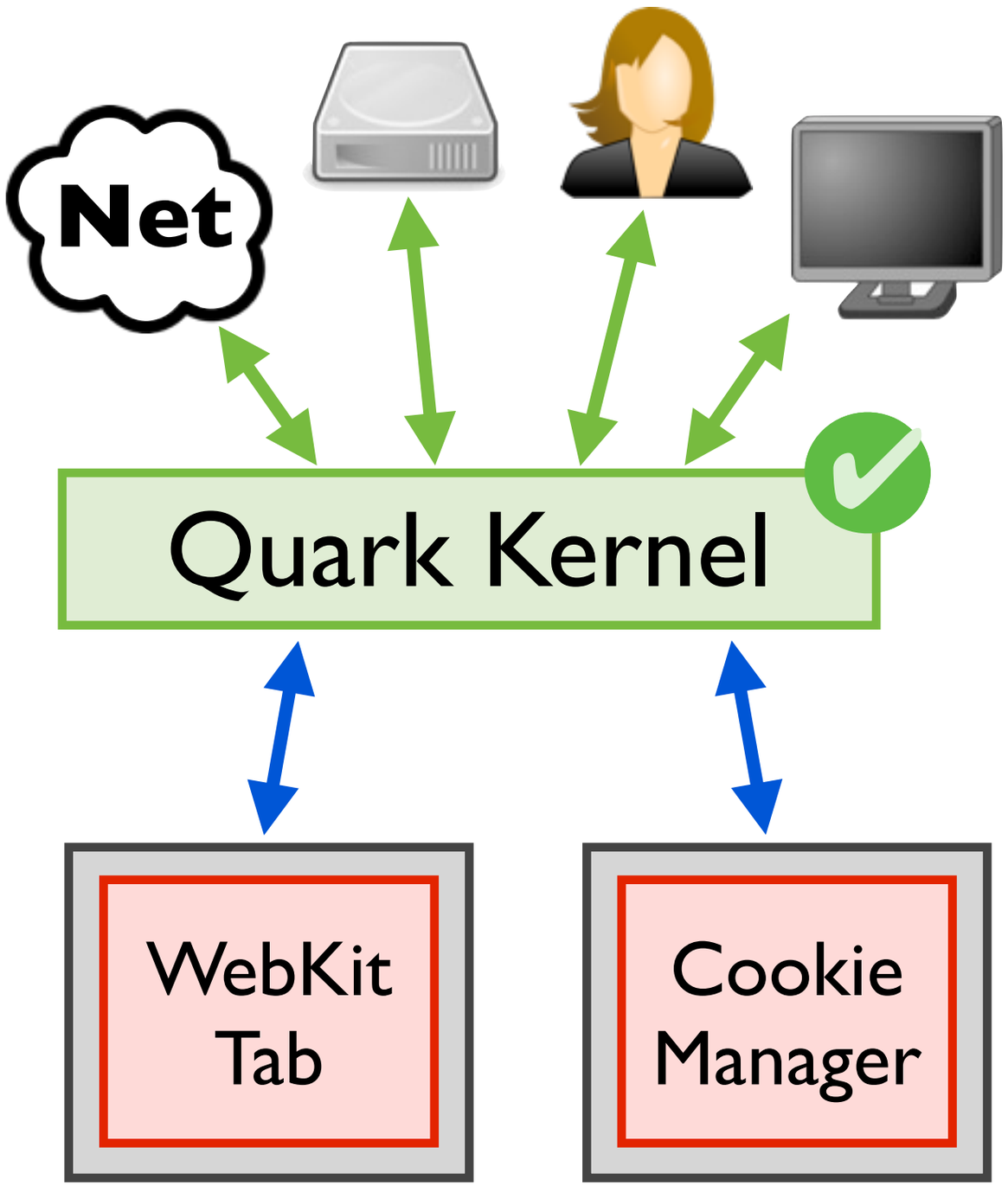
Resources

Shim

Untrusted Code

two component types

Quark: Verified Browser



Resources

Shim

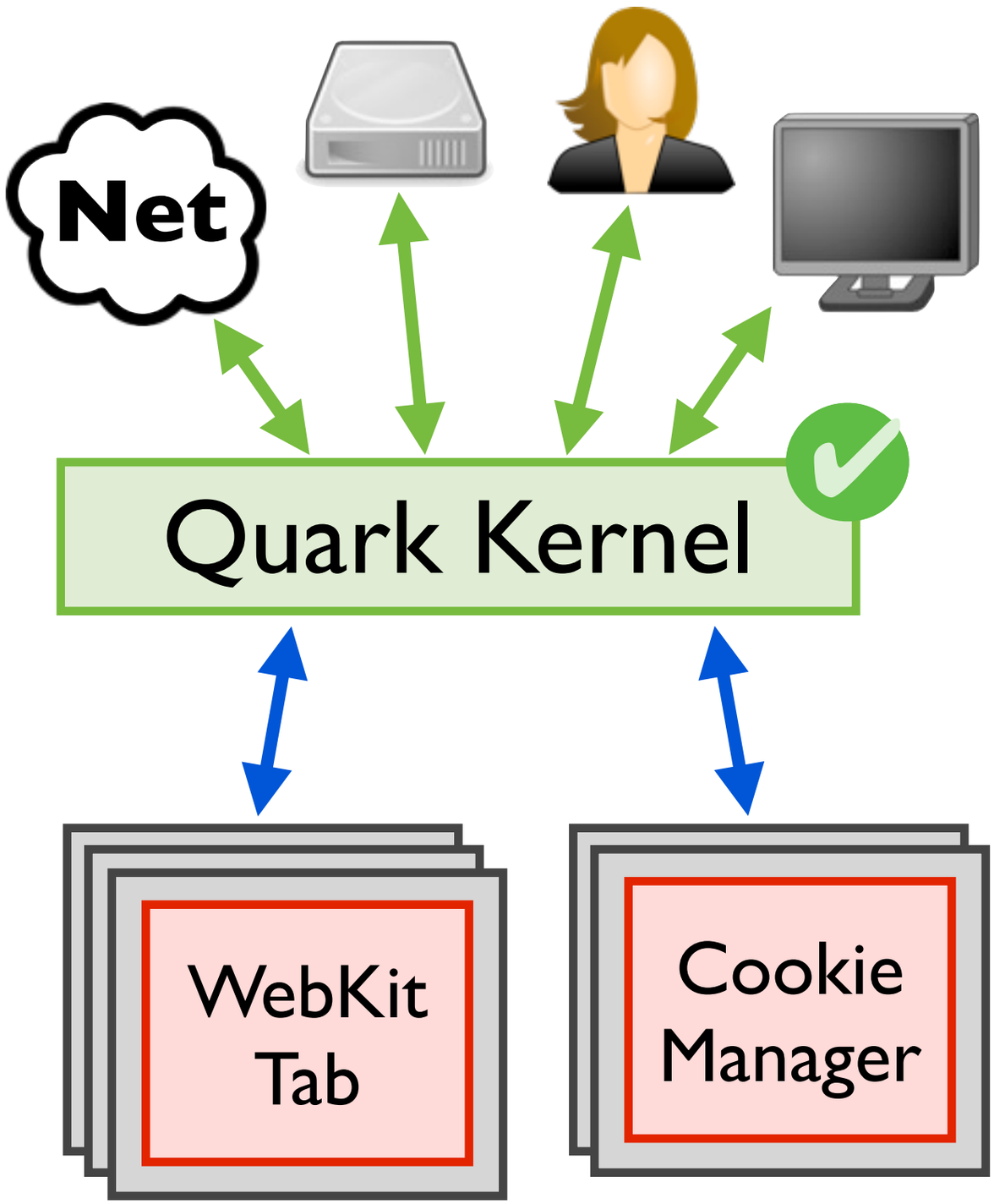
Untrusted Code

two component types

WebKit tabs

cookie managers

Quark: Verified Browser



Resources

Shim

Untrusted Code

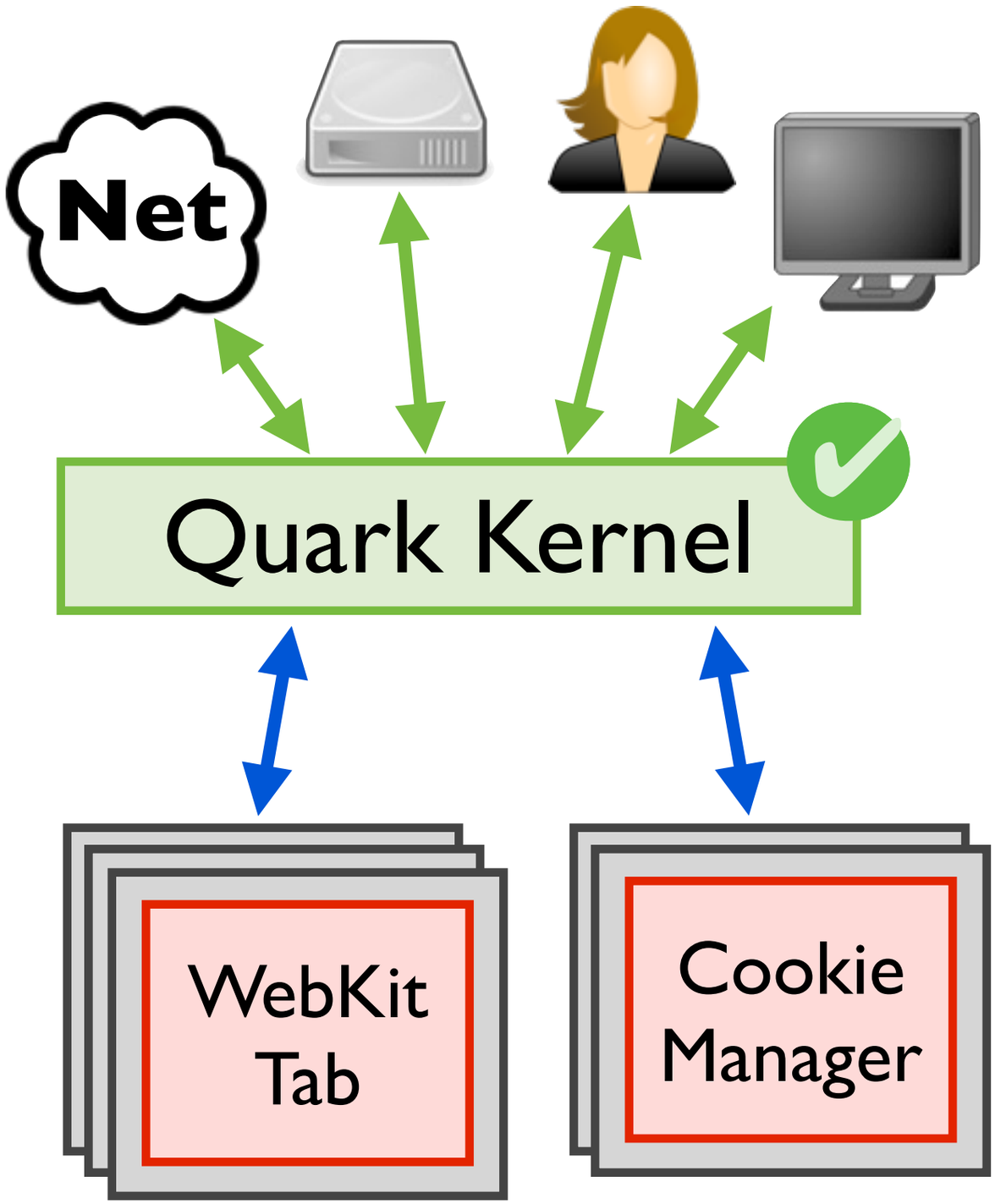
two component types

