Automating Formal Proofs for Reactive Systems

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University of California, San Diego

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University of Washington

Proof Assistant Based Verification

Proof Assistant Based Verification

Testing tool for C compilers [Yang et al. PLDI 11]

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Testing tool for C compilers [Yang et al. PLDI 11]

Compiler	*Bugs Found*

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Testing tool for C compilers [Yang et al. PLDI 11]

Compiler	*Bugs Found*
GCC	122

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Testing tool for C compilers [Yang et al. PLDI 11]

Compiler	*Bugs Found*
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Clang/LLVM	181

Proof Assistant Based Verification

Testing tool for C compilers [Yang et al. PLDI 11]

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CompCert	?

Proof Assistant Based Verification

Testing tool for C compilers [Yang et al. PLDI 11]

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Proof Assistant Based Verification

Testing tool for C compilers

[Yang et al. PLDI 11]
[Le et al. PLDI 14]

Compiler	*Bugs Found*
GCC	122
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CompCert	0

Proof Assistant Based Verification

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Proof Assistant

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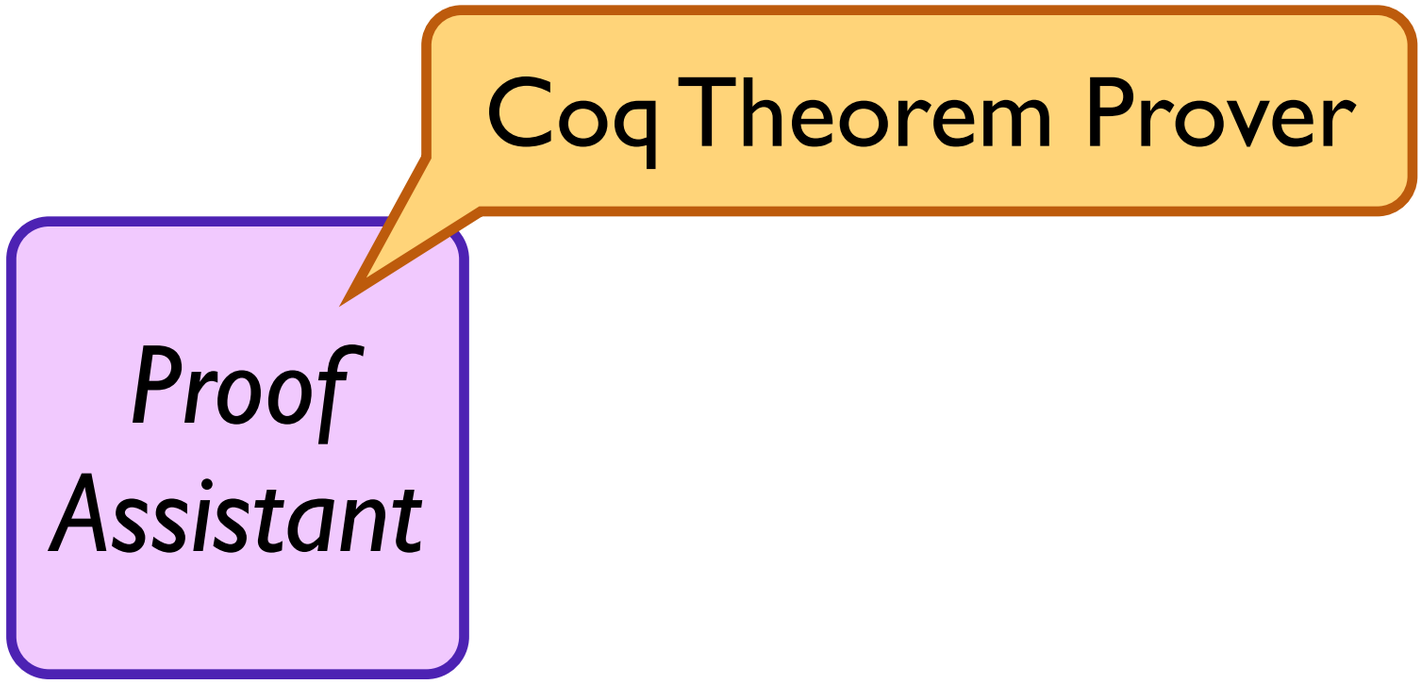

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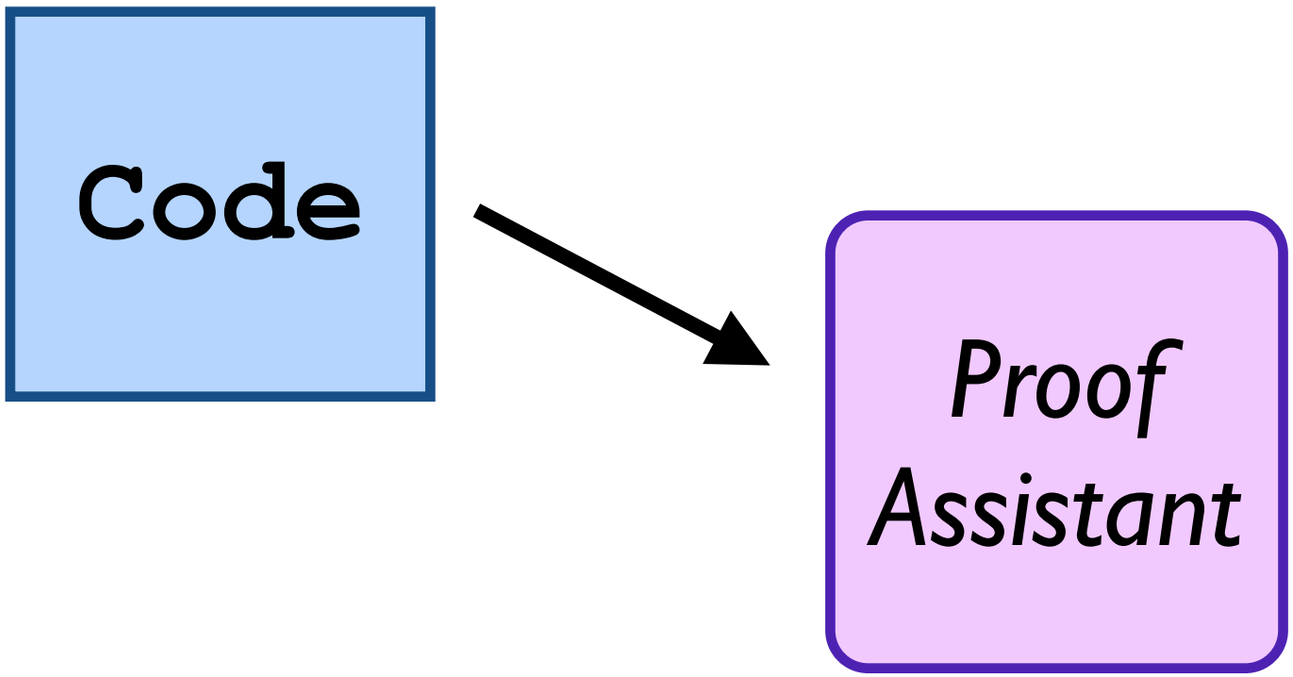

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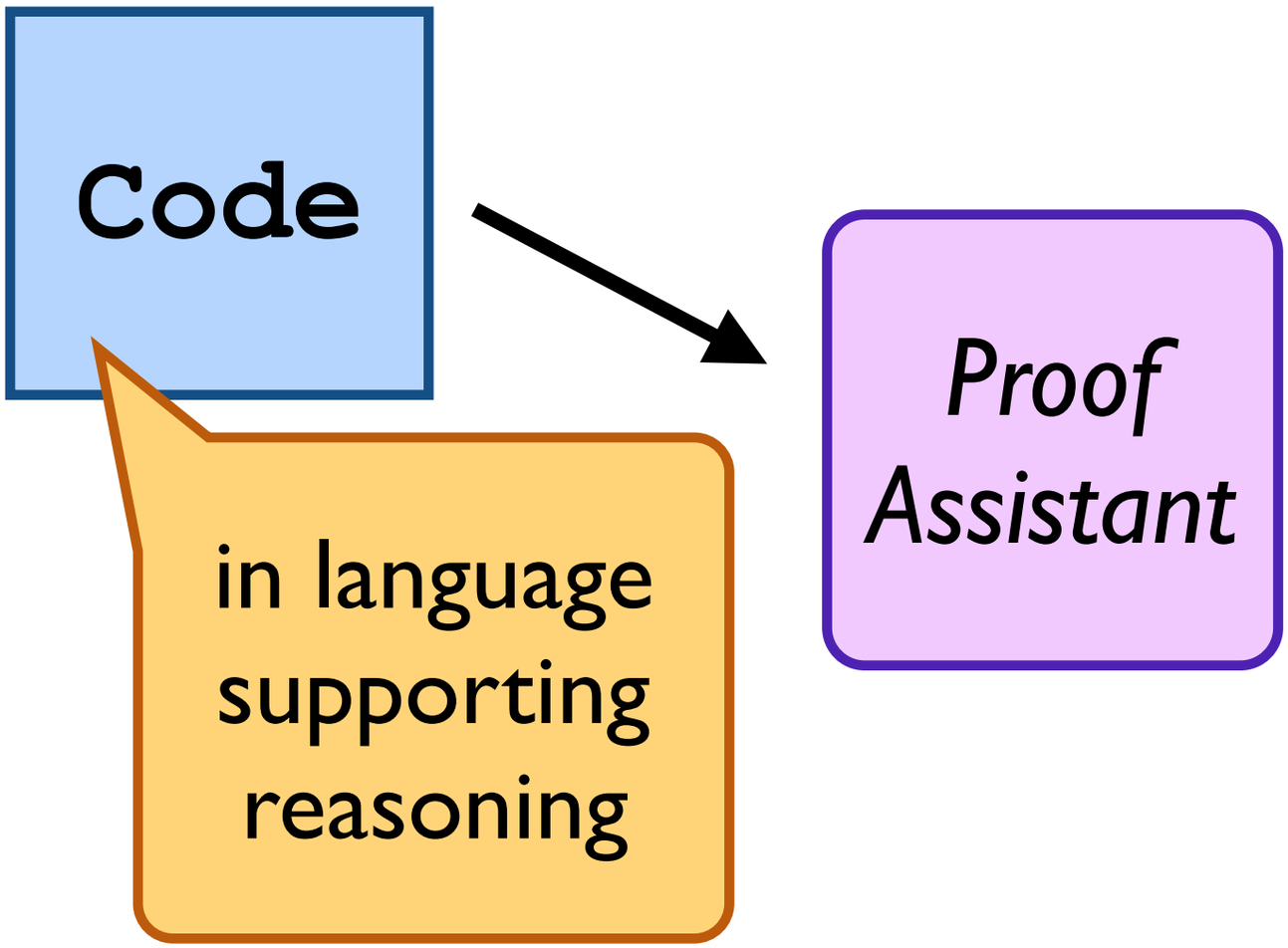

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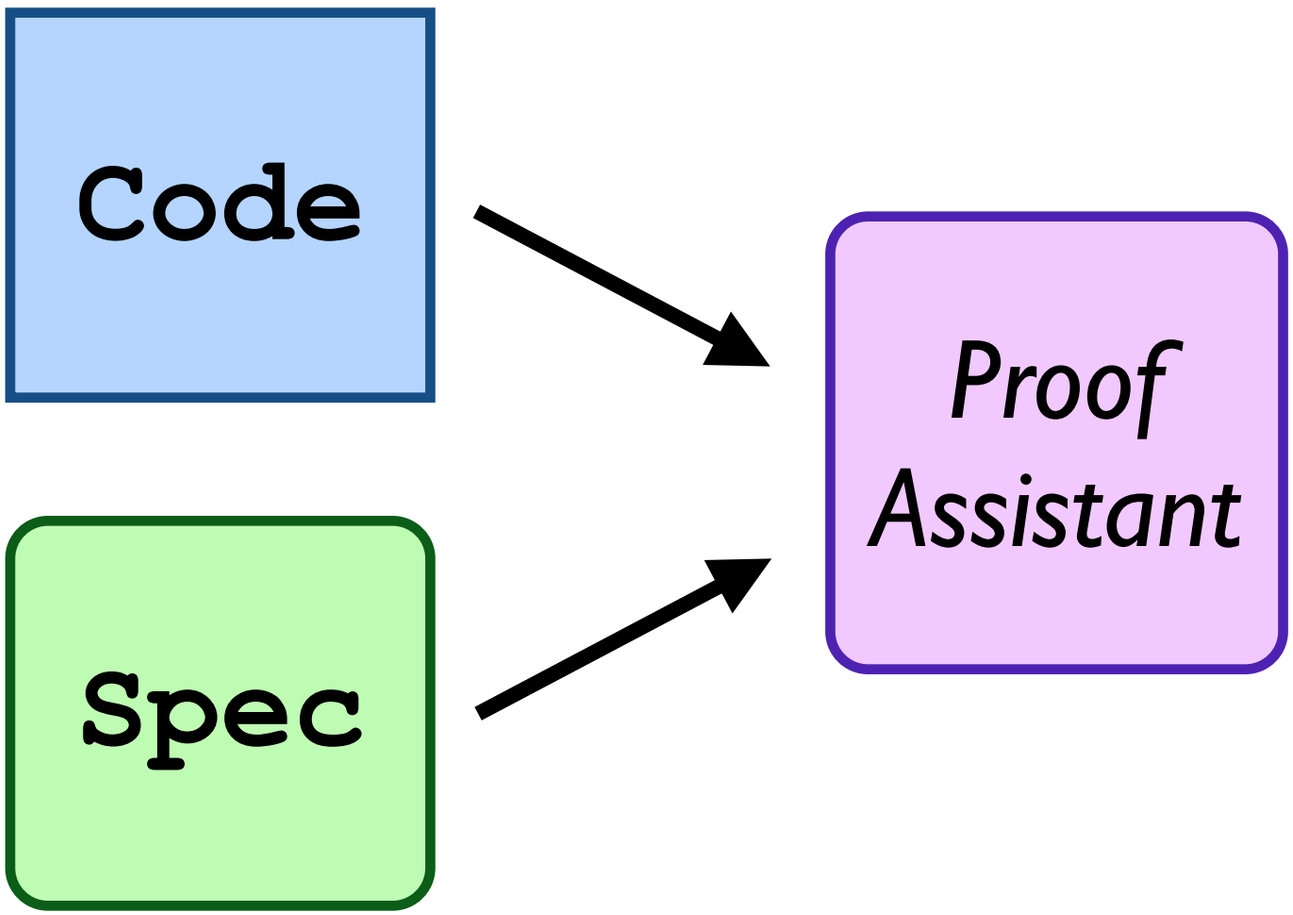

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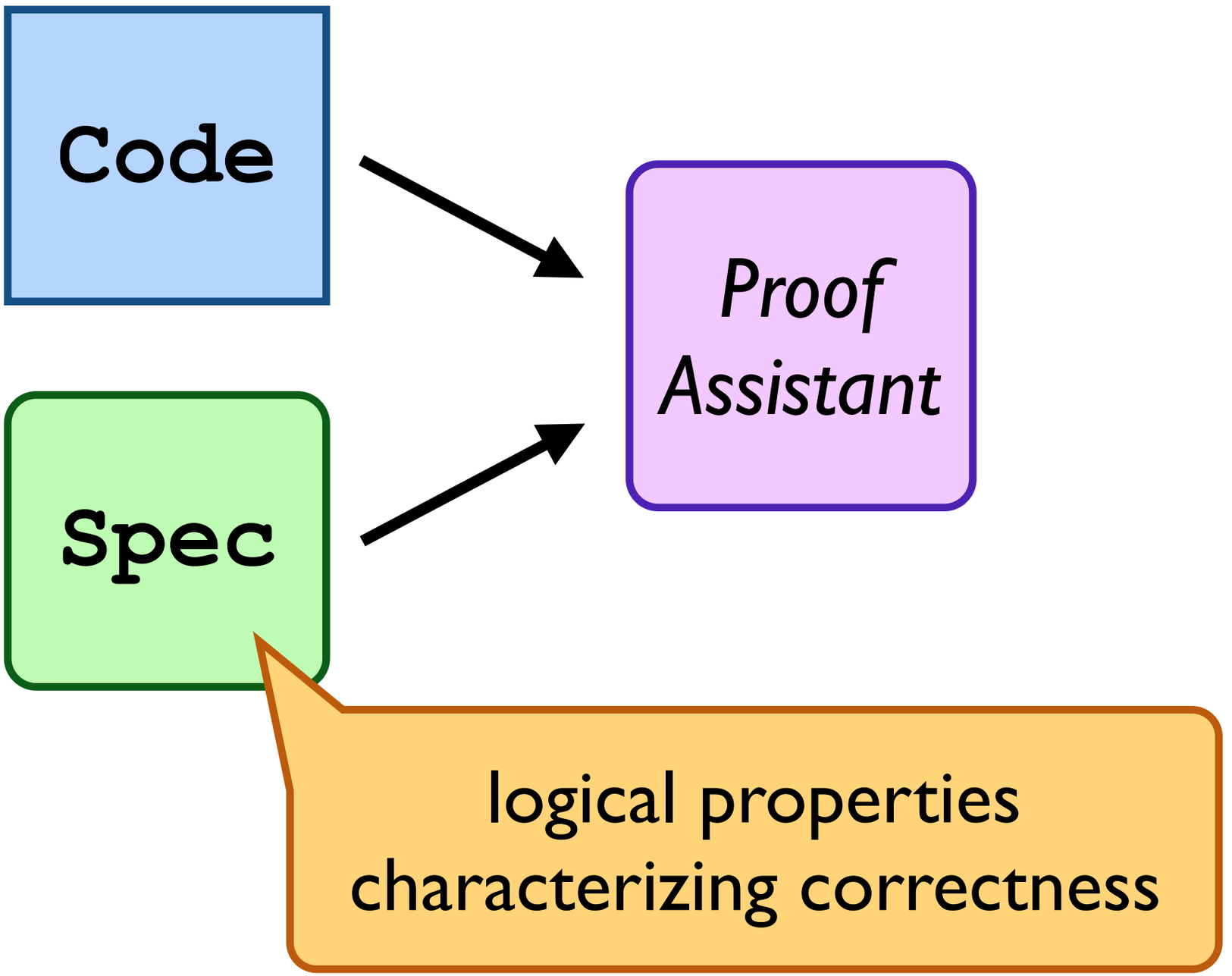

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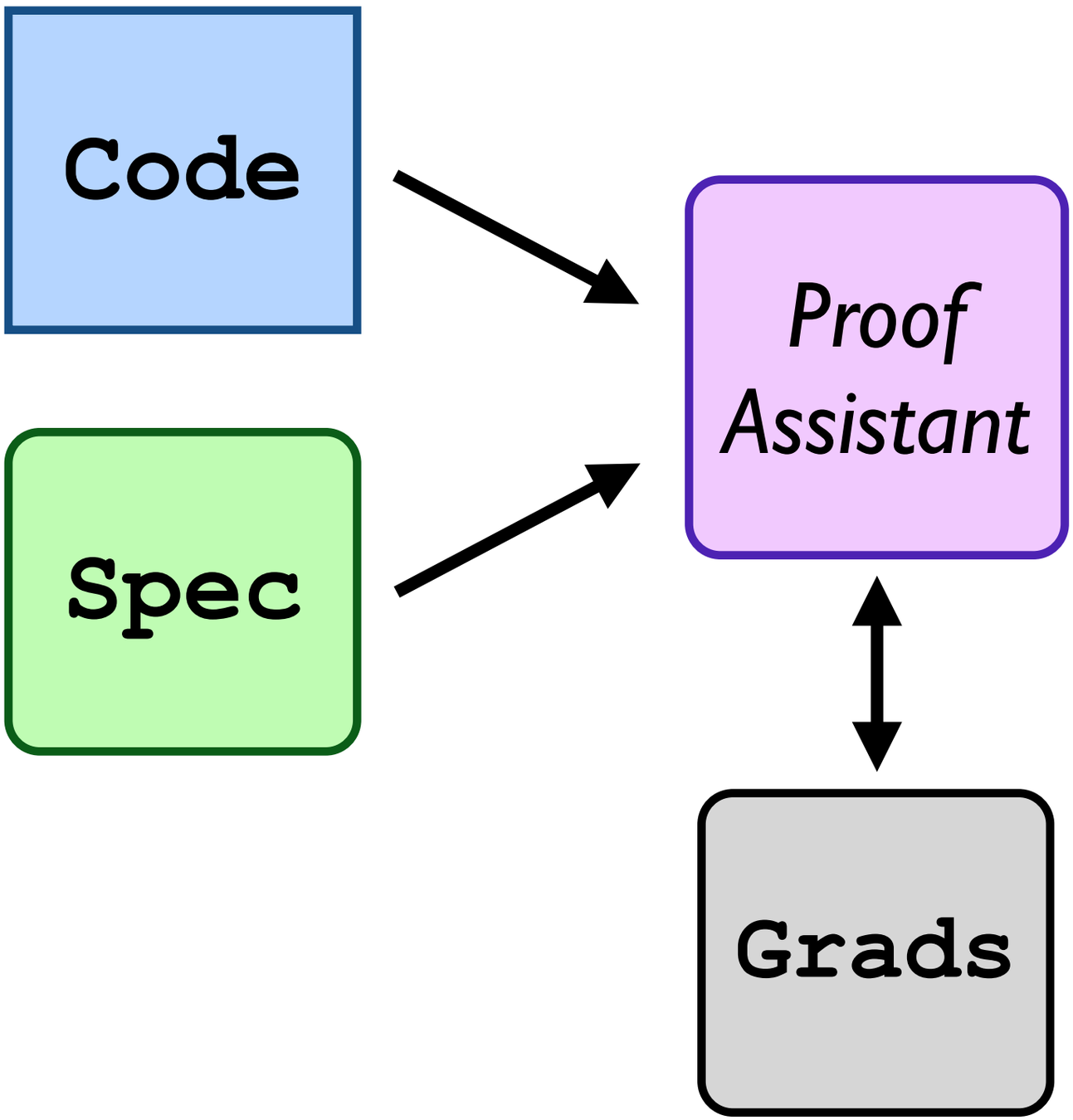

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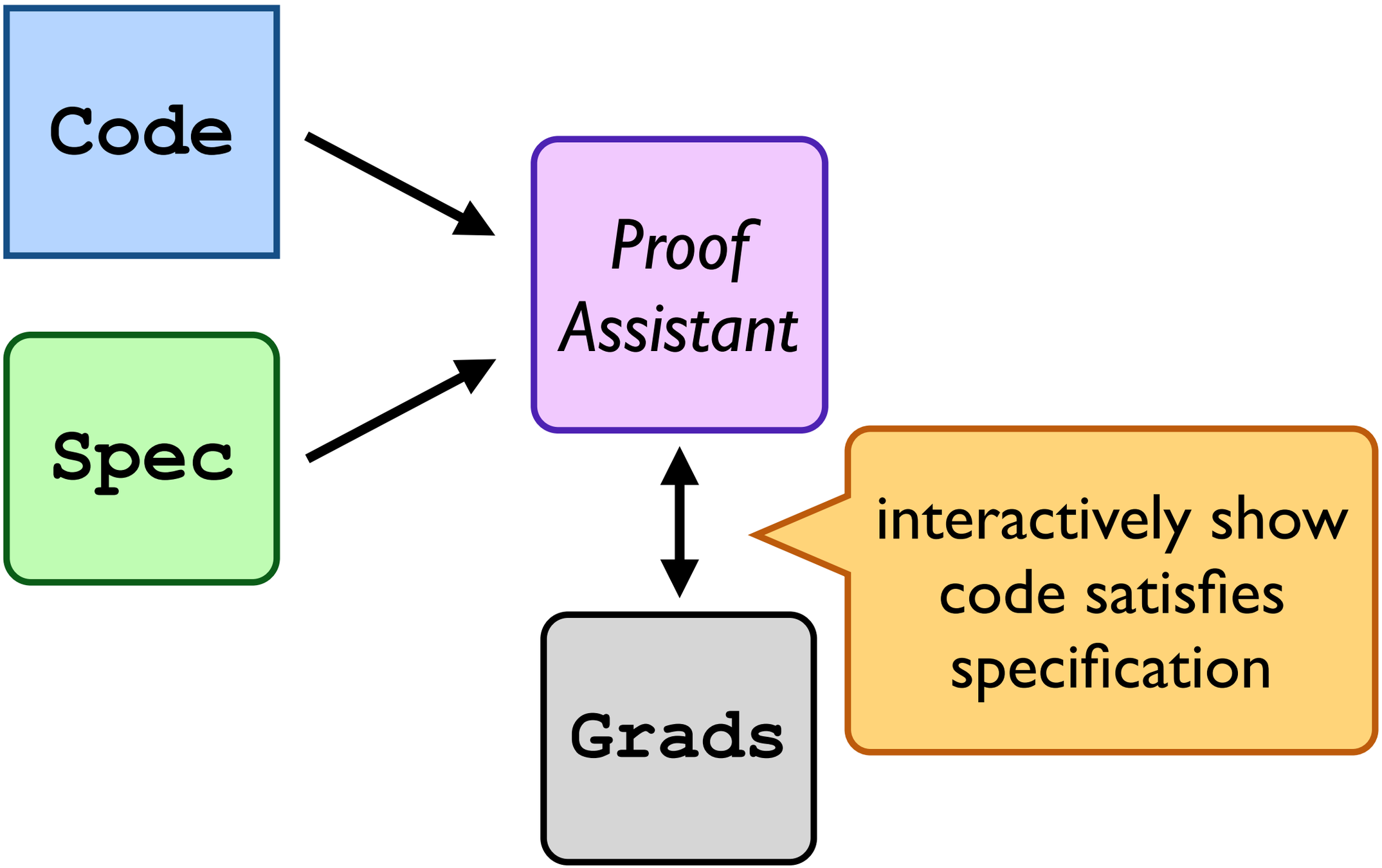

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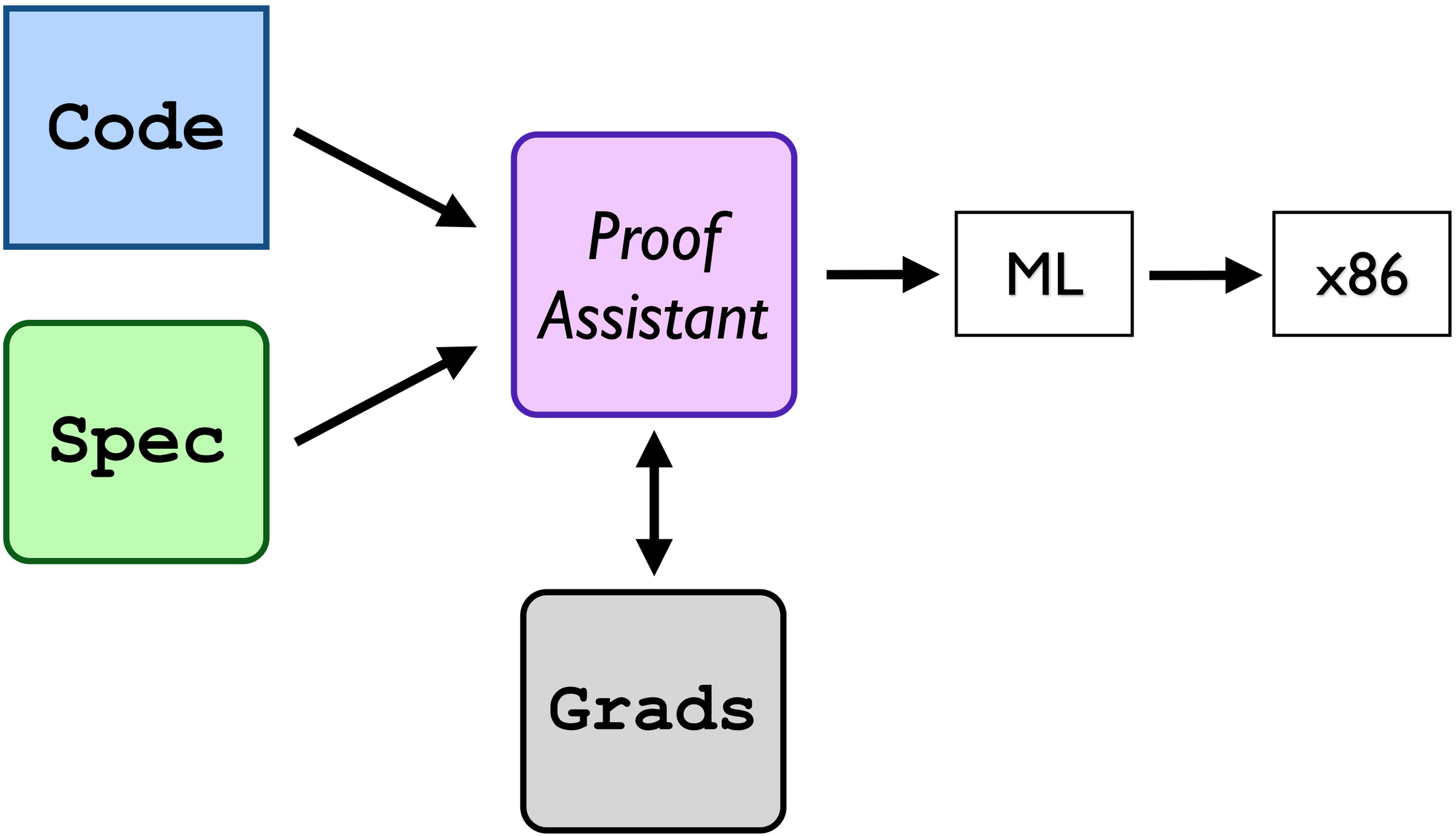

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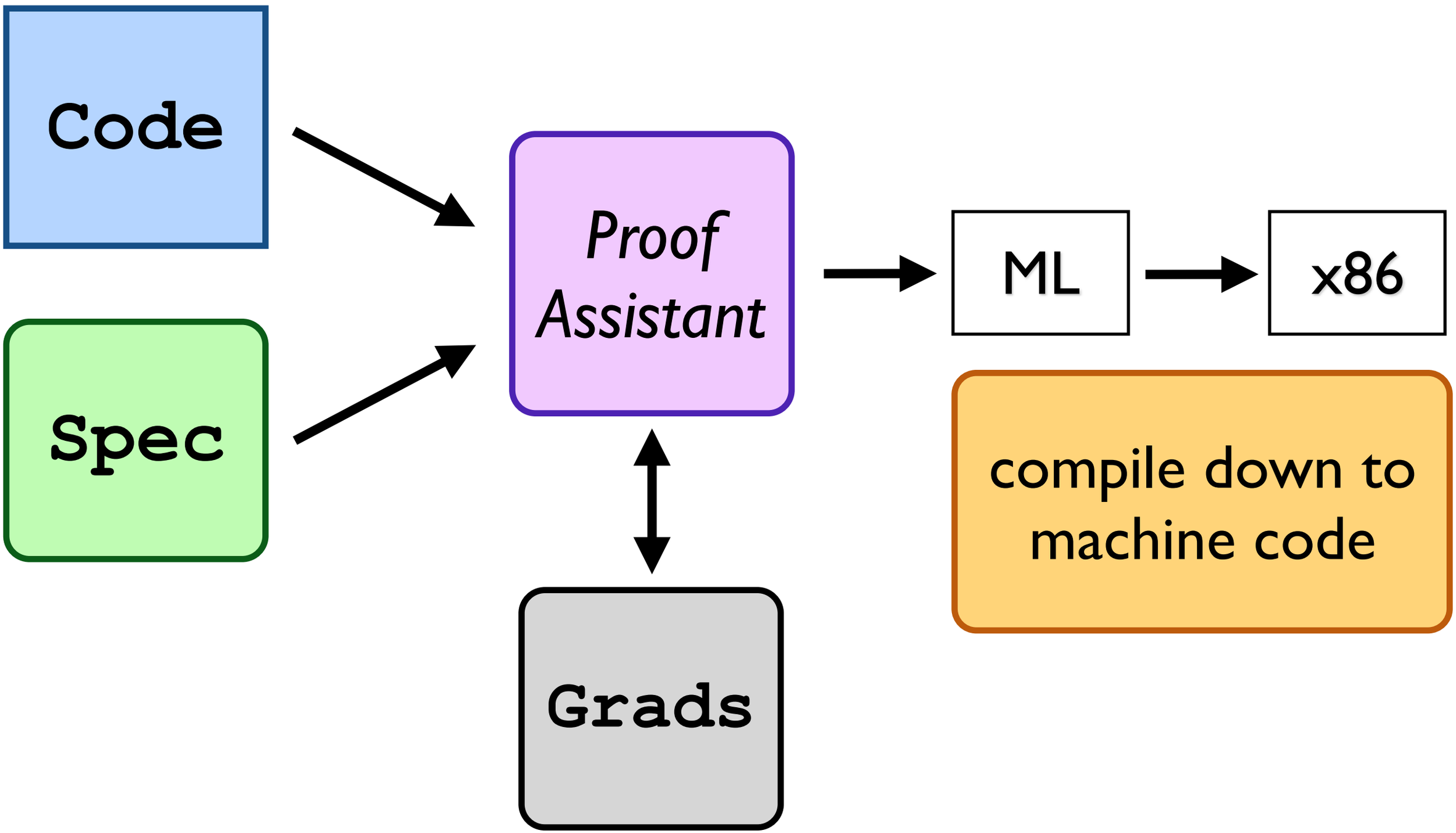

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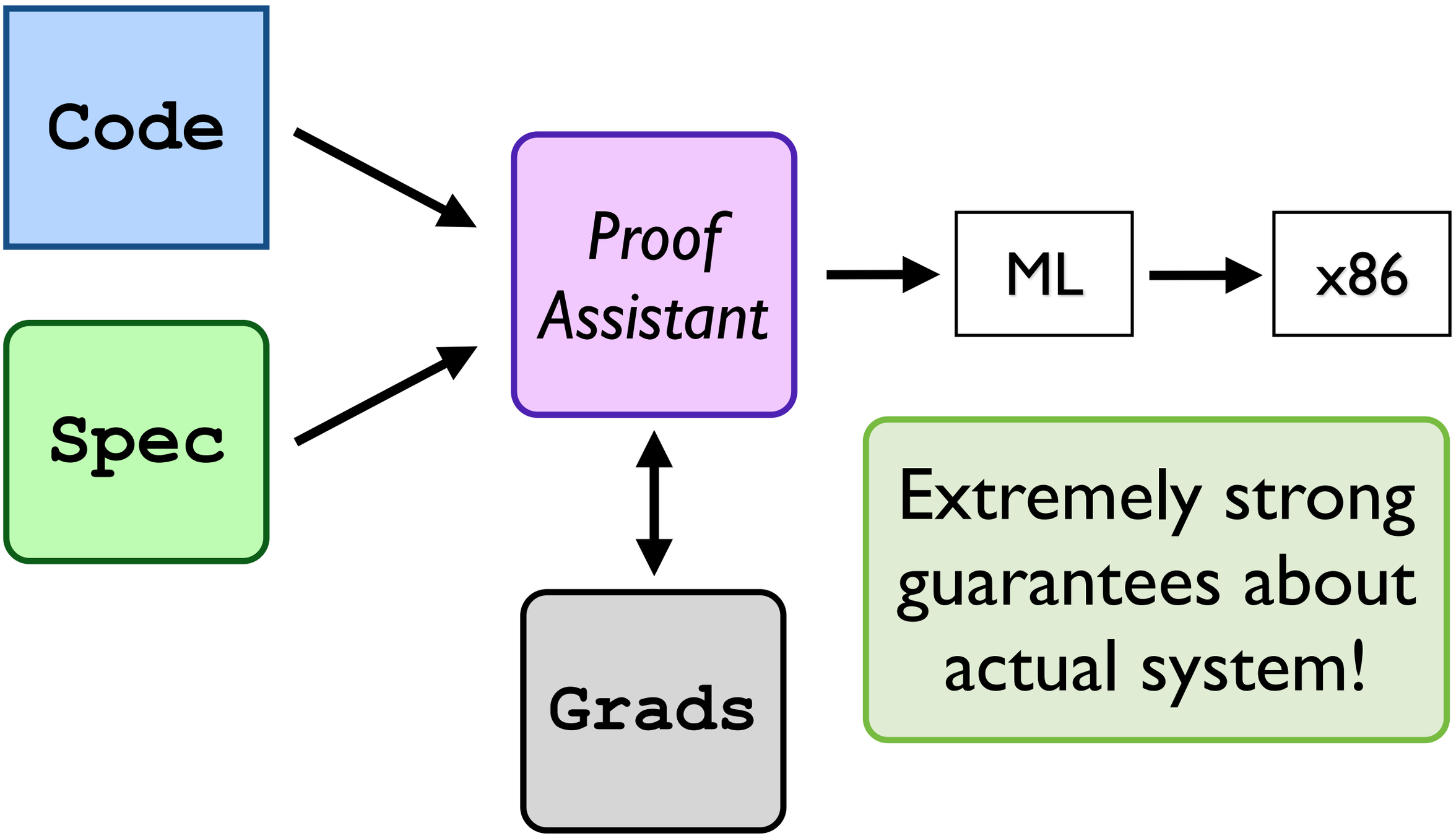

Proof Assistant Based Verification

Verified Compiler: CompCert

[Leroy POPL 06]

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[Leroy POPL 06]

Verified OS micro-kernel: seL4

[Klein et al. SOSP 09]

Proof Assistant Based Verification

Verified Compiler: CompCert

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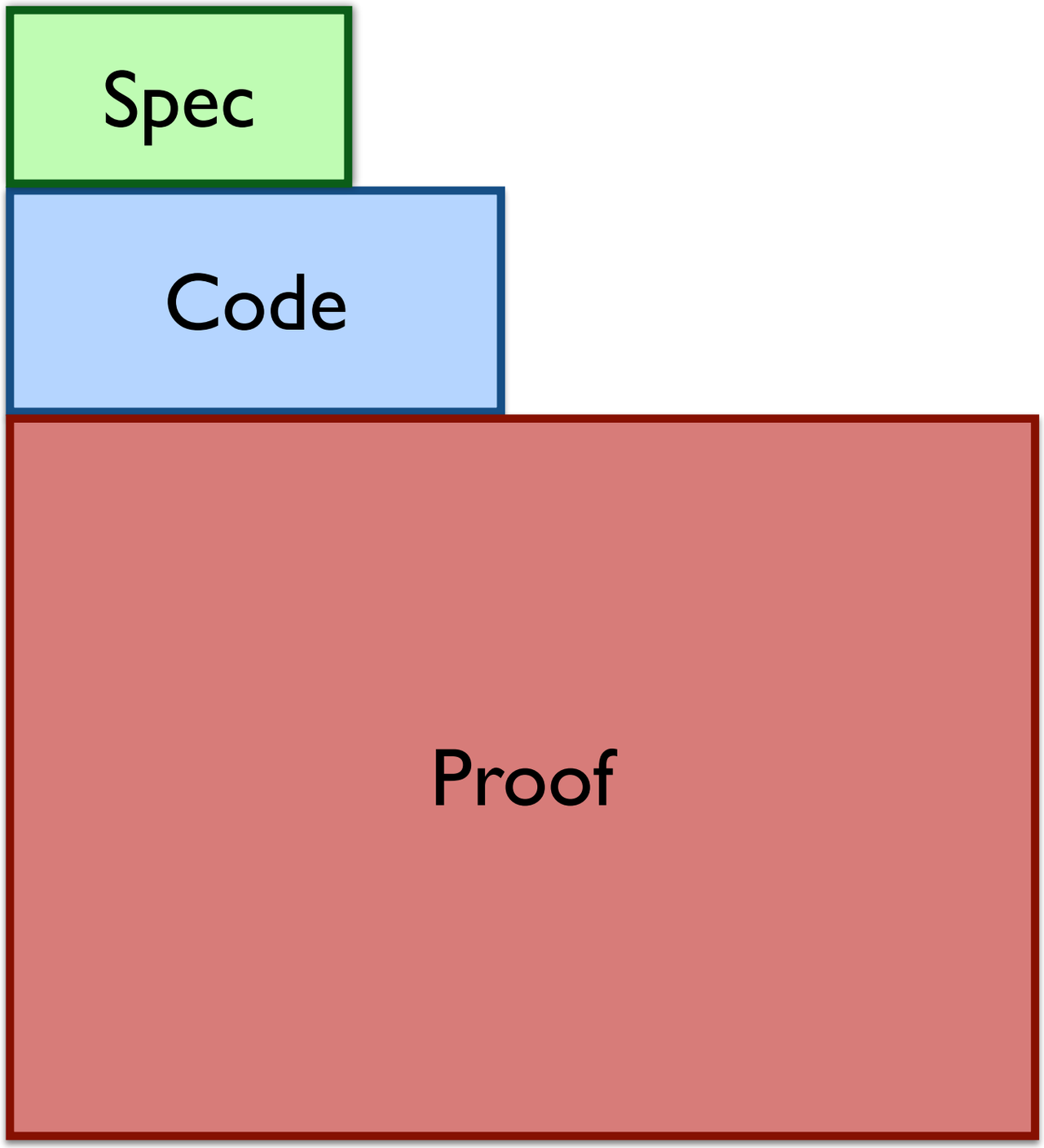
Verified OS micro-kernel: seL4