WebKit tabs

cookie managers

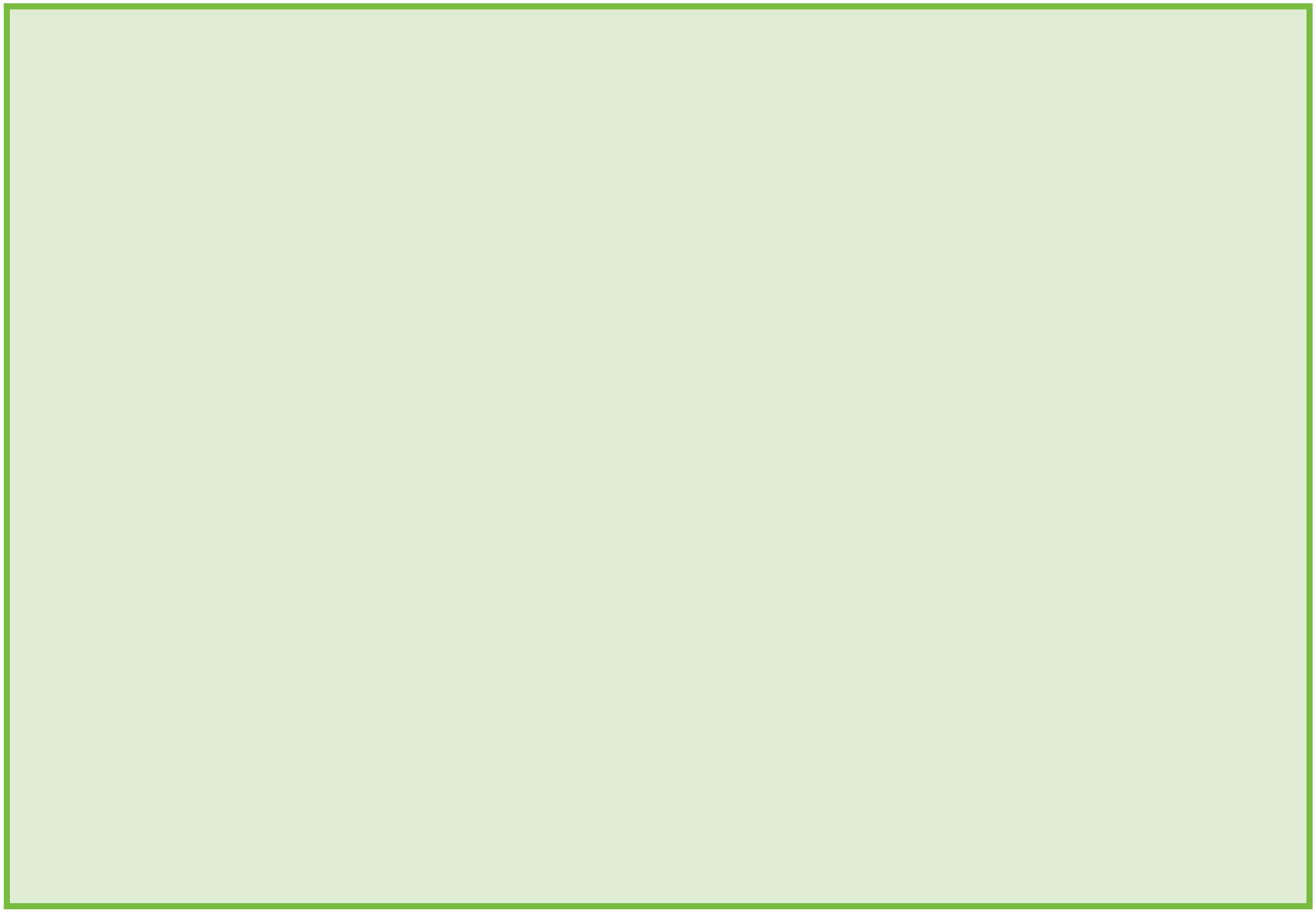
several instances each

Quark: Verified Browser



Quark Kernel: Code, Spec, Proof

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 =>
    ...
```

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

Specify correct behavior wrt syscall seqs

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