[Klein et al. SOSP 09]

Verified Web browser: Quark

[Jang et al. Security 12]

Manual Proof Burden



Manual Proof Burden

Verified OS micro-kernel: seL4

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9,000 lines of C code

Manual Proof Burden

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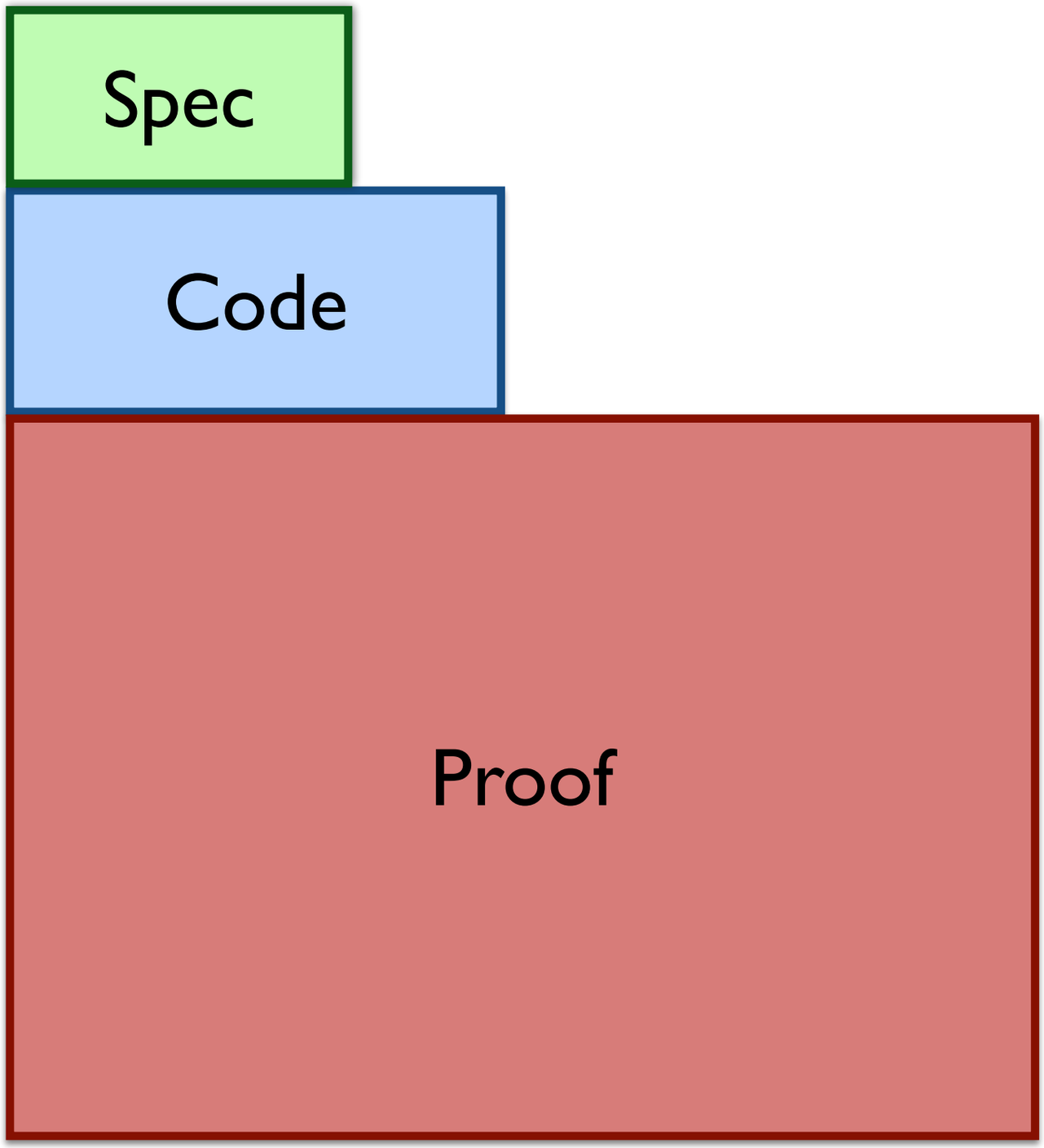
9,000 lines of C code

20 person-years for verification

Manual Proof Burden



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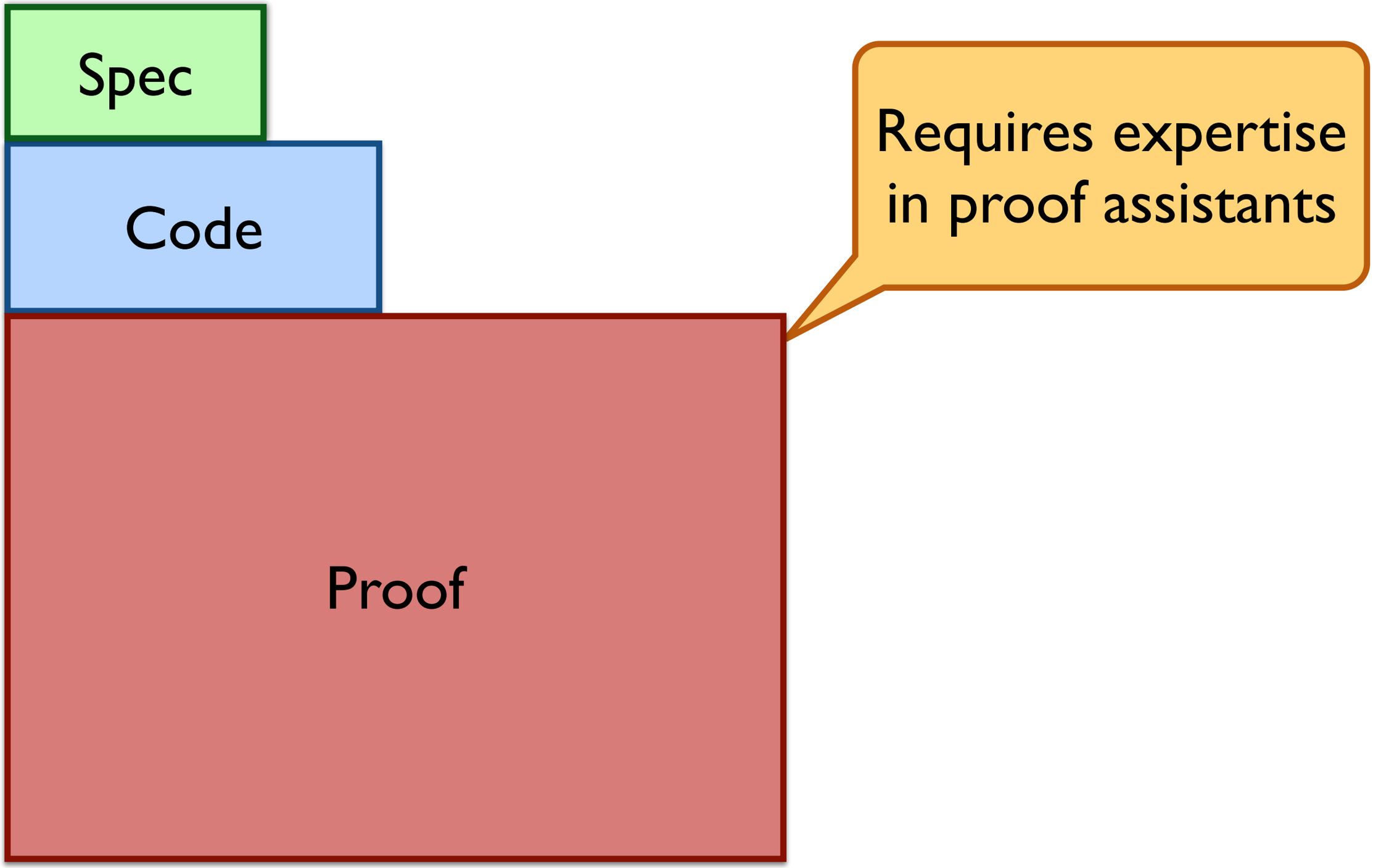

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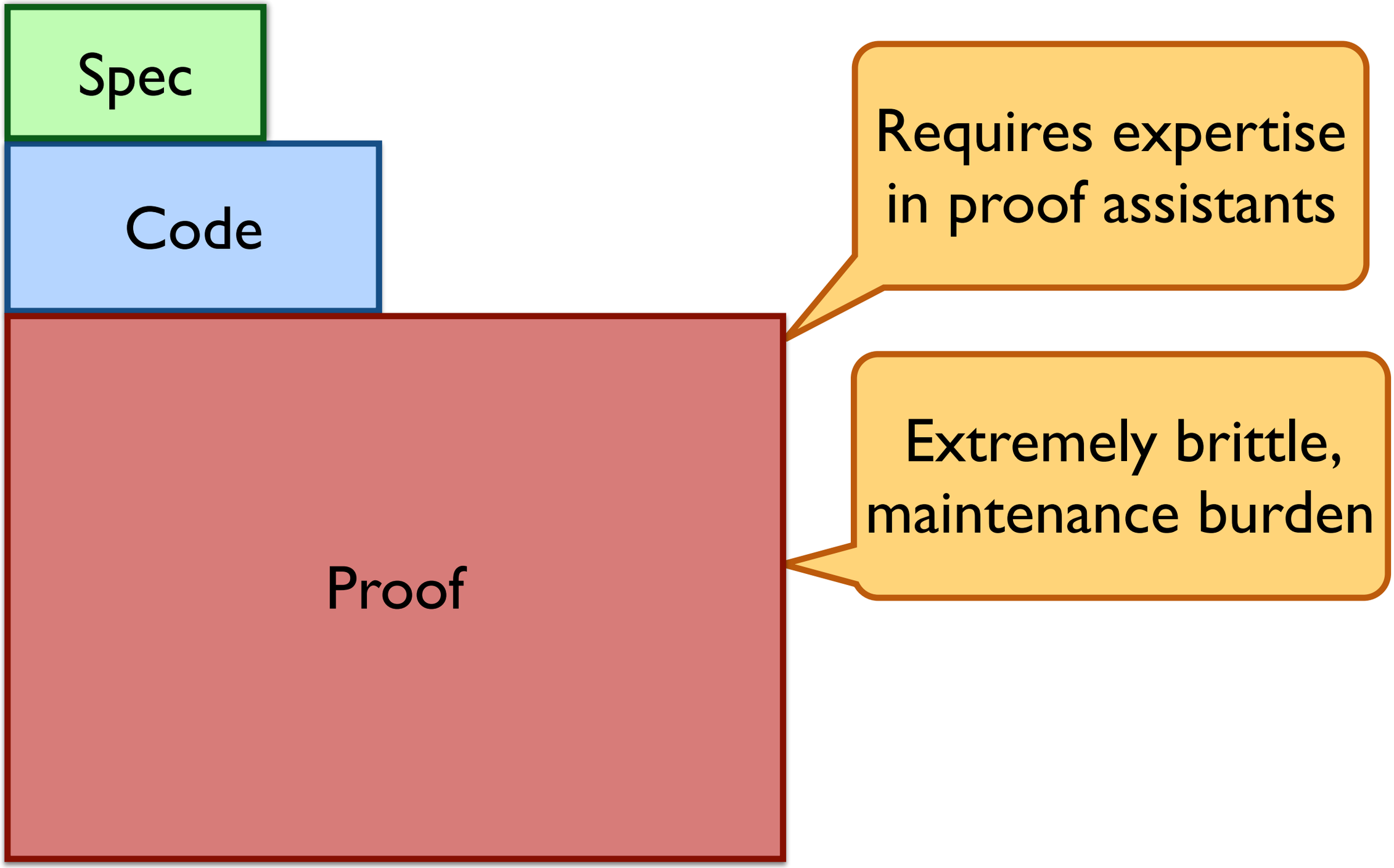

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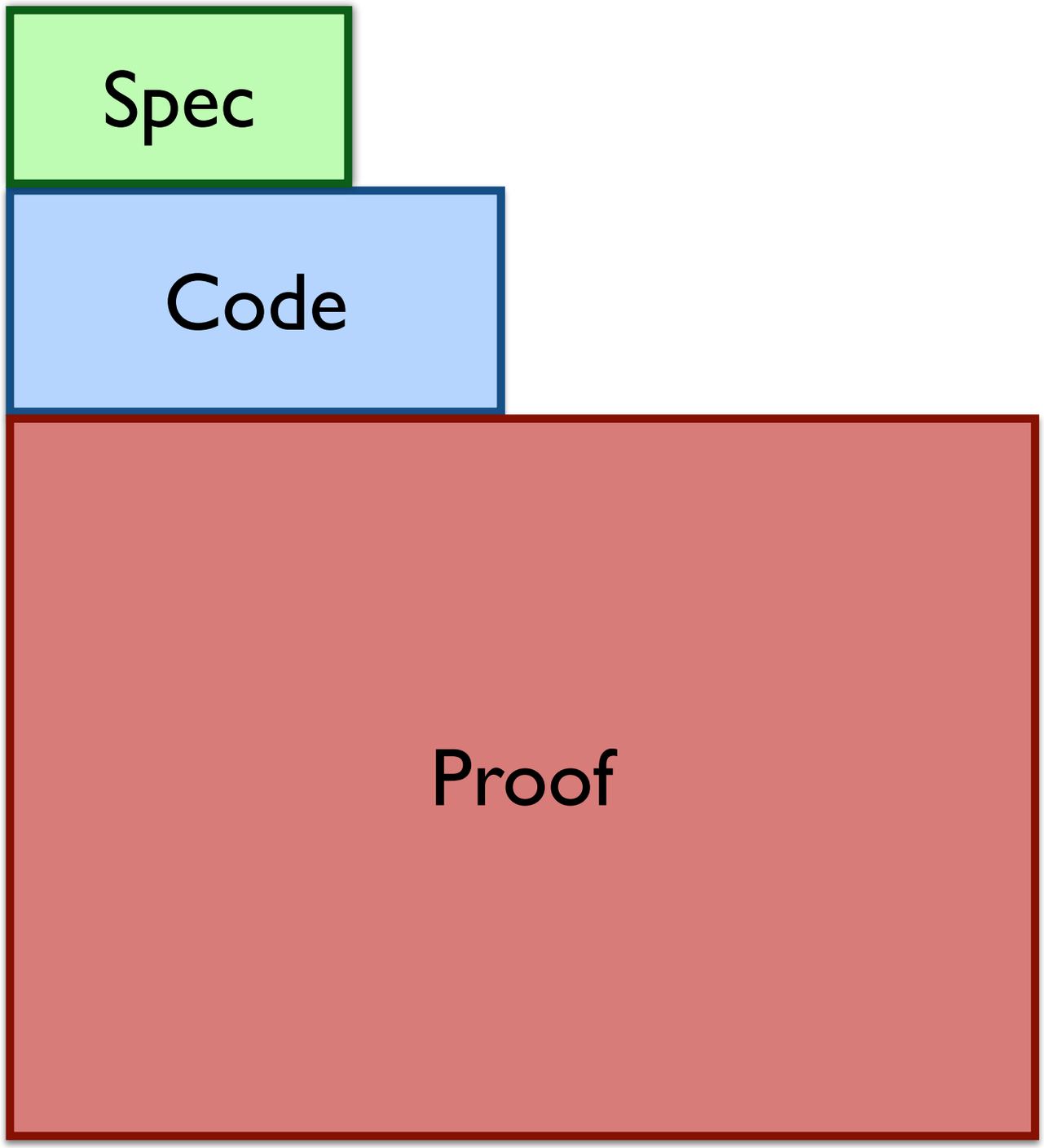

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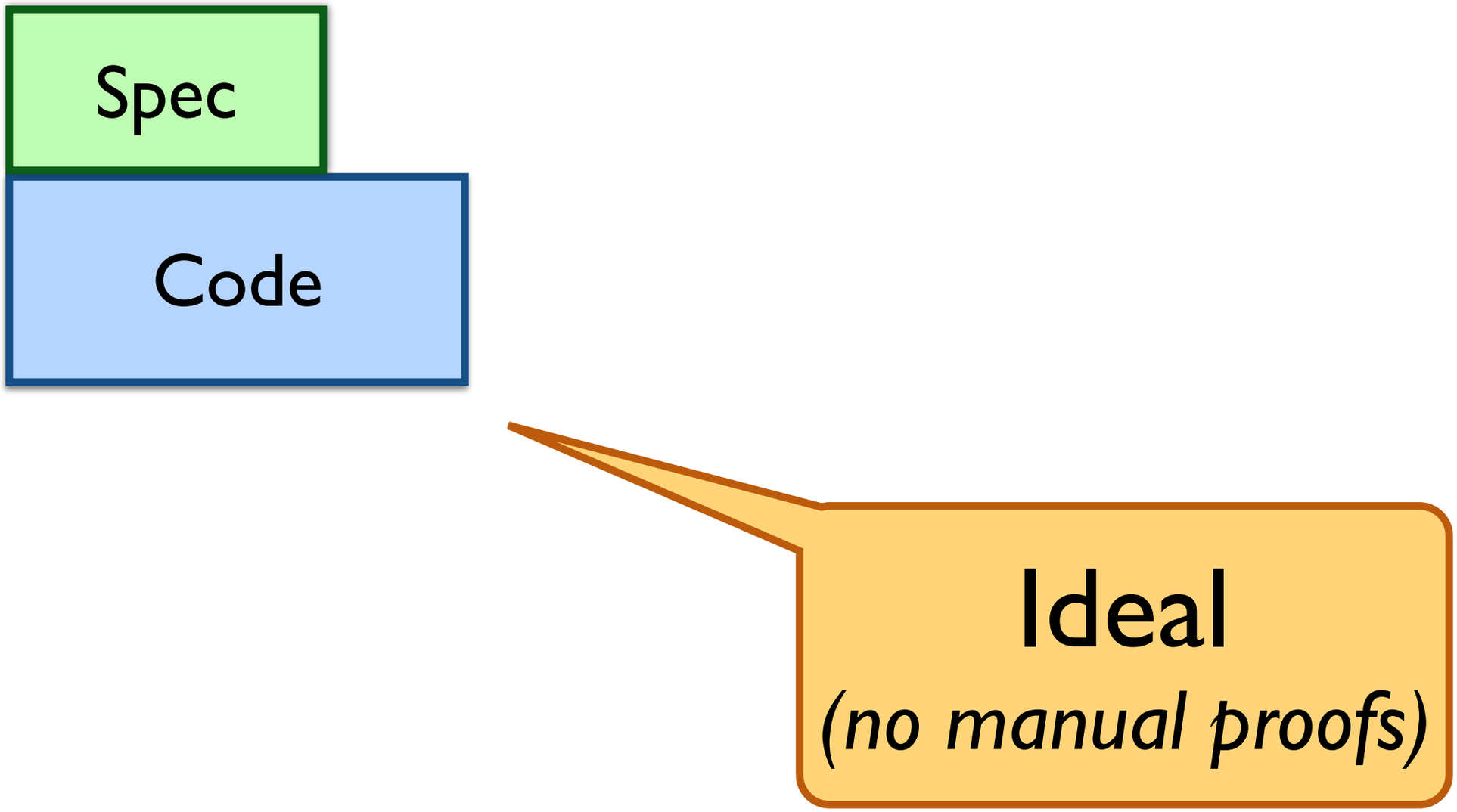

Single application domain

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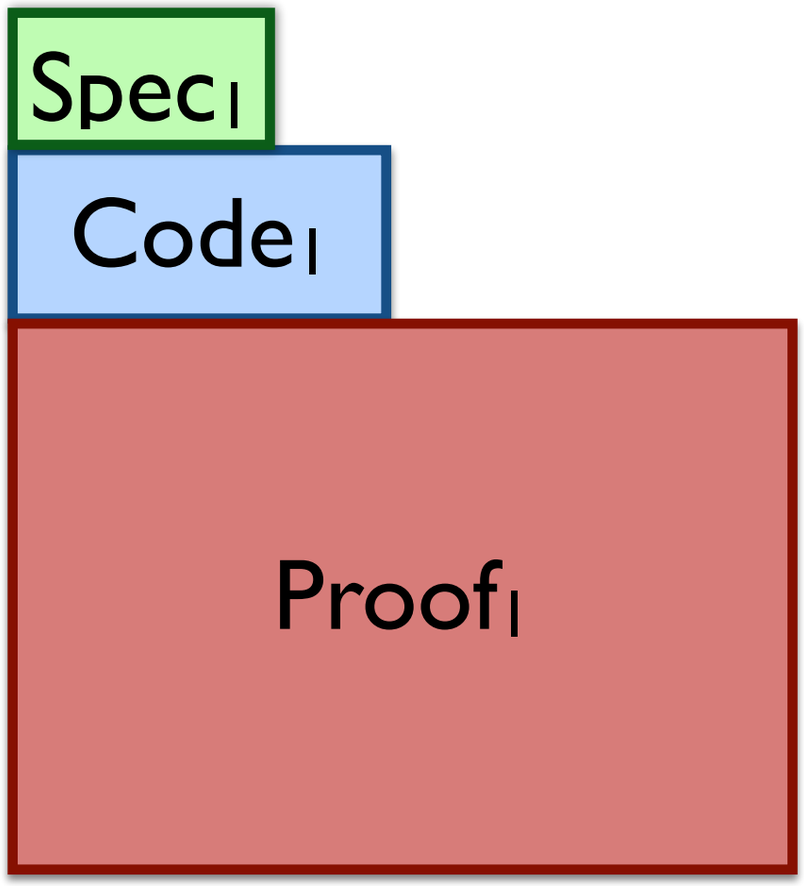

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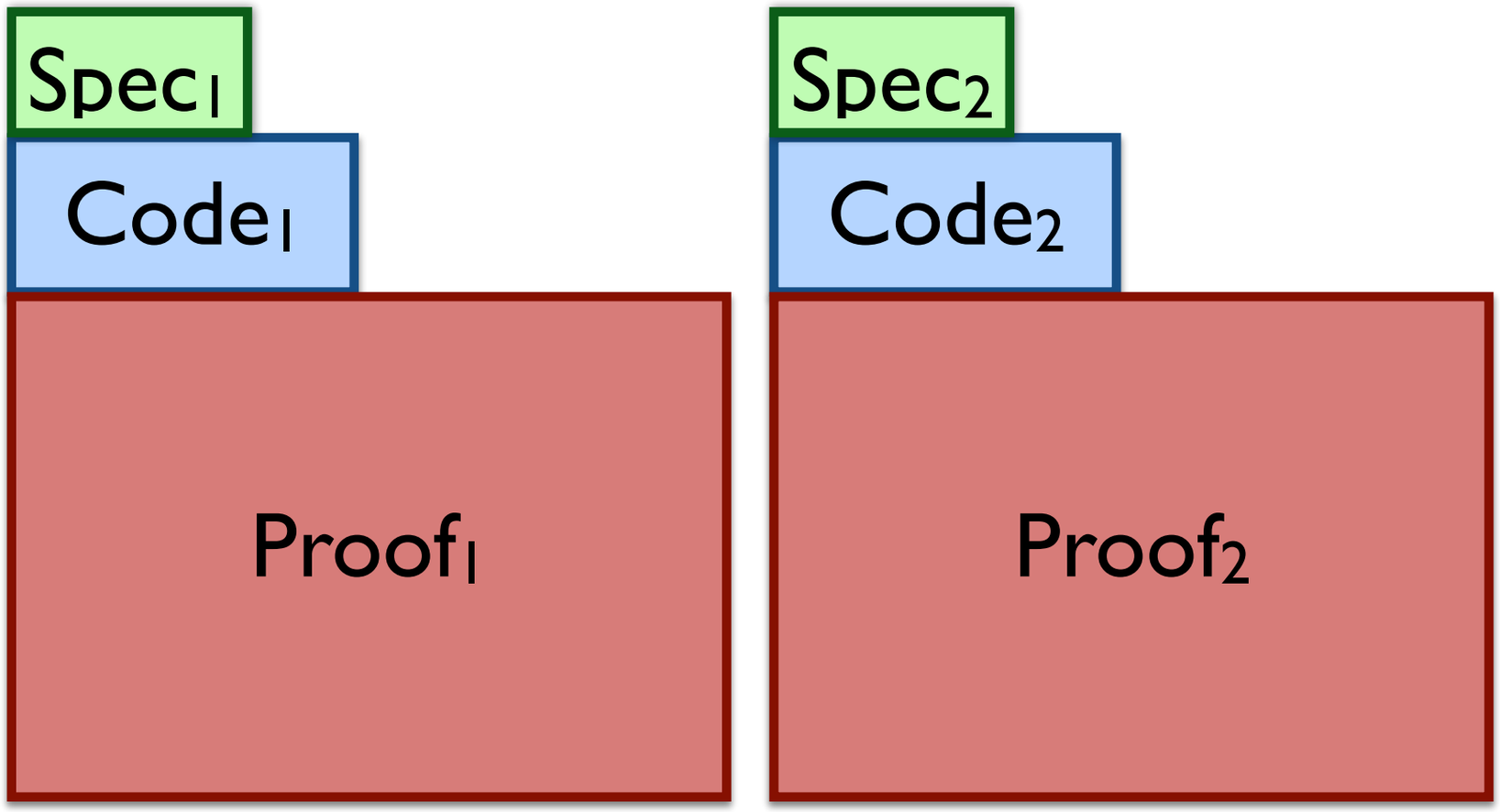

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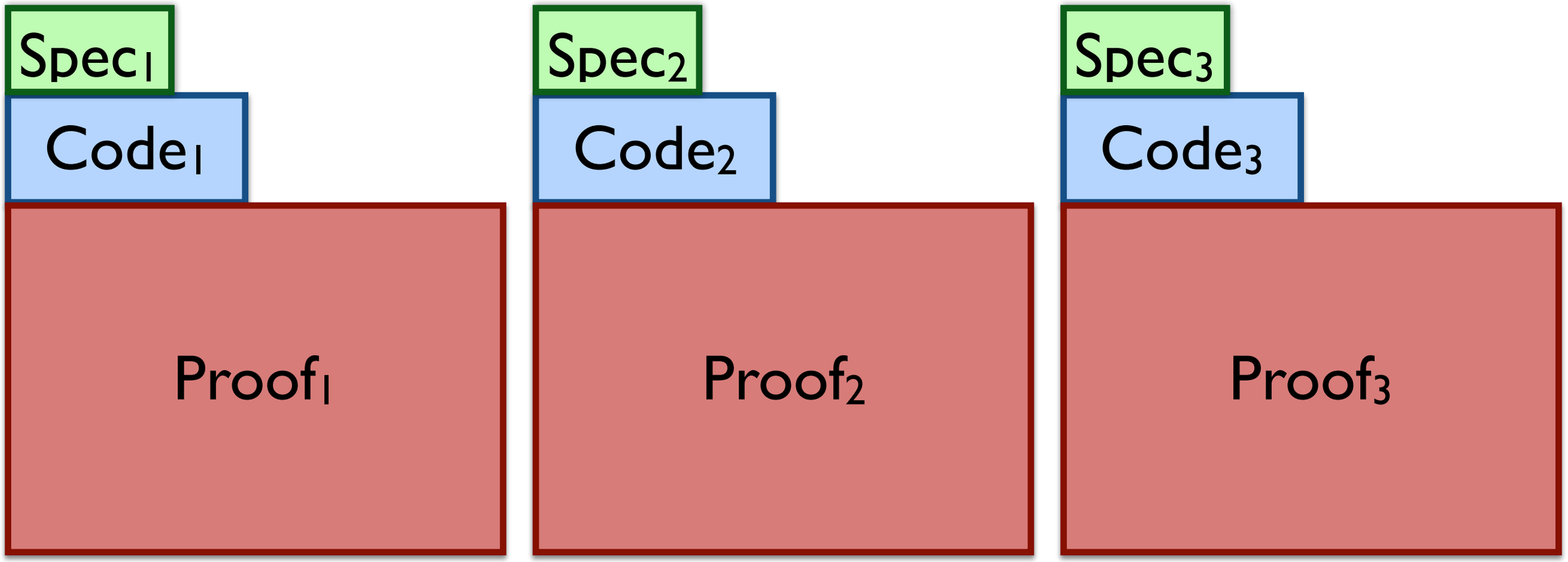
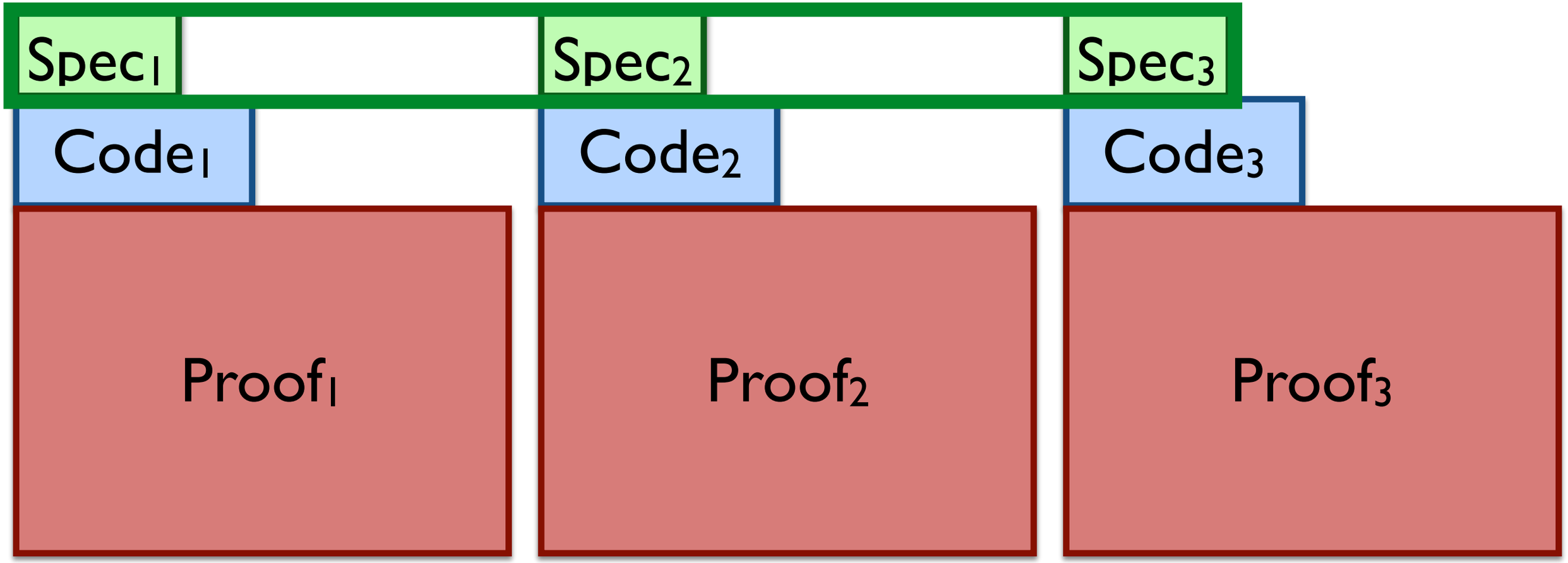