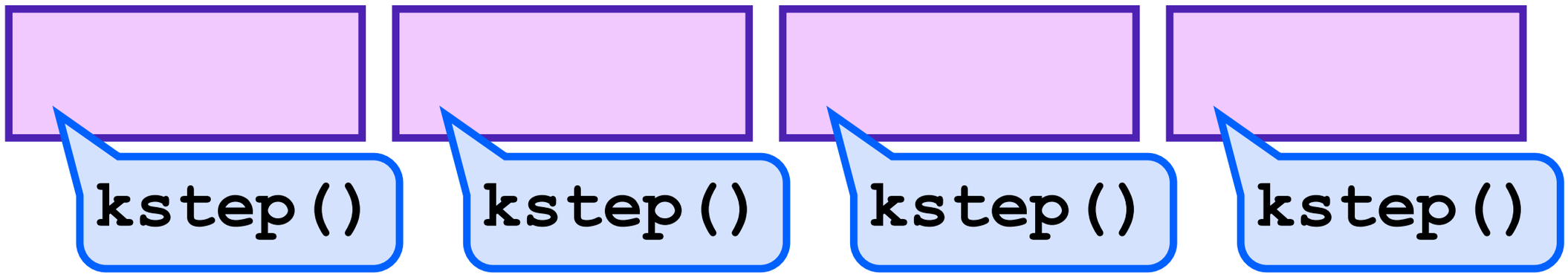
Quark Kernel: Code, *Spec*, Proof

Specify correct behavior wrt syscall seqs

trace: all syscalls made by Quark kernel during execution

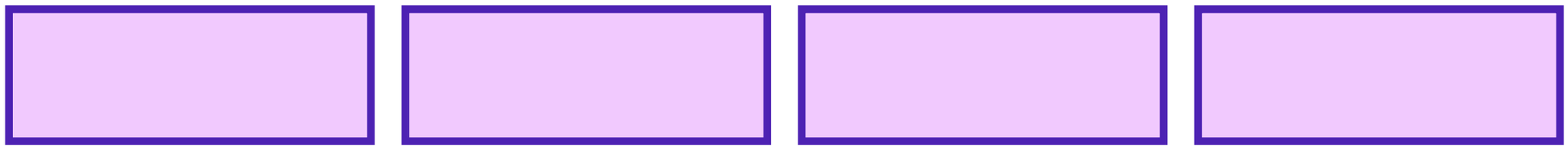
Quark Kernel: Code, *Spec*, Proof

Specify correct behavior wrt syscall seqs



Quark Kernel: Code, *Spec*, Proof

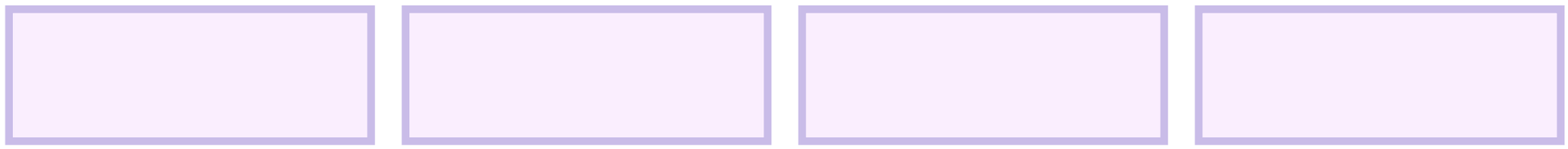
Specify correct behavior wrt syscall seqs



structure of produceable traces supports spec & proof

Quark Kernel: Code, *Spec*, Proof

Specify correct behavior wrt syscall seqs

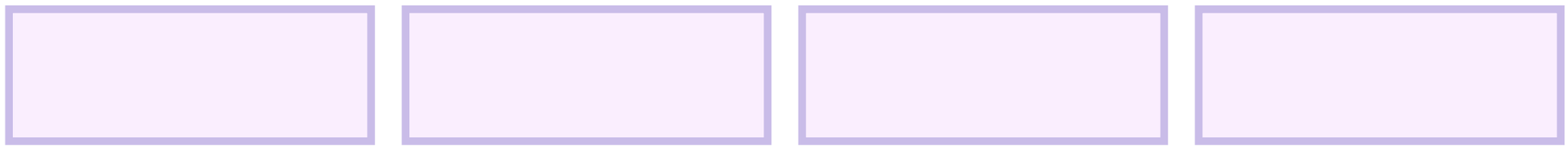


structure of produceable traces supports spec & proof

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