Single application domain

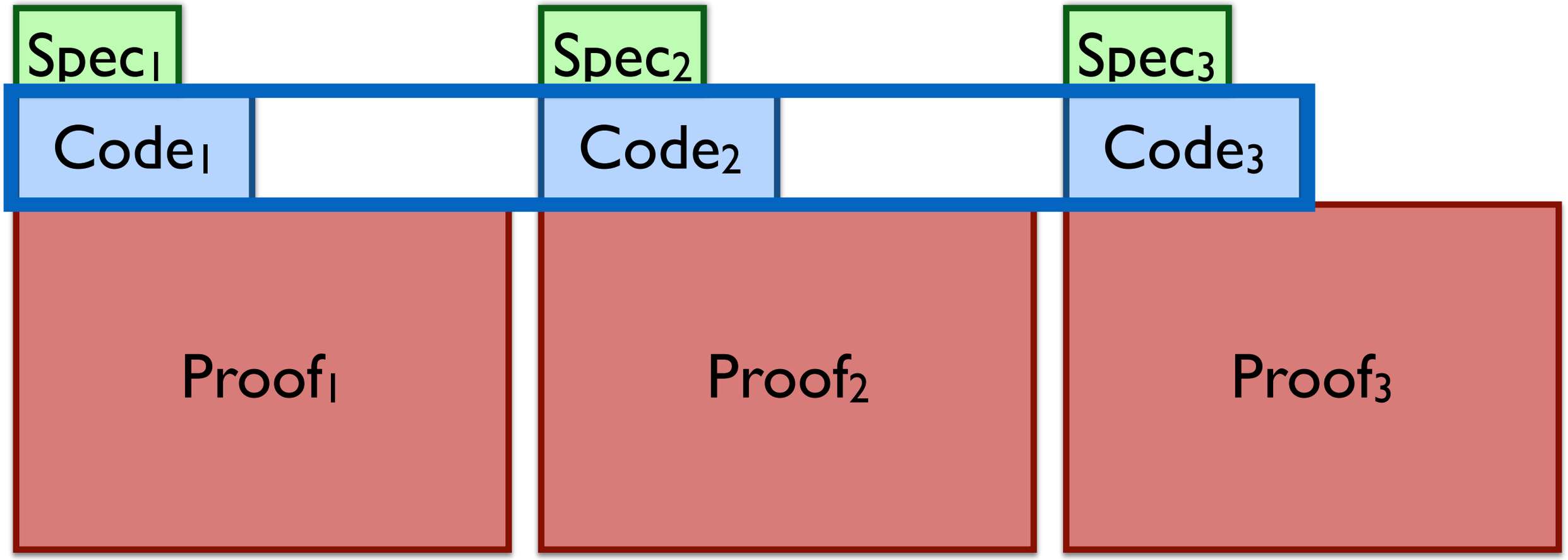
Similar properties



Single application domain

Similar properties

Similar architecture

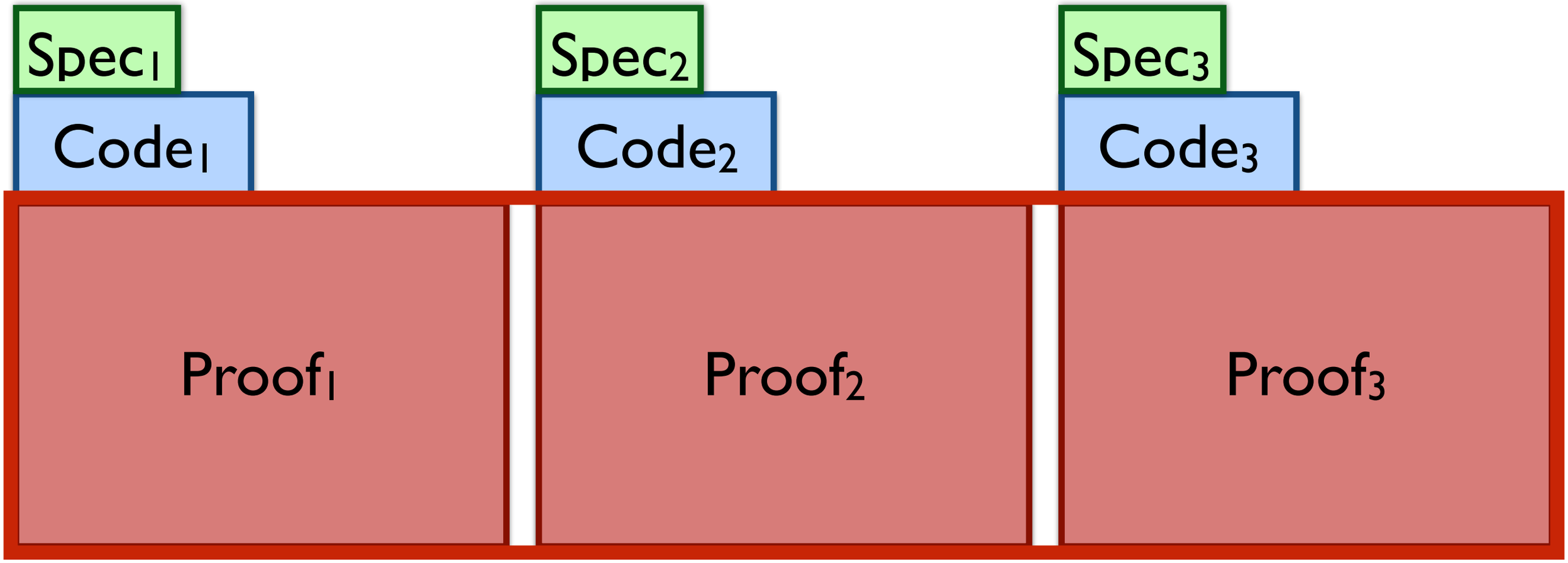


Single application domain

Similar properties

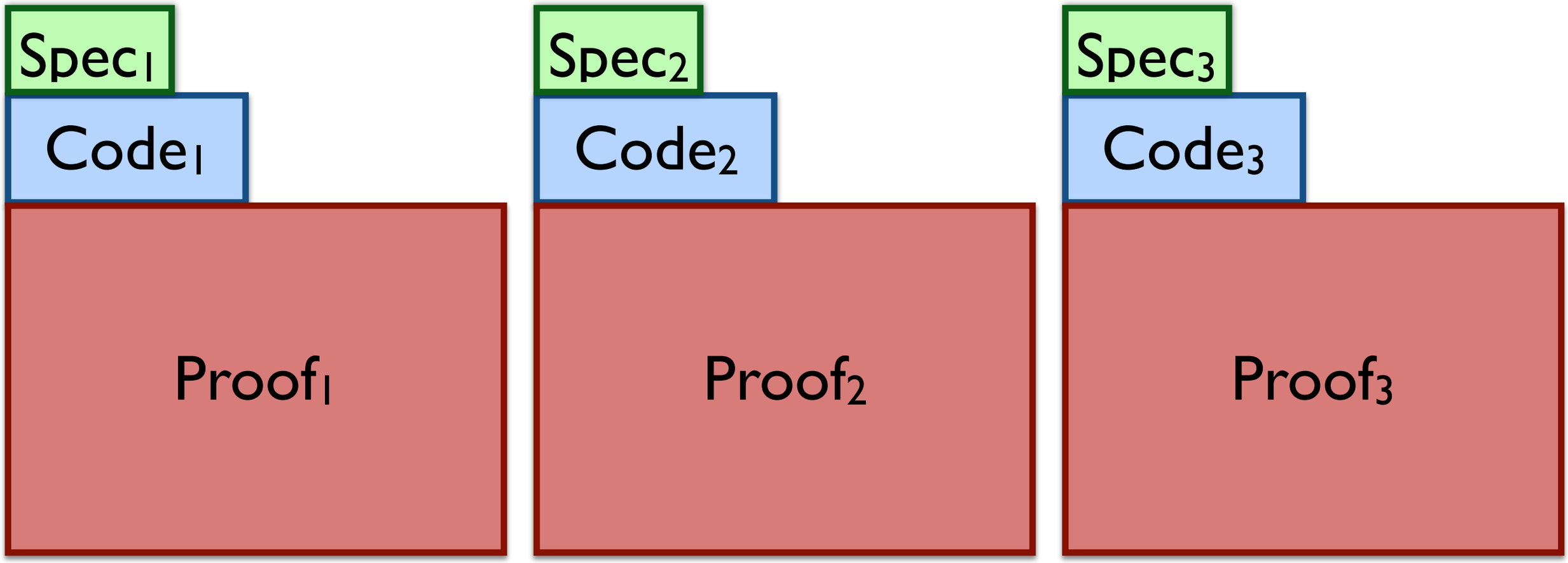
Similar architecture

Similar reasoning



Single application domain

DSL for Specs

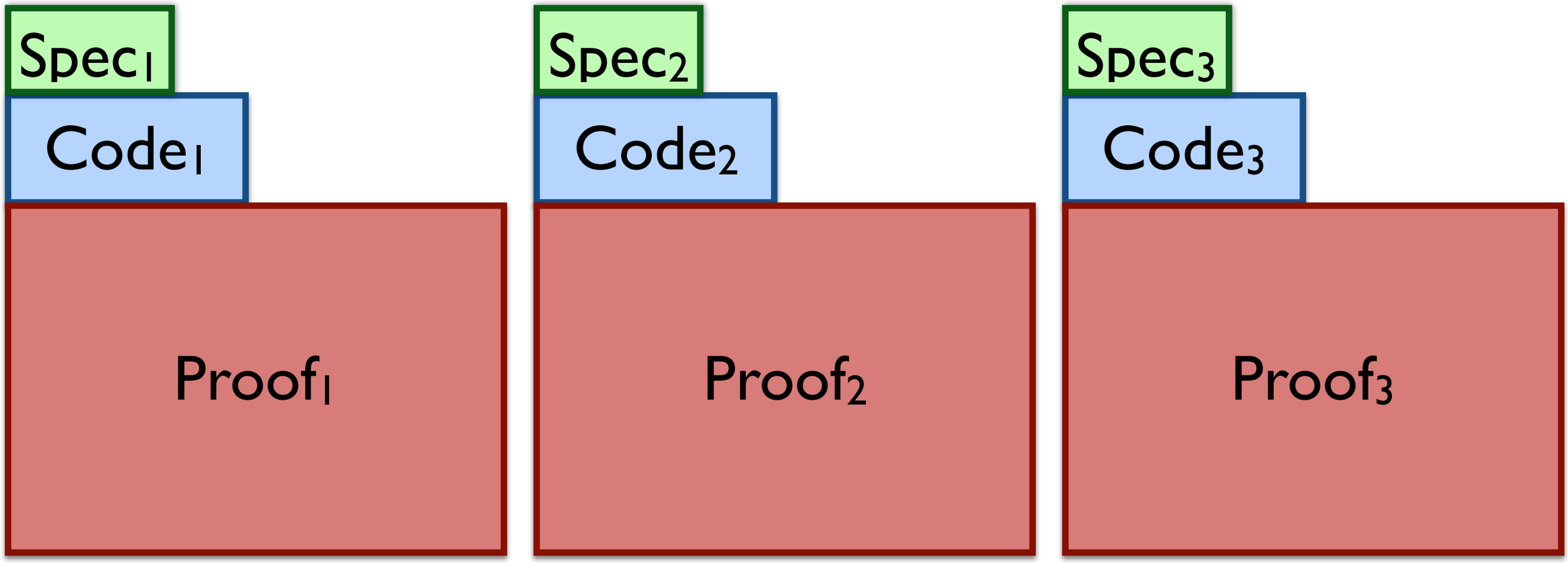


Single application domain

DSL for Specs

Similar architecture

Similar reasoning



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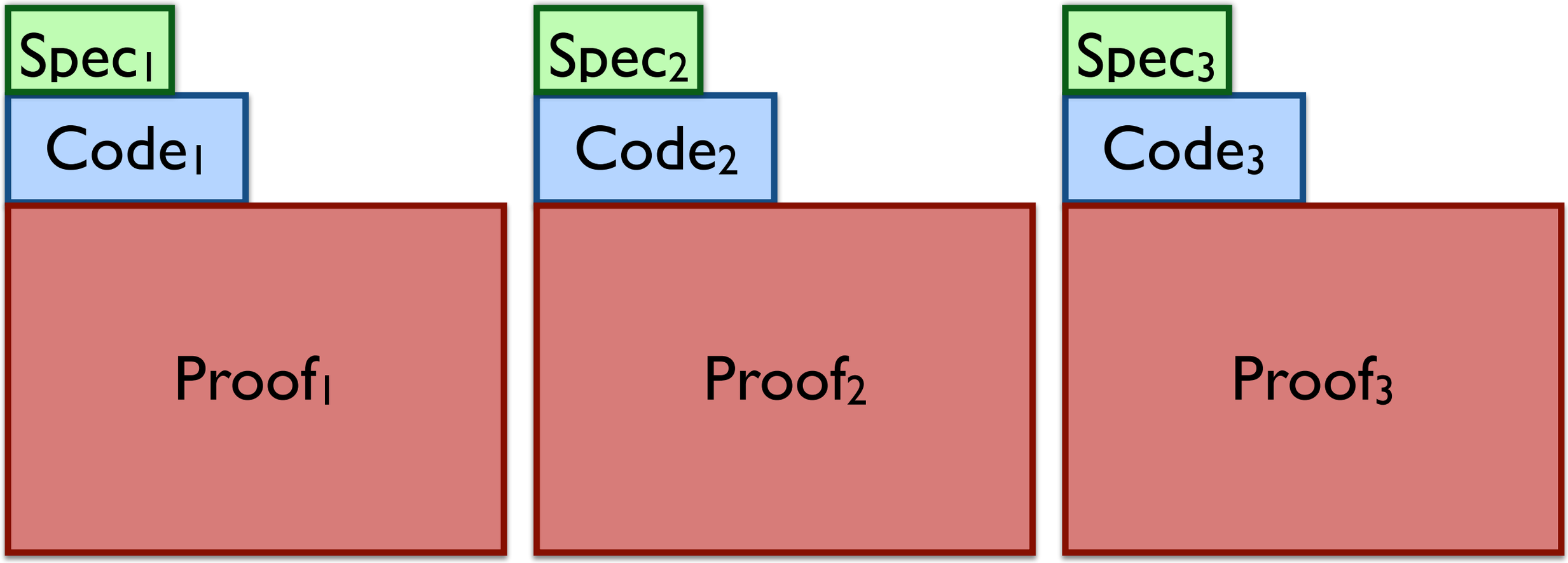
DSL for Code



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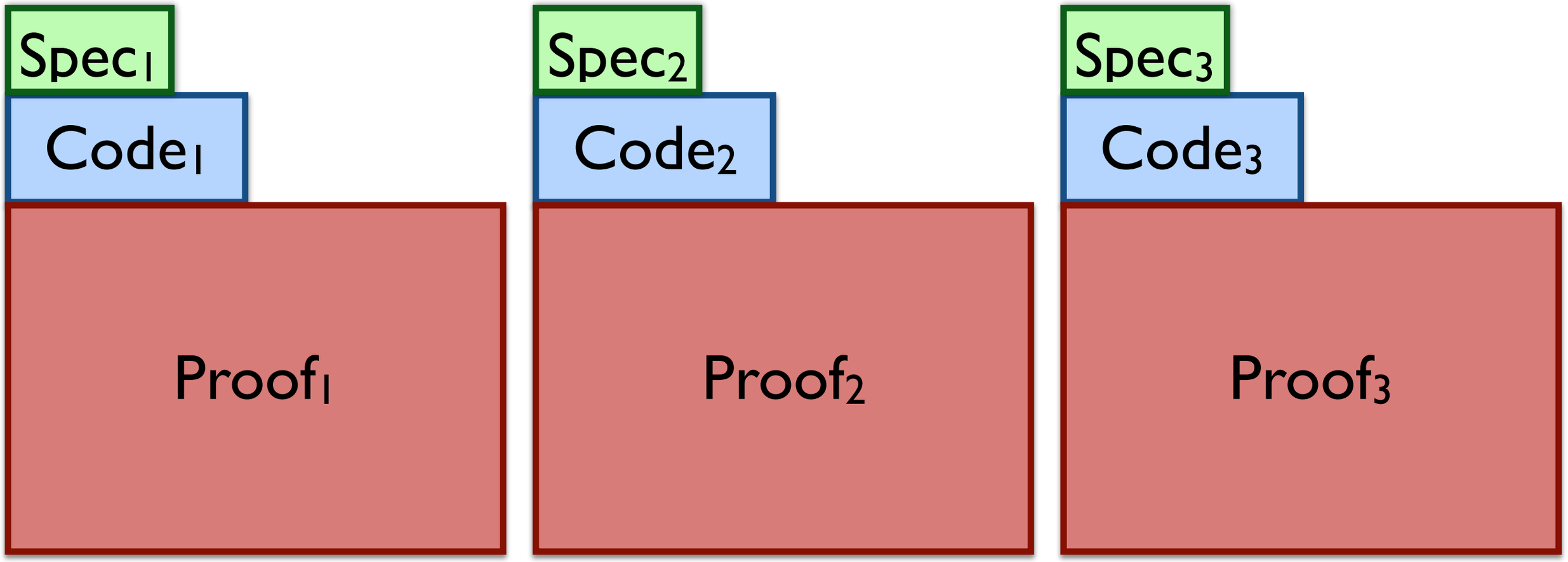

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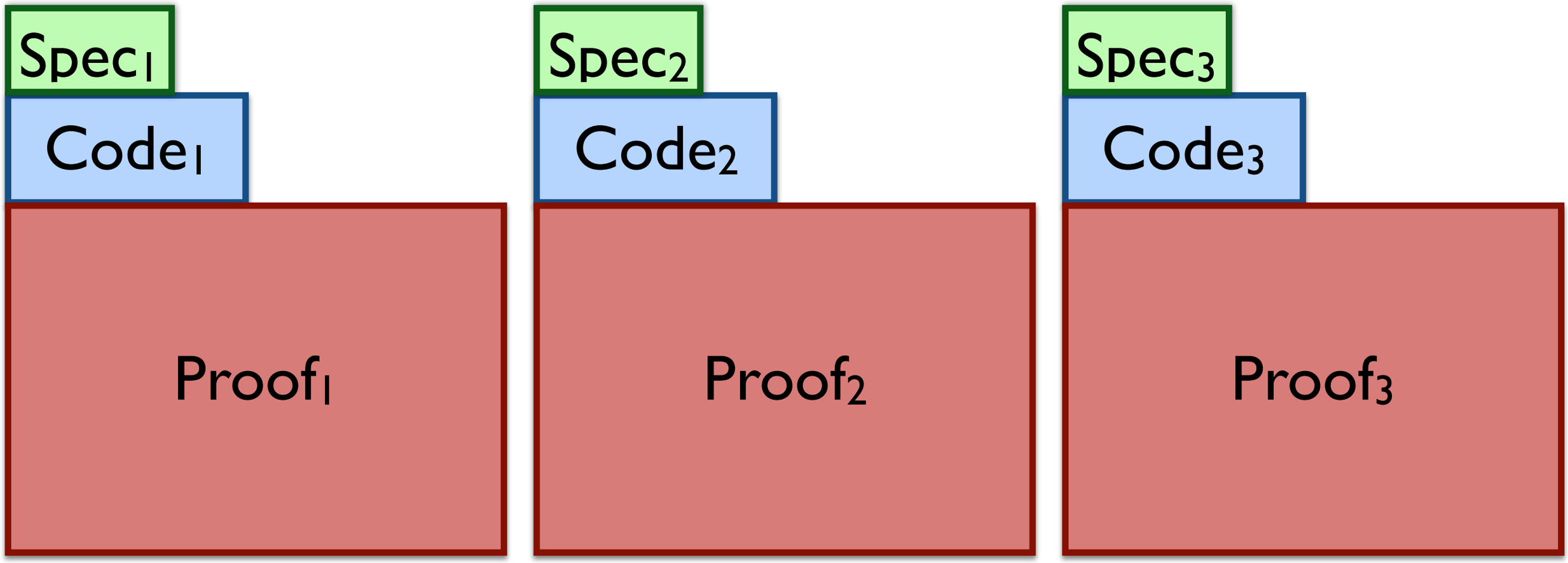
DSL for Code

Proof Automation



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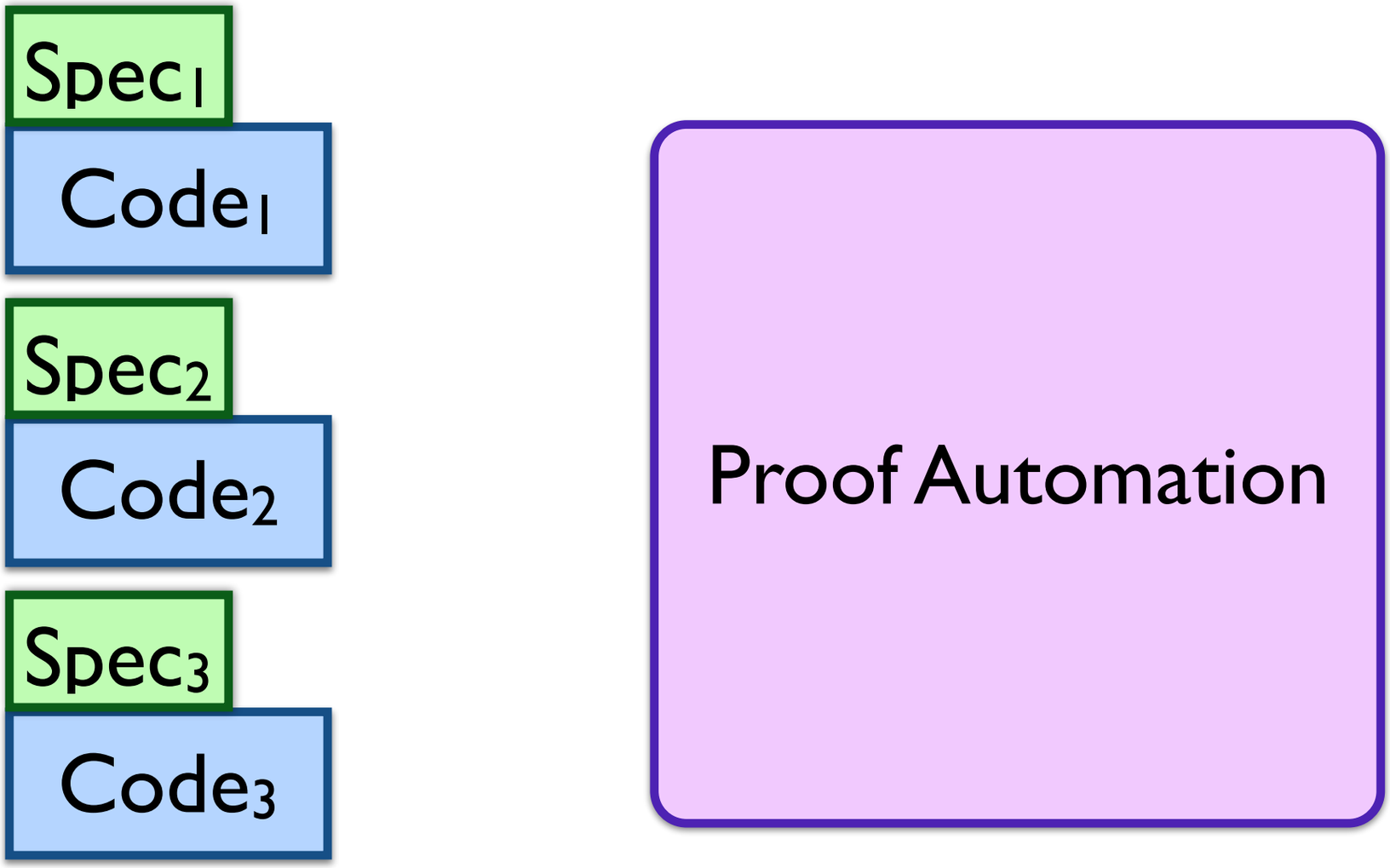

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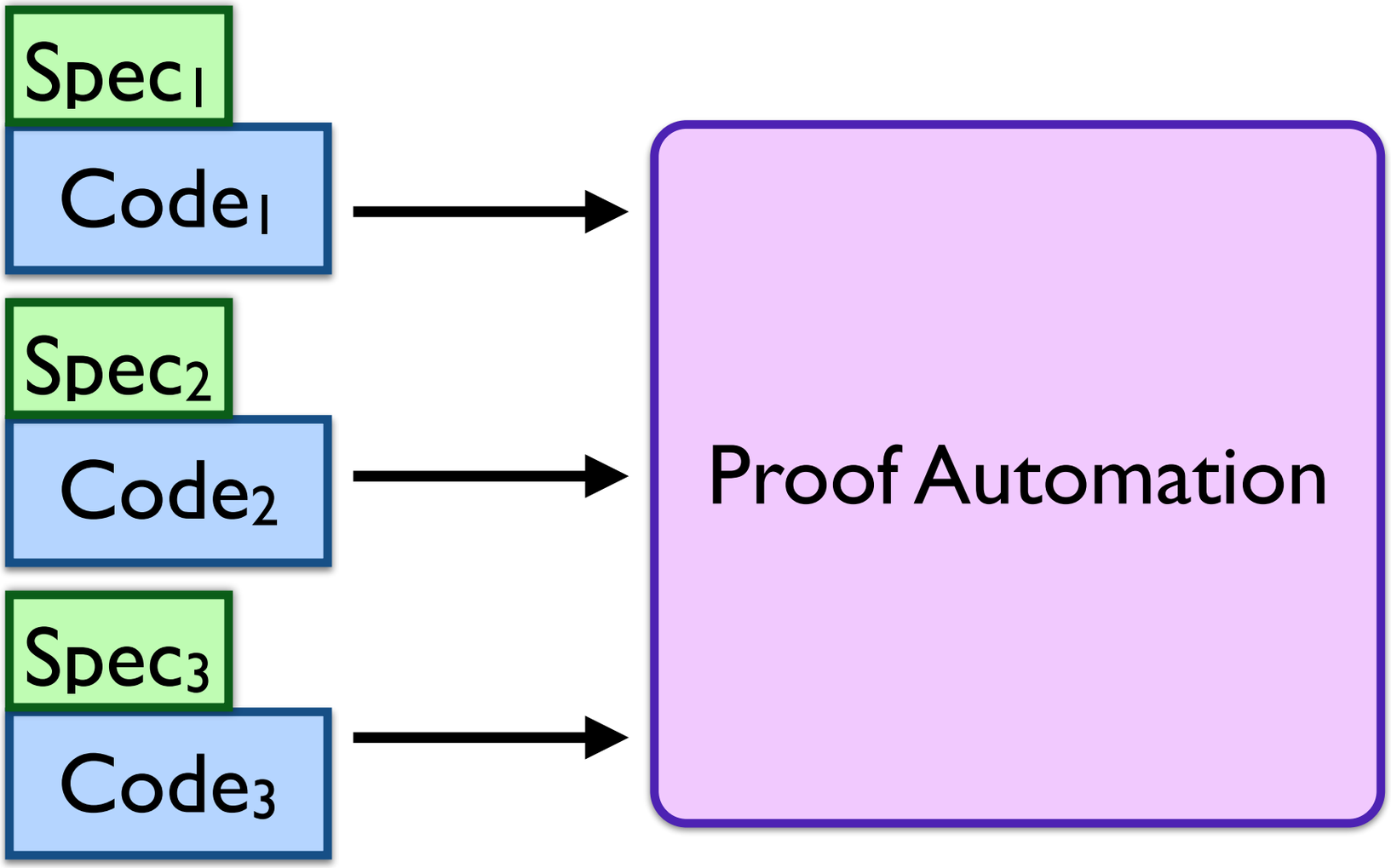

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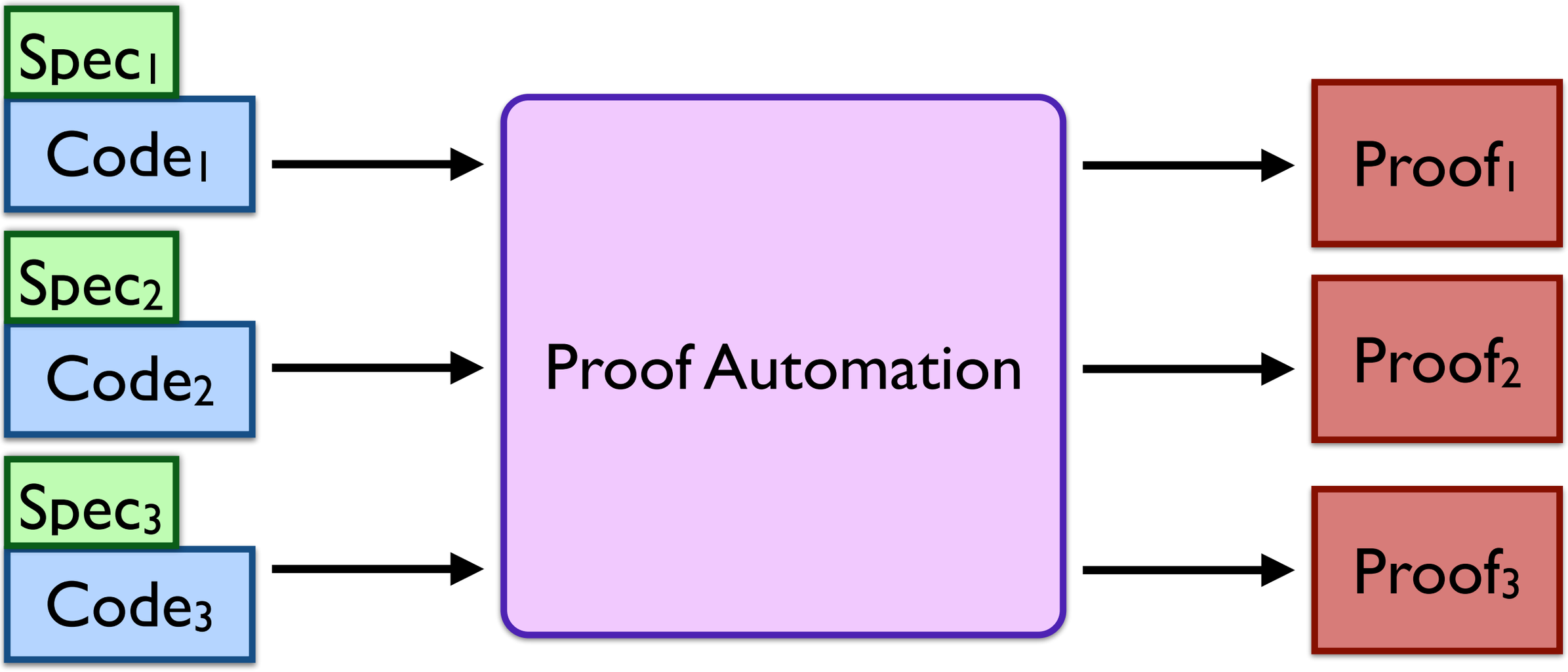
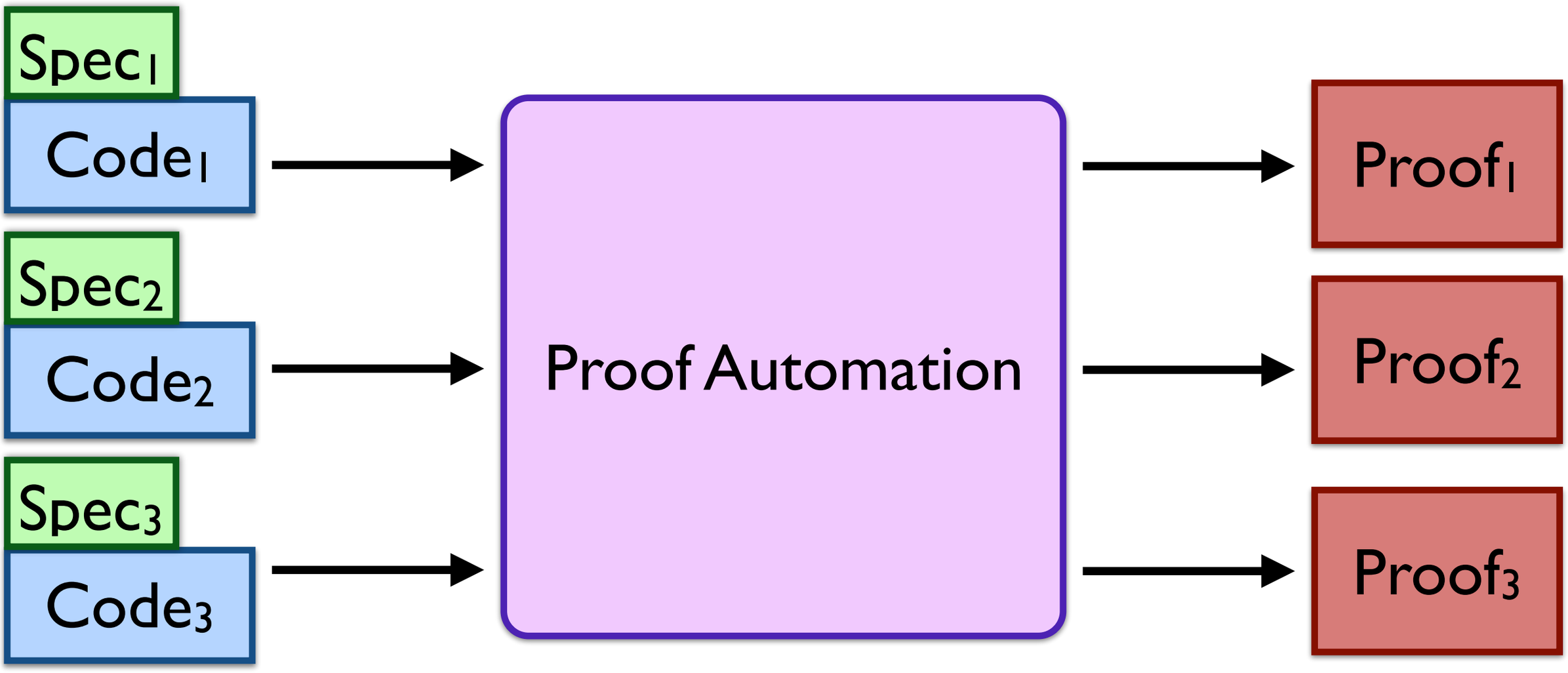


Reactive systems

DSL for Specs

DSL for Code



Reactive systems

DSL for Specs

DSL for Code

Reactive systems

REFLEX

Reactive systems

REFLEX

No manual proofs,

Reactive systems

REFLEX

No manual proofs,

yet proof assistant guarantee.

Reactive systems

REFLEX

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Automation incomplete,

Reactive systems

REFLEX

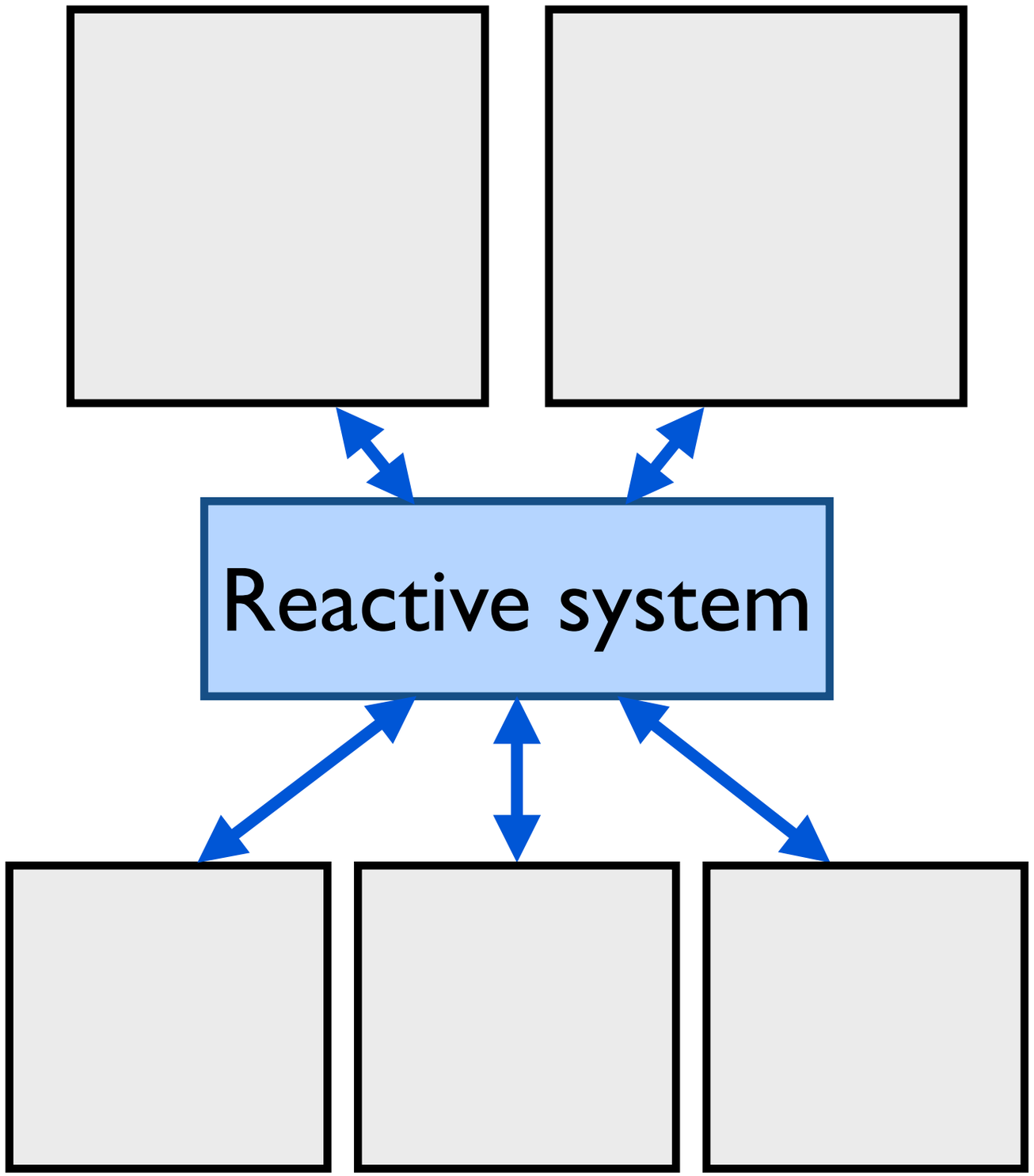
No manual proofs,

yet proof assistant guarantee.

Automation incomplete,

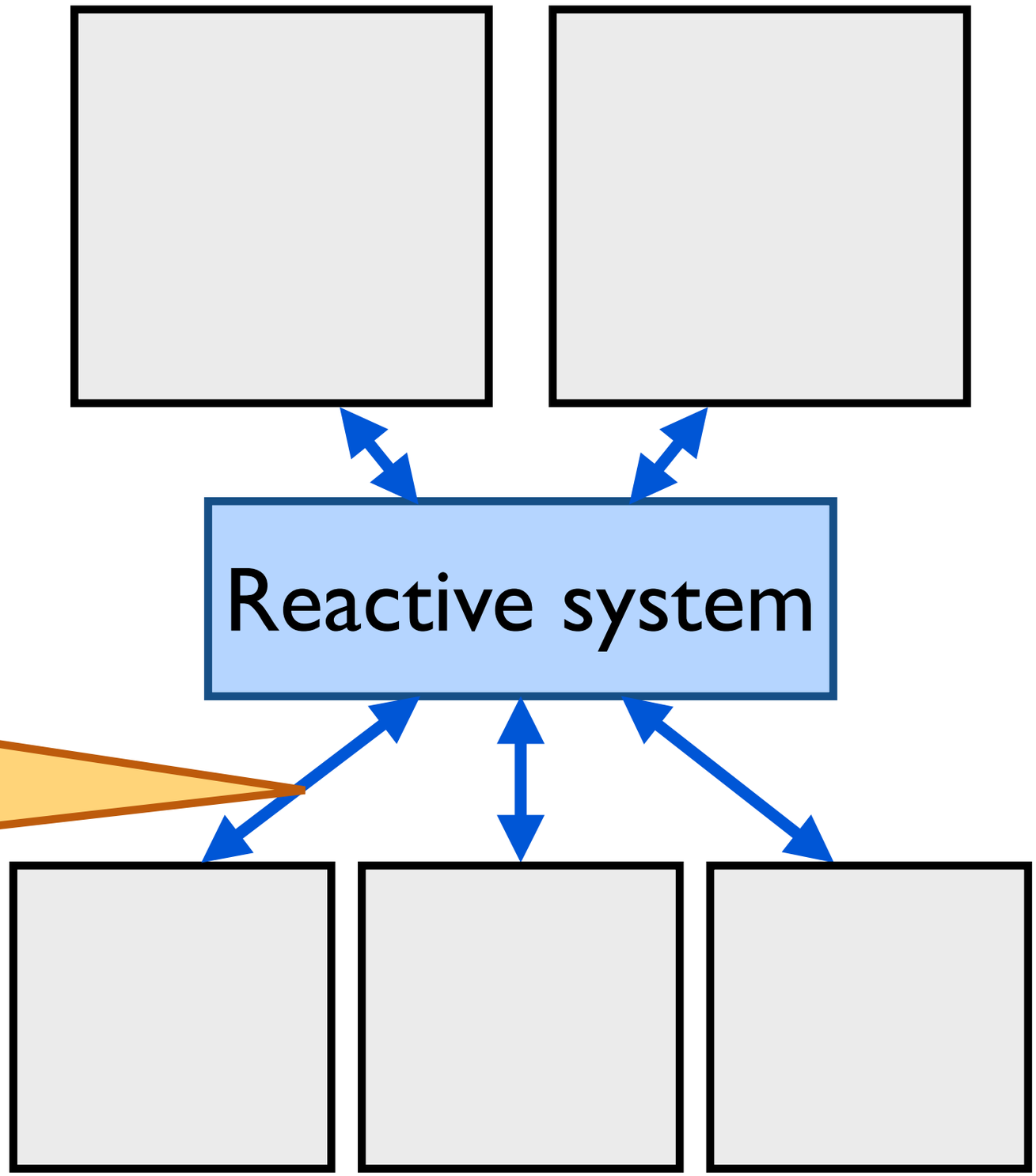
but verified browser, ssh, web server.

Reactive systems



Reactive systems

Continuously read messages from components and send messages to components



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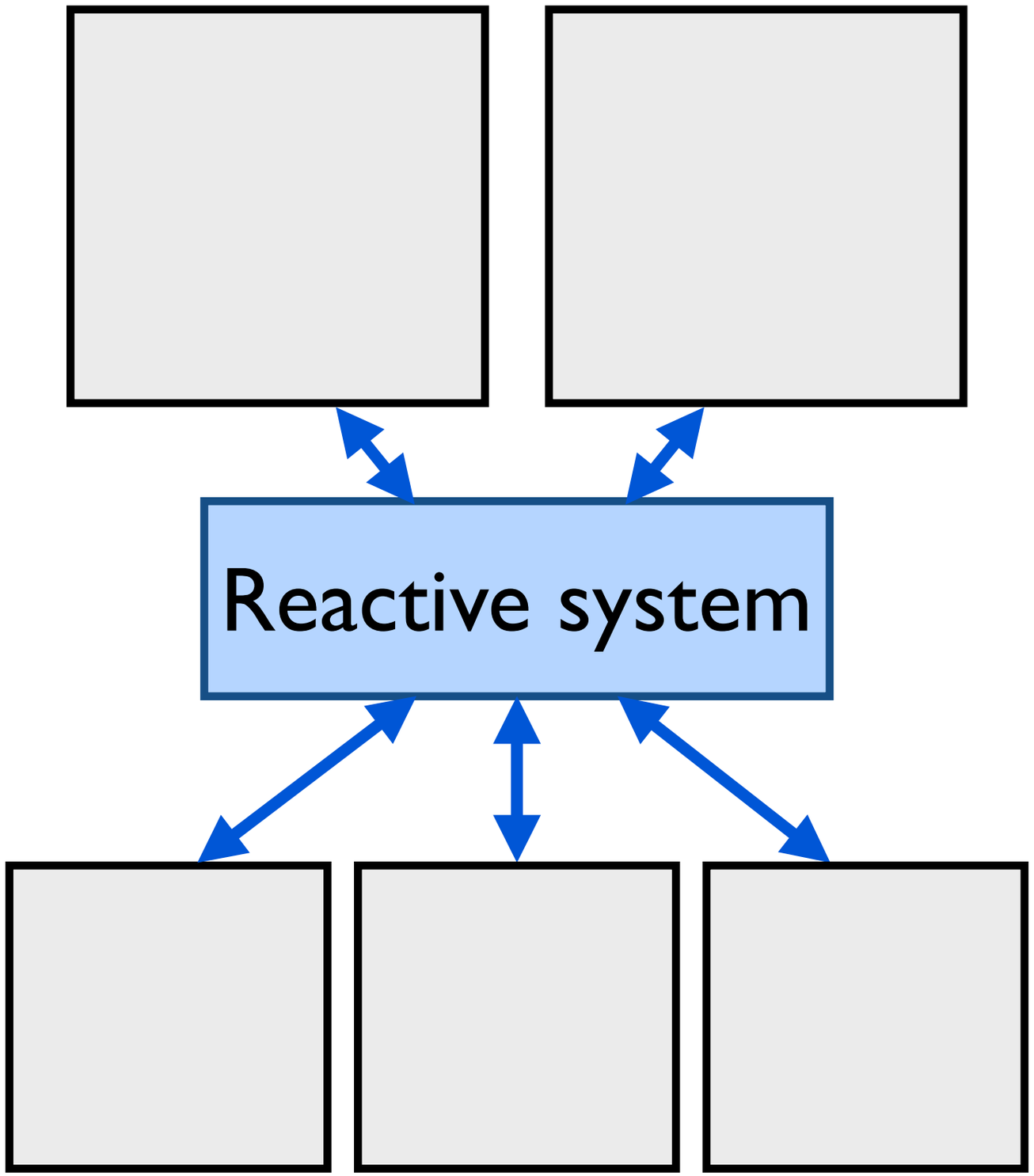
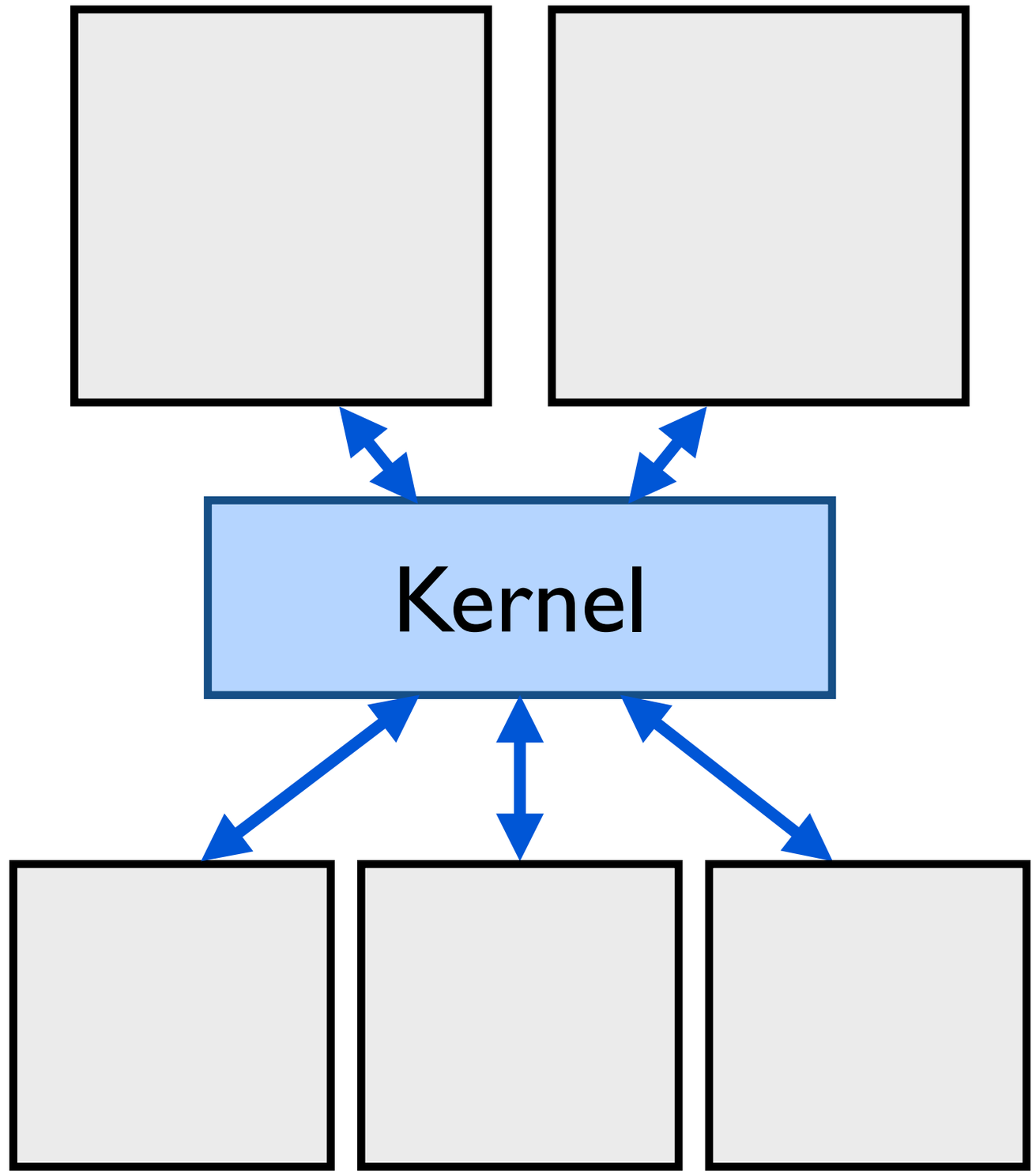