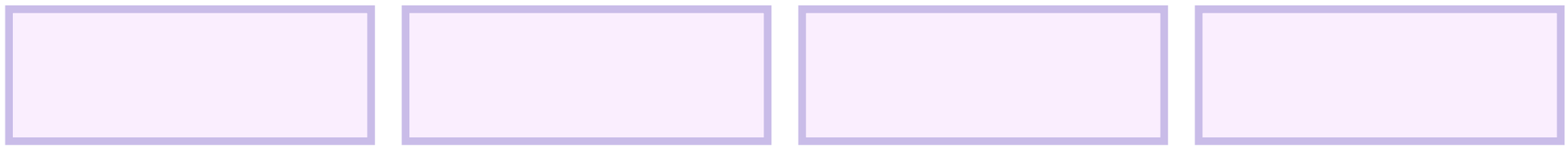
```
forall trace tab domain,
```

for *any* trace, tab, and domain

where trace is a sequence of syscalls

Quark Kernel: Code, *Spec*, Proof

Specify correct behavior wrt syscall seqs



structure of produceable traces supports spec & proof

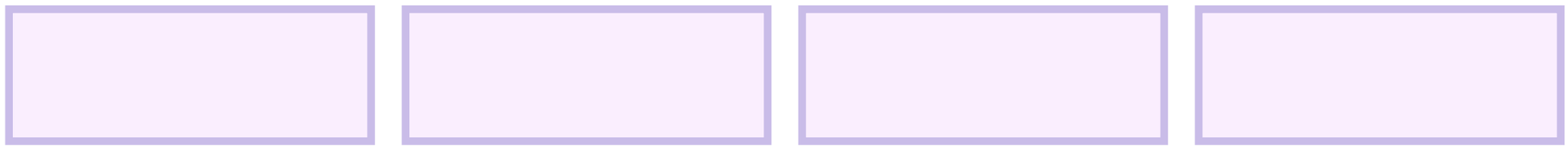
Example: address bar correctness

```
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

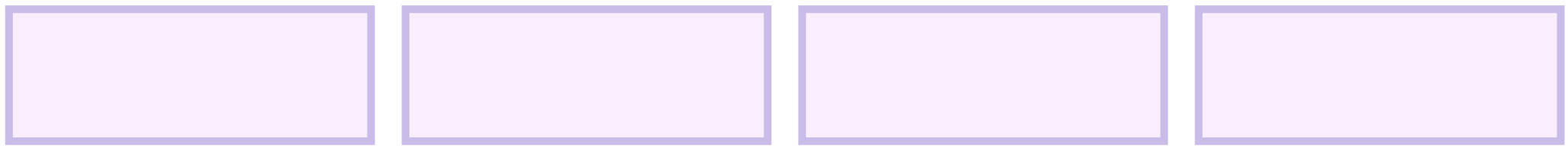
Example: address bar correctness

```
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

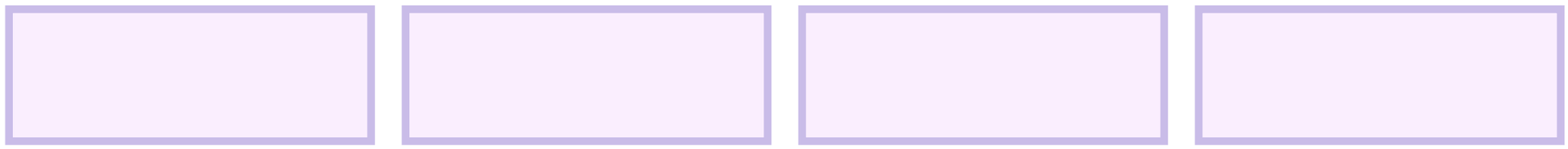
Example: address bar correctness

```
forall trace ta
  quark_produce
  tab = cur_ta (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