Example: Web browser kernel



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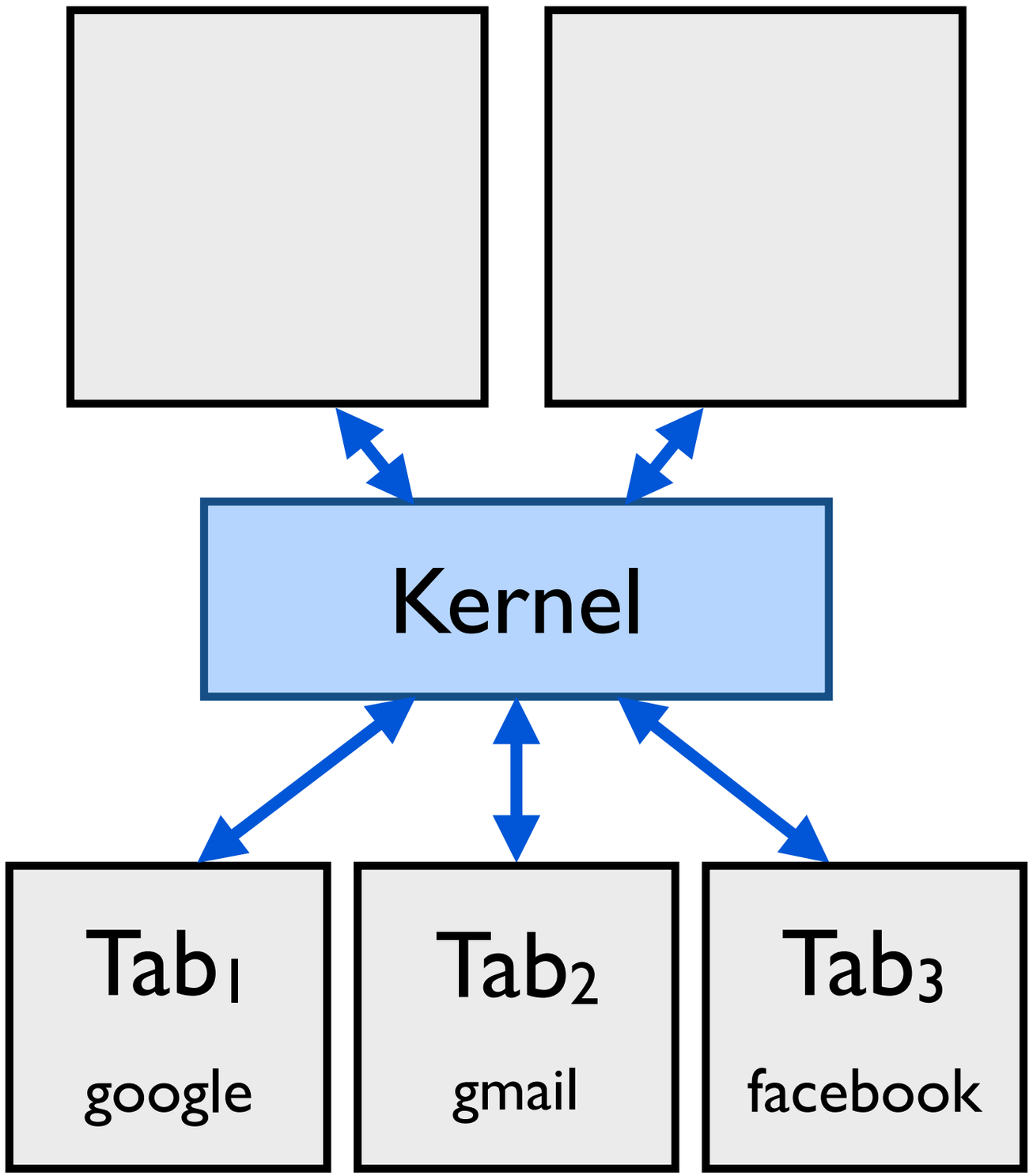

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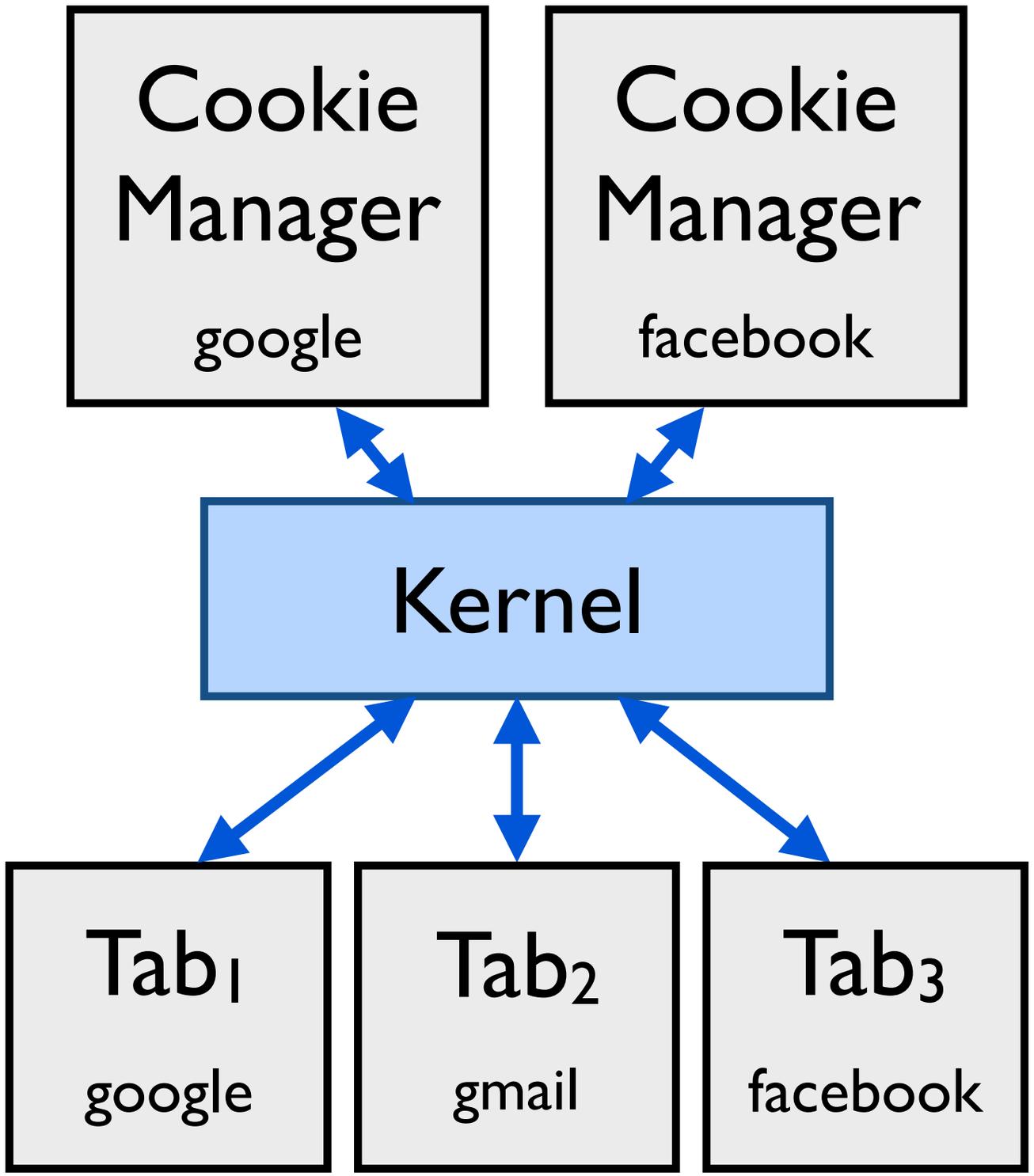

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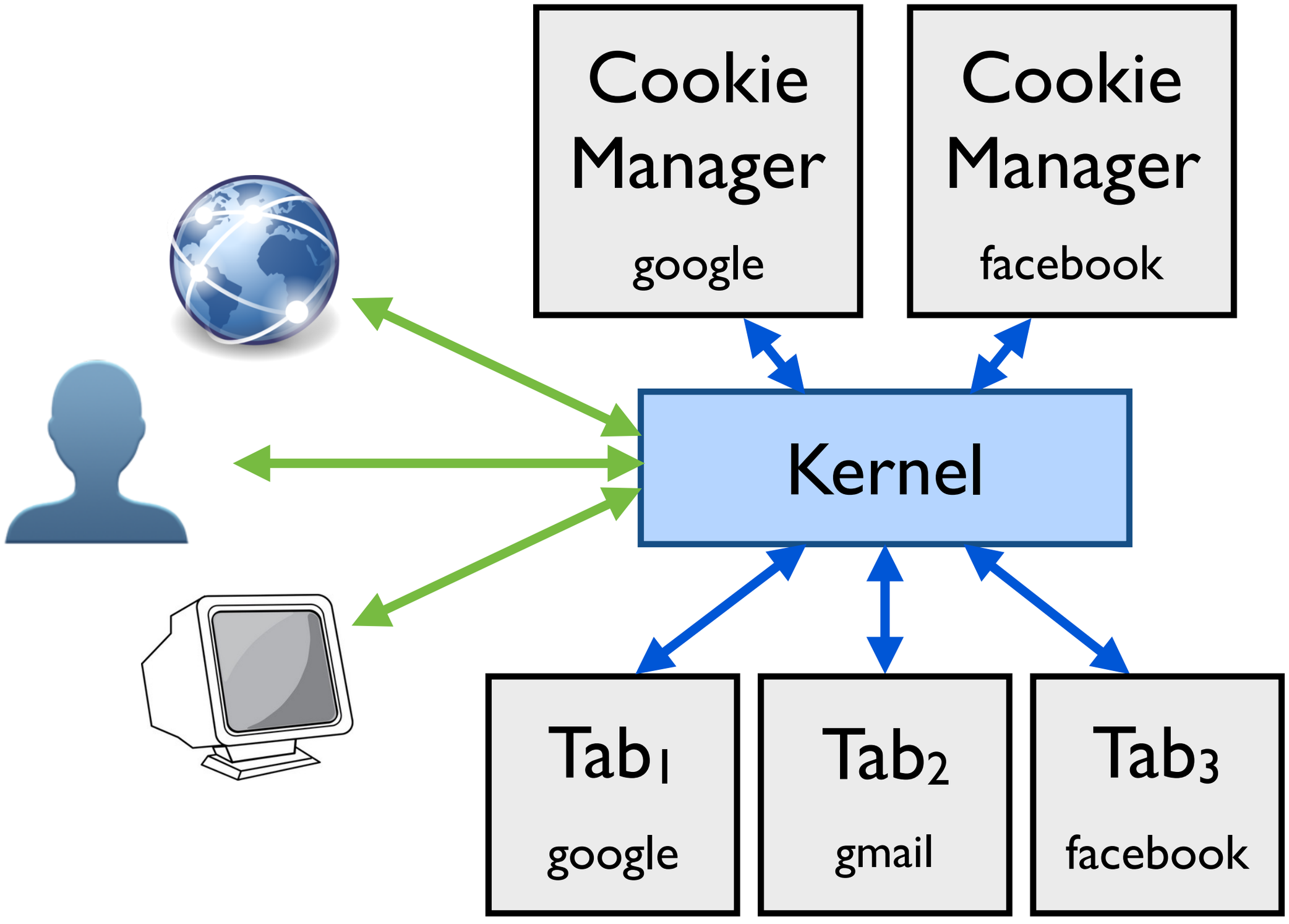

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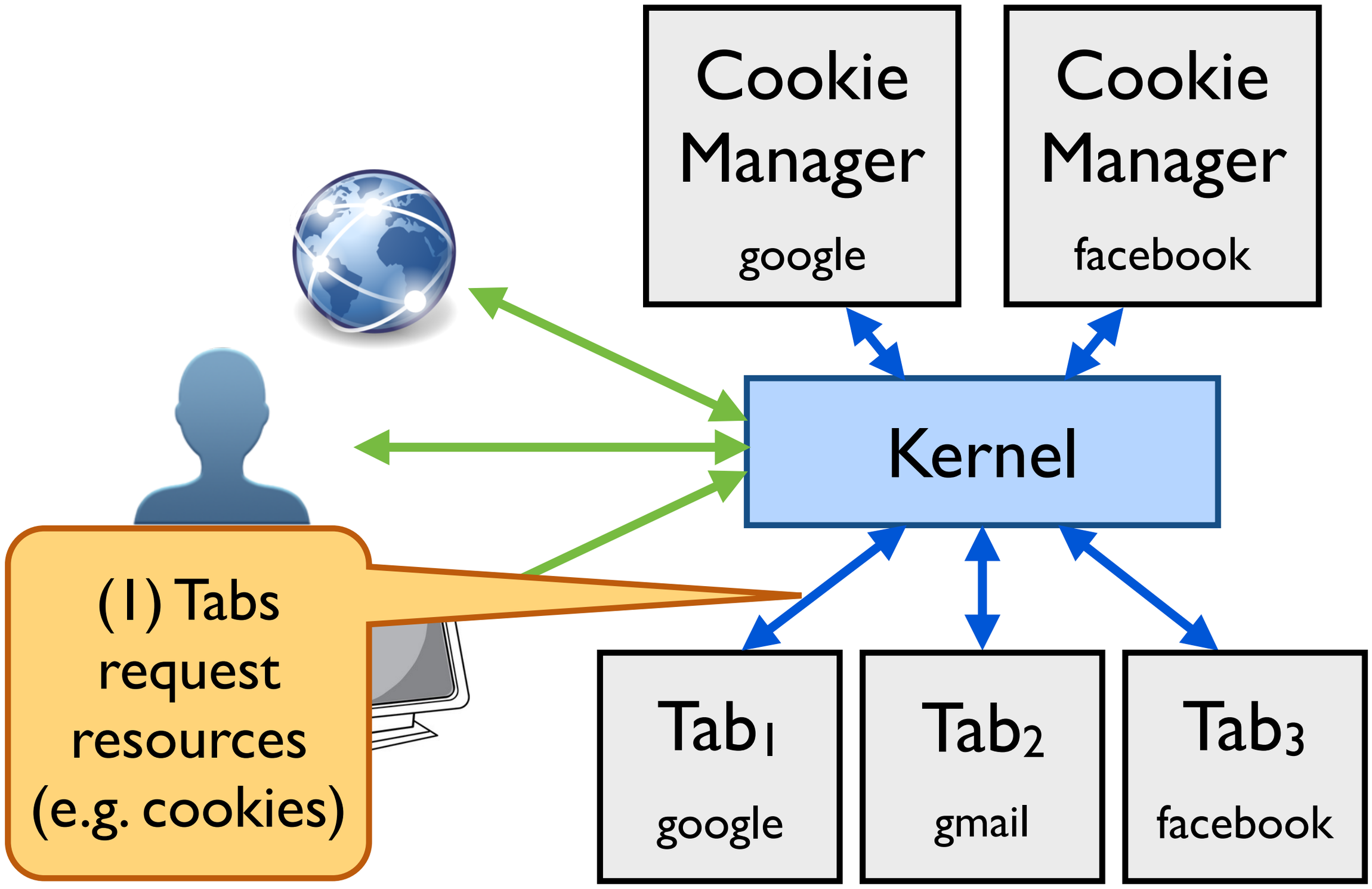

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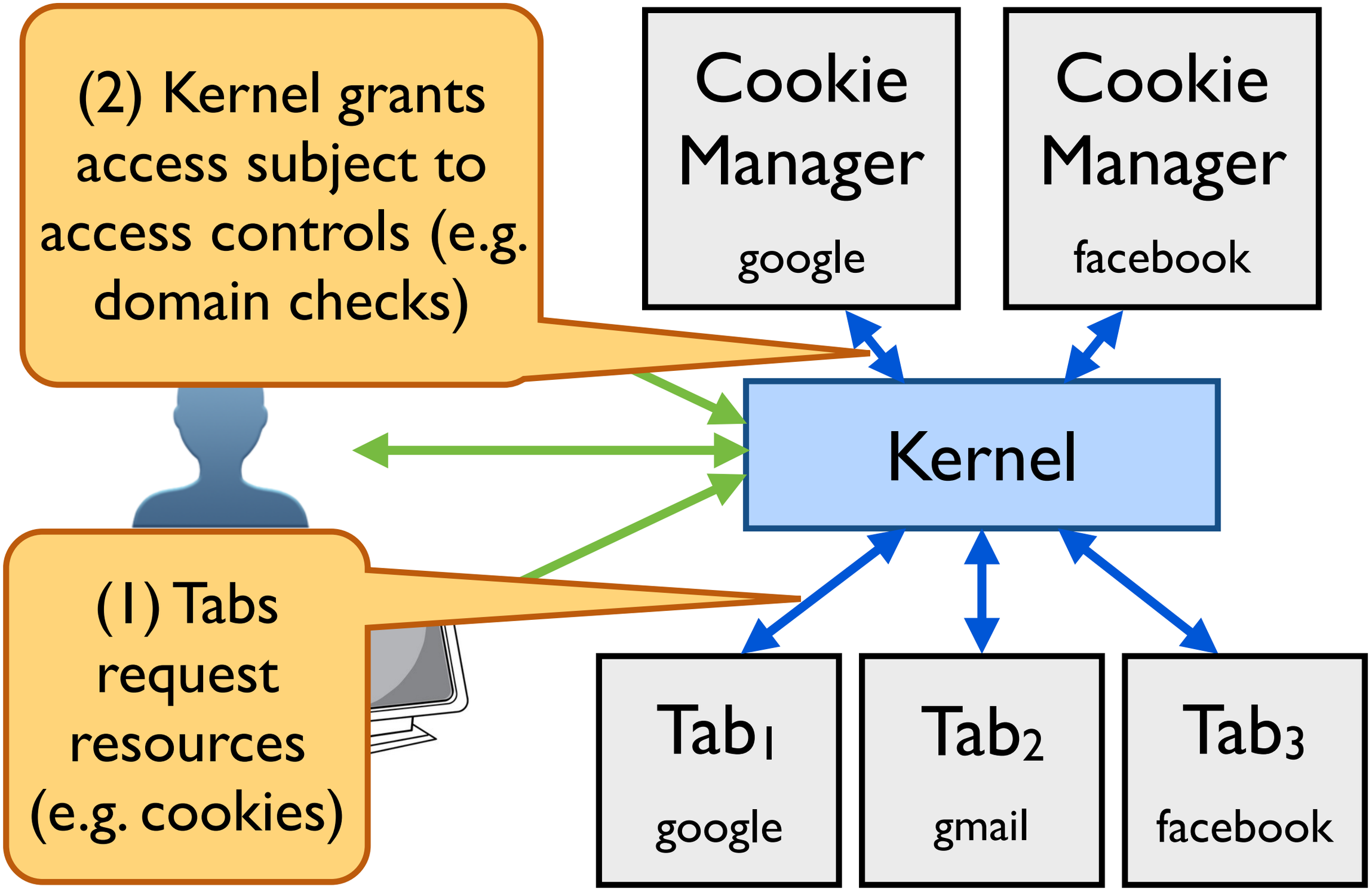

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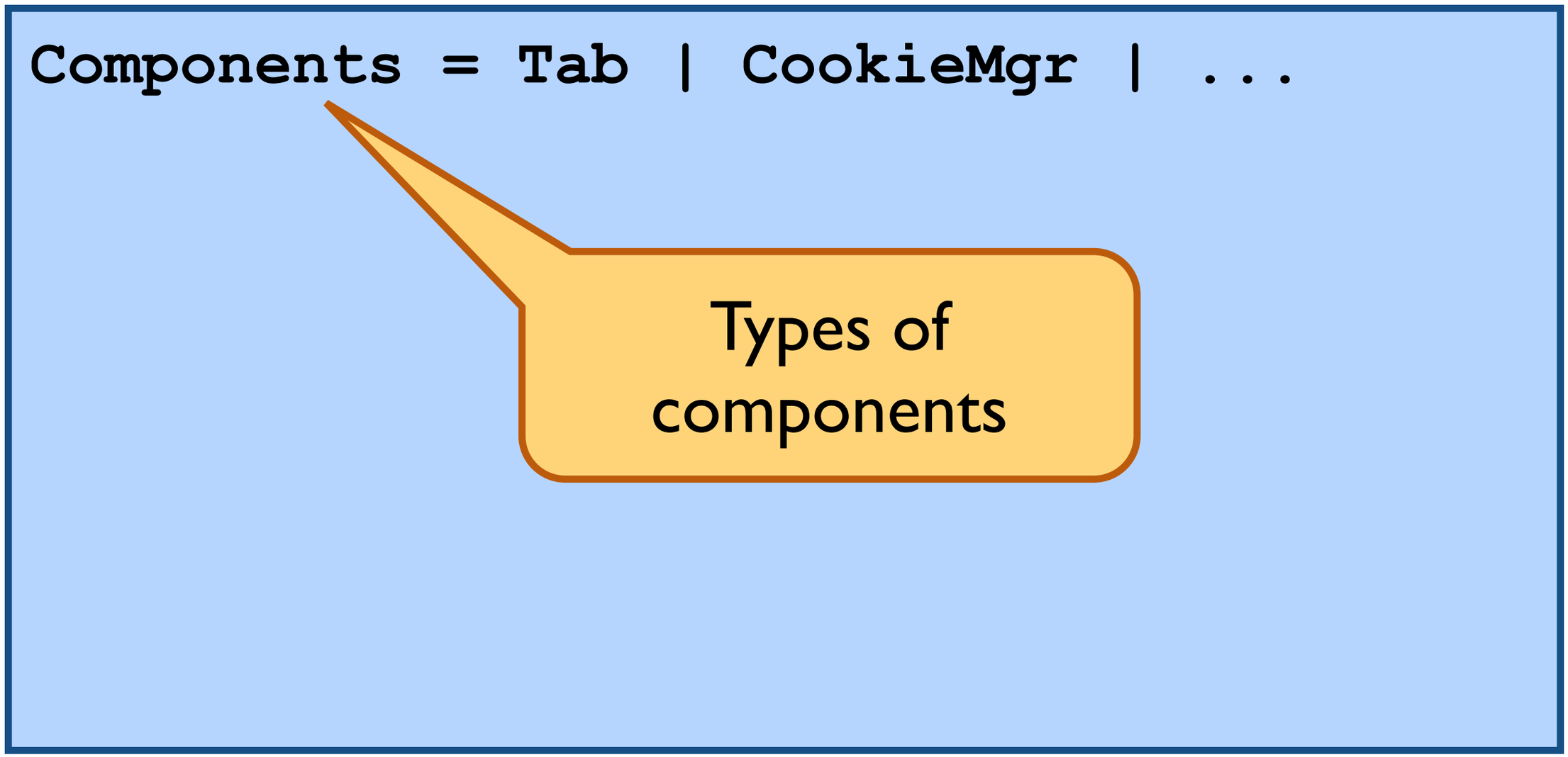

Example: Web browser kernel

```
Components = Tab | CookieMgr | ...
Messages = CookieSet | CookieGet | ...
```

Types of messages

Example: Web browser kernel

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Components = Tab | CookieMgr | ...
Messages = CookieSet | CookieGet | ...