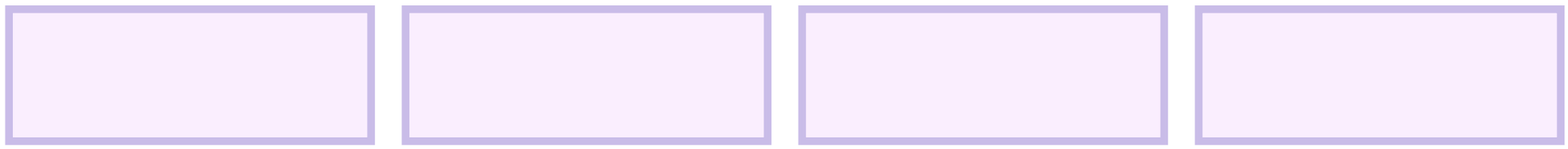
Example: address bar correctness

```
forall trace tab do
  quark_produced(tr
  tab = cur_tab(tra
  domain = addr_ba
  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*

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

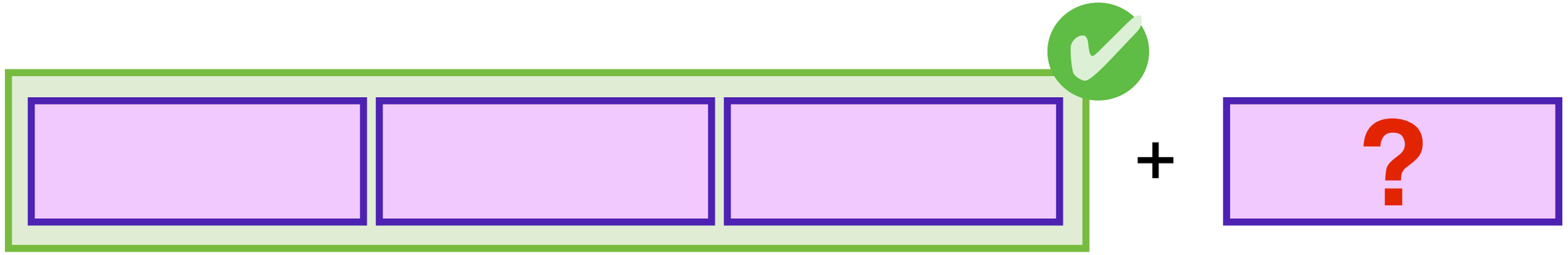
induction hypothesis:

trace valid up to this point

Quark Kernel: Code, Spec, *Proof*

Prove kernel code satisfies sec props

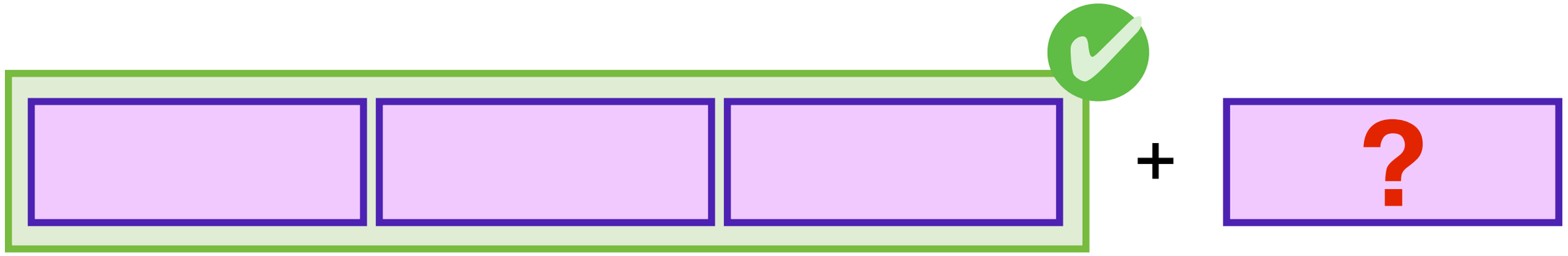
by induction on traces Quark can produce



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 using interactive proof assistant

Quark Kernel: Code, Spec, Proof

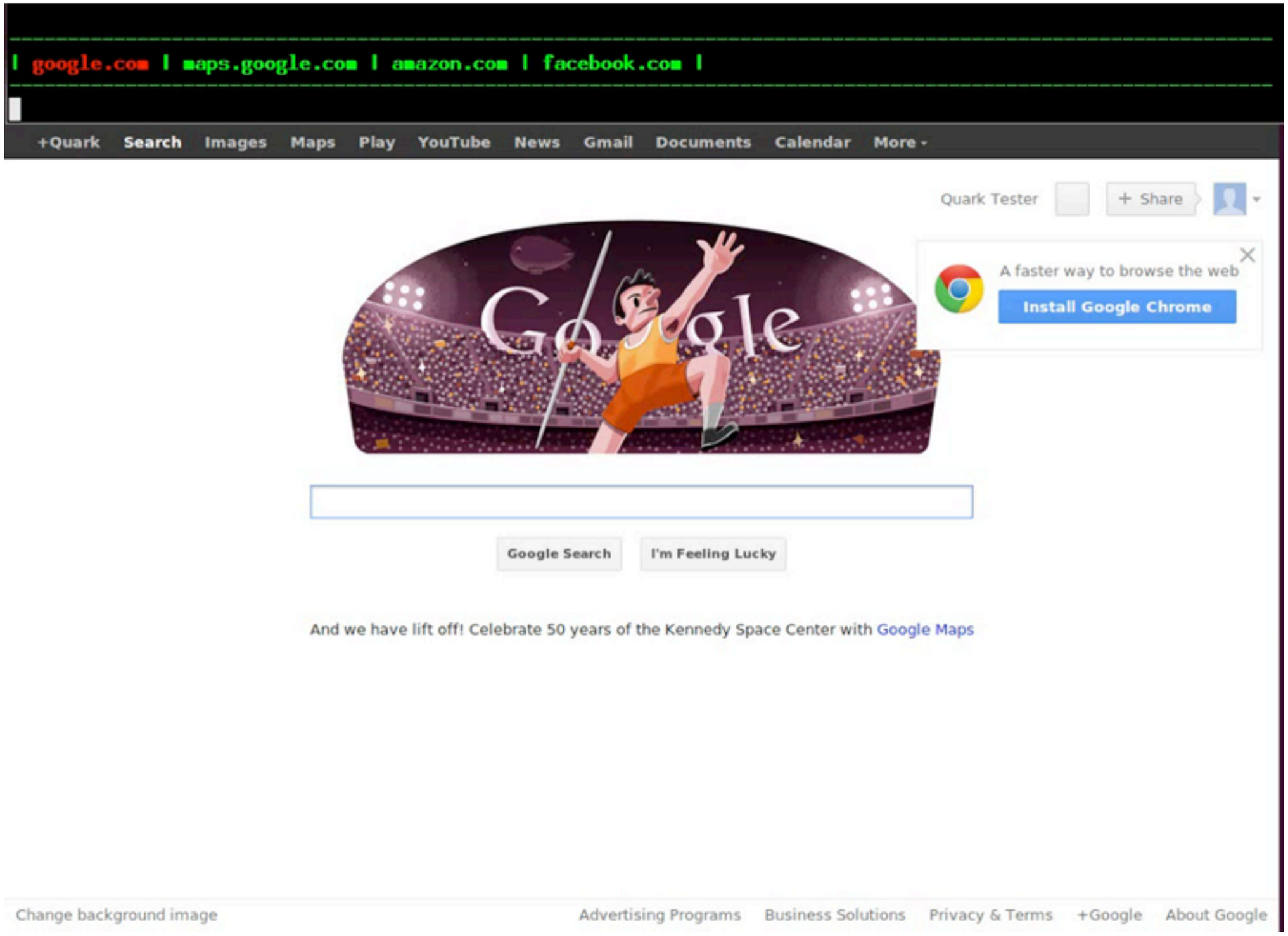
Key Insight

Guarantee sec props for browser

Use state-of-the-art components

Only prove simple browser kernel

Usability Demo Video



Trusted Computing Base

Infrastructure we assume correct

any 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]

...

Security Analysis

Formally prove important sec props

WebKit defenses remain in effect

Other desirable security policies

Future Work

Filesystem access, sound, history

could be implemented w/out major redesign

Finer grained resource accesses

support mashups and plugins

Liveness properties

formally prove that kernel never blocks

Conclusion

Formal Shim Verification

- Guarantee sec props for entire system
- Only reason about small shim
- Radically ease verification burden

Quark: Verified Browser

- Guarantee sec props for browser
- Only prove simple browser kernel
- Use state-of-the-art components

http://goto.ucsd.edu/quark