Handlers:
```

How the kernel responds to messages from components

Example: Web browser kernel

```
Components = Tab | CookieMgr | ...
Messages = CookieSet | CookieGet | ...

Handlers:
   When [Tab t] sends CookieSet(c):
```

When tab **`t`** sends the kernel a **`CookieSet`** message with payload **`c`**

Example: Web browser kernel

```
Components = Tab | CookieMgr | ...
Messages = CookieSet | CookieGet | ...

Handlers:
   When [Tab t] sends CookieSet(c):
     cp <- find CookieMgr(t.domain)
```

Get existing cookie manager with domain of `t` or spawn a new one

Example: Web browser kernel

```
Components = Tab | CookieMgr | ...
Messages = CookieSet | CookieGet | ...

Handlers:
   When [Tab t] sends CookieSet(c):
      cp <- find CookieMgr(t.domain)
      send(cp, CookieSet(c))
```

Send the cookie **c** to the found cookie manager

Example: Web browser kernel

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Components = Tab | CookieMgr | ...
Messages = CookieSet | CookieGet | ...

Handlers:
   When [Tab t] sends CookieSet(c):
     cp <- find CookieMgr(t.domain)
     send(cp, CookieSet(c))

  When [Tab t] sends CookieGet(c):
     ...
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More handlers

Properties

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Handlers:
   When [Tab t] sends CookieSet(c):
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   When [Tab t] sends CookieSet(c):
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When [Tab t] sends CookieGet(c):
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Specify allowed behaviors

Properties

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Components = Tab | CookieMgr | ...
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Specify allowed behaviors wrt sequence of system calls

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Components = Tab | CookieMgr | ...
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Handlers:
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  When [Tab t] sends CookieGet(c):
    ...
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Specify allowed behaviors wrt sequence of system calls

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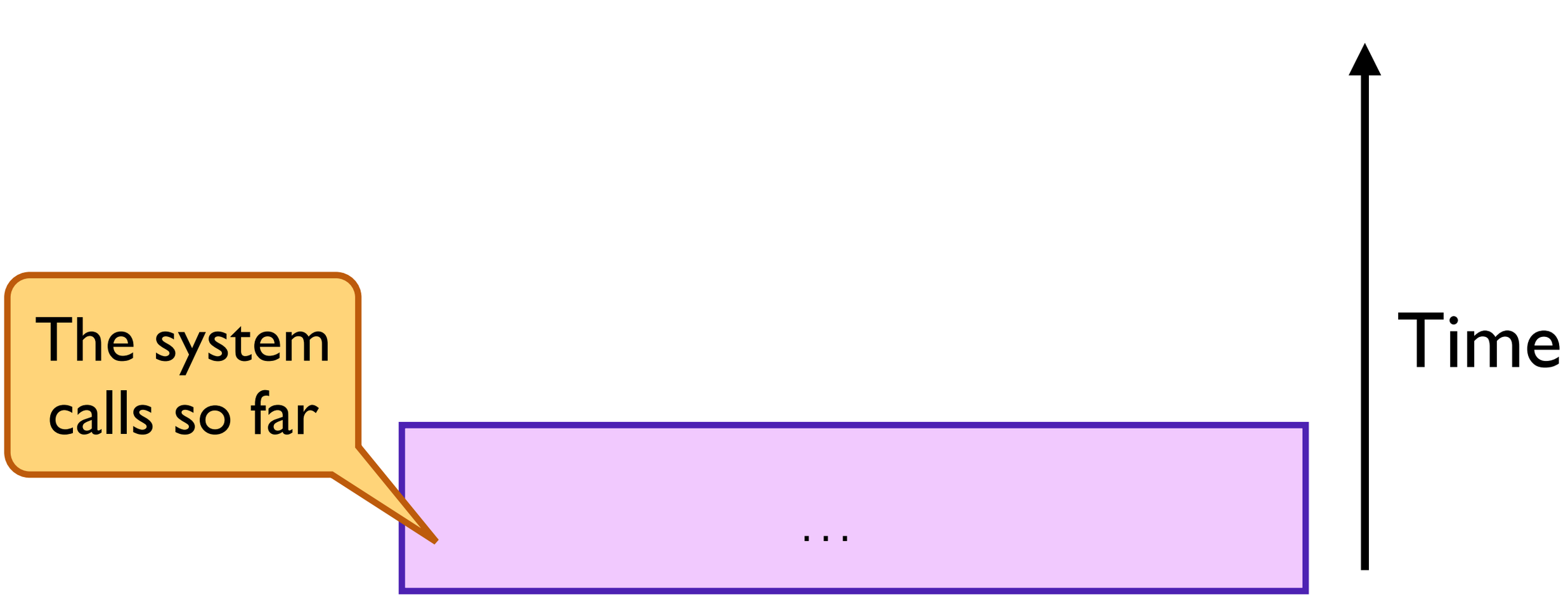

Properties

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When [Tab t] sends CookieSet(c):
  cp <- find CookieMgr(t.domain)
  send(cp, CookieSet(c))
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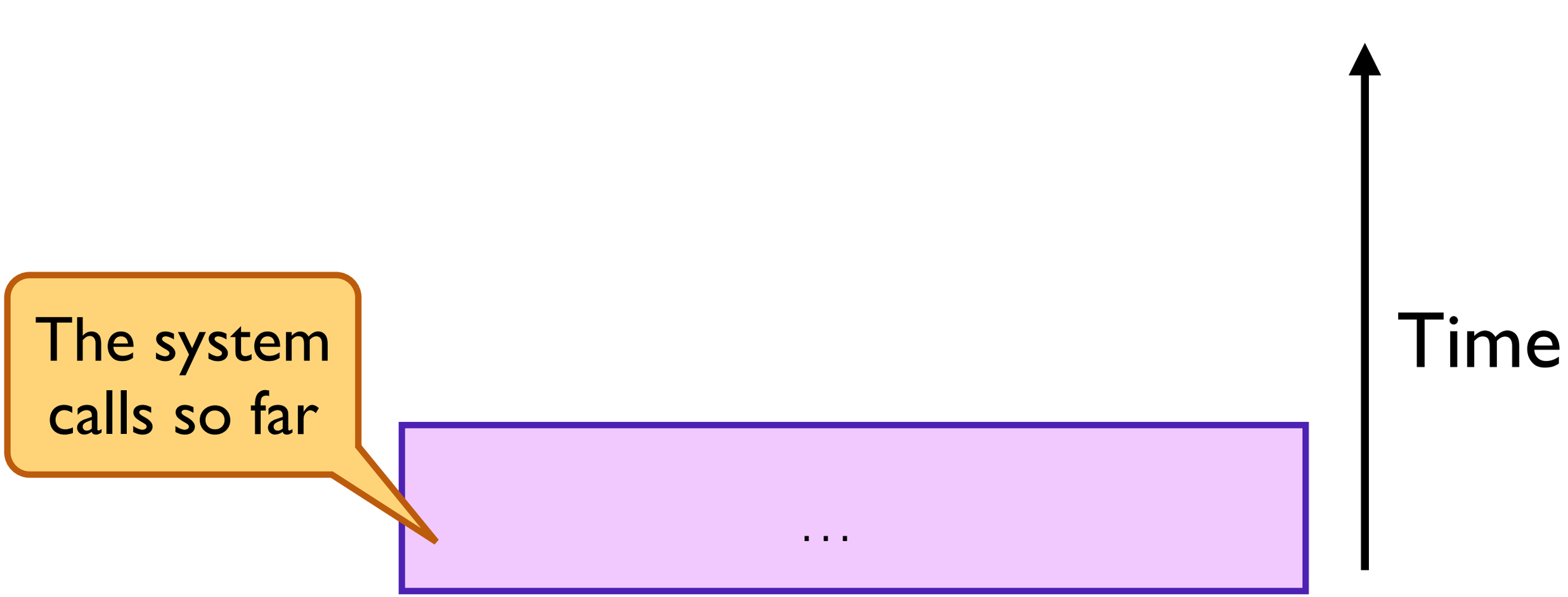
Specify allowed behaviors wrt sequence of system calls



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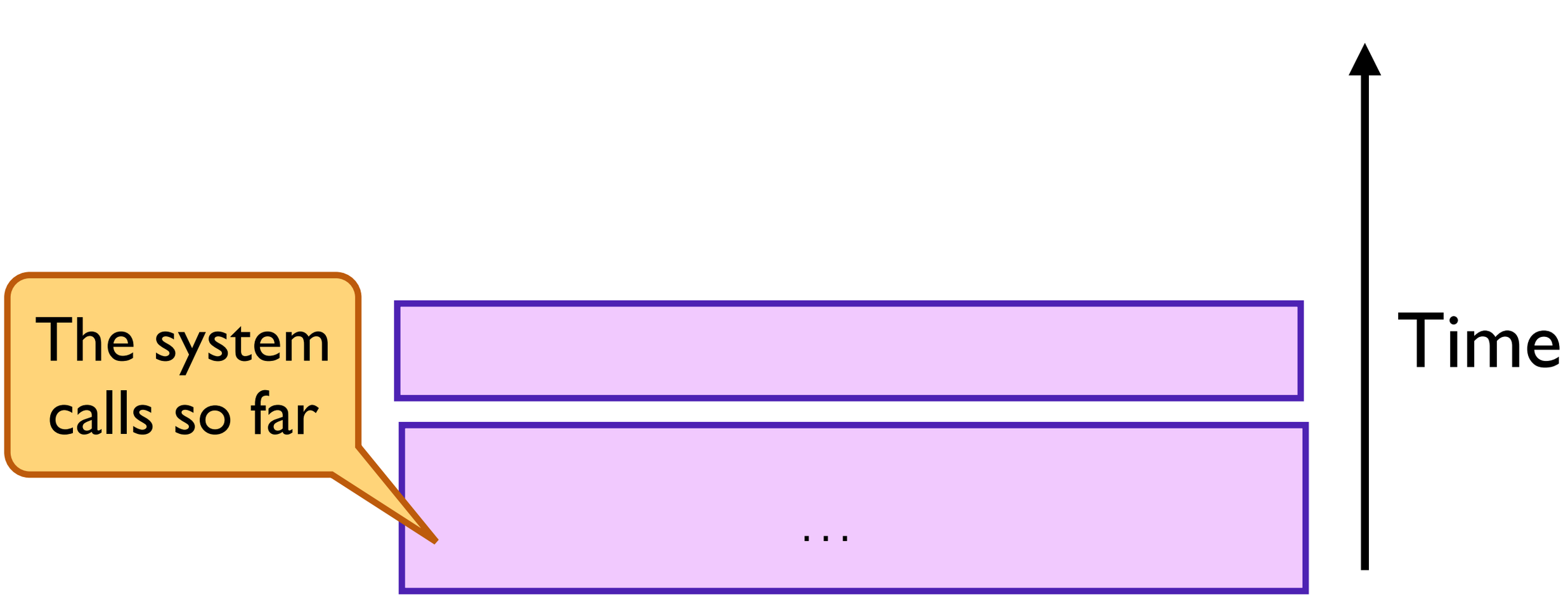

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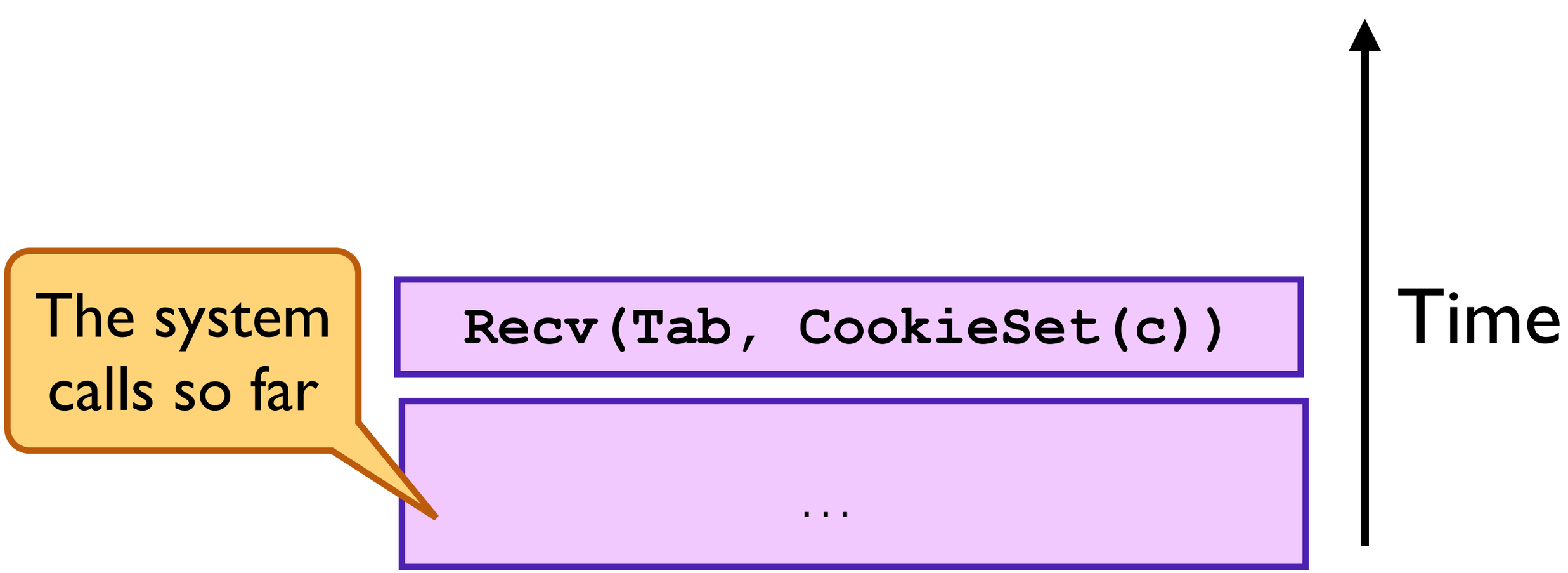

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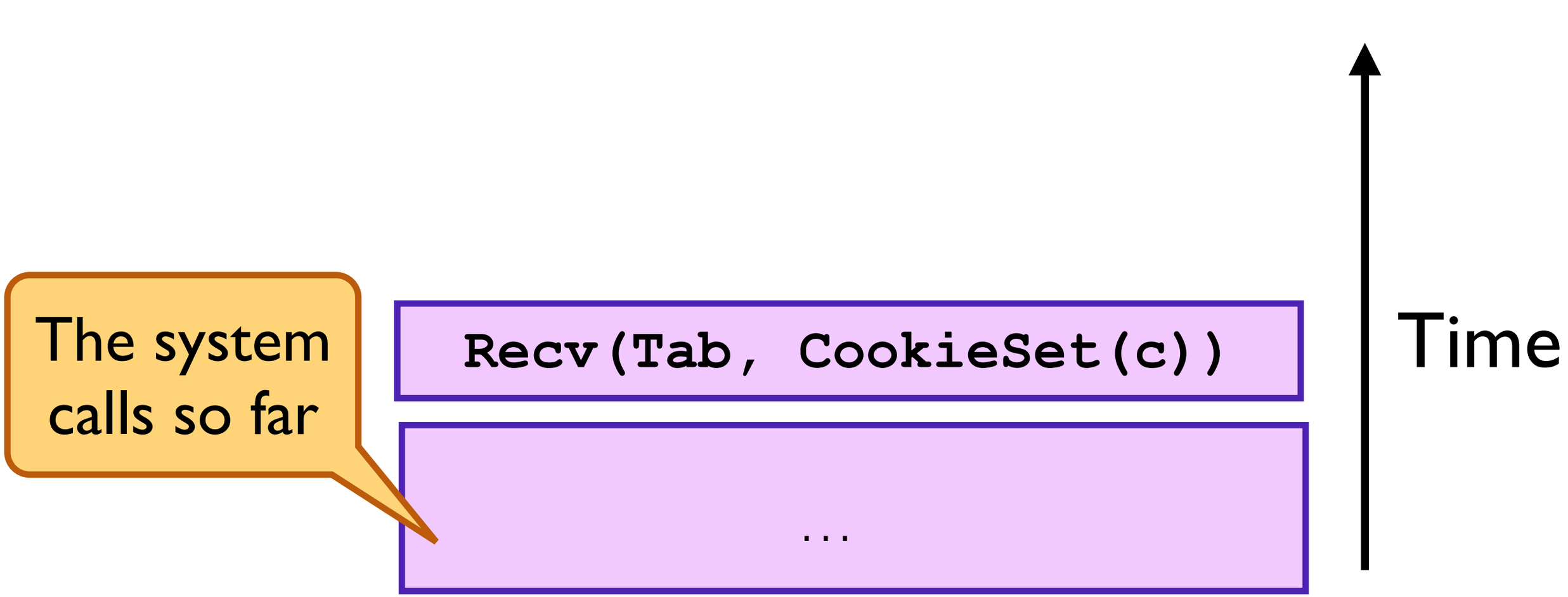

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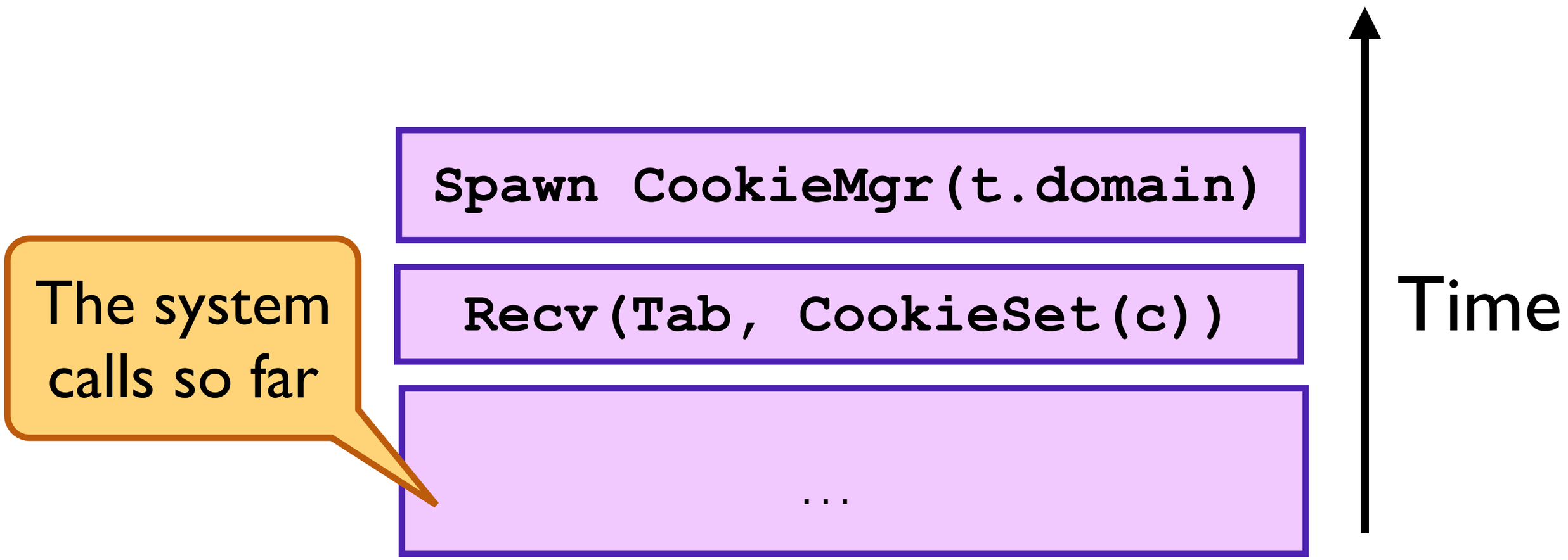

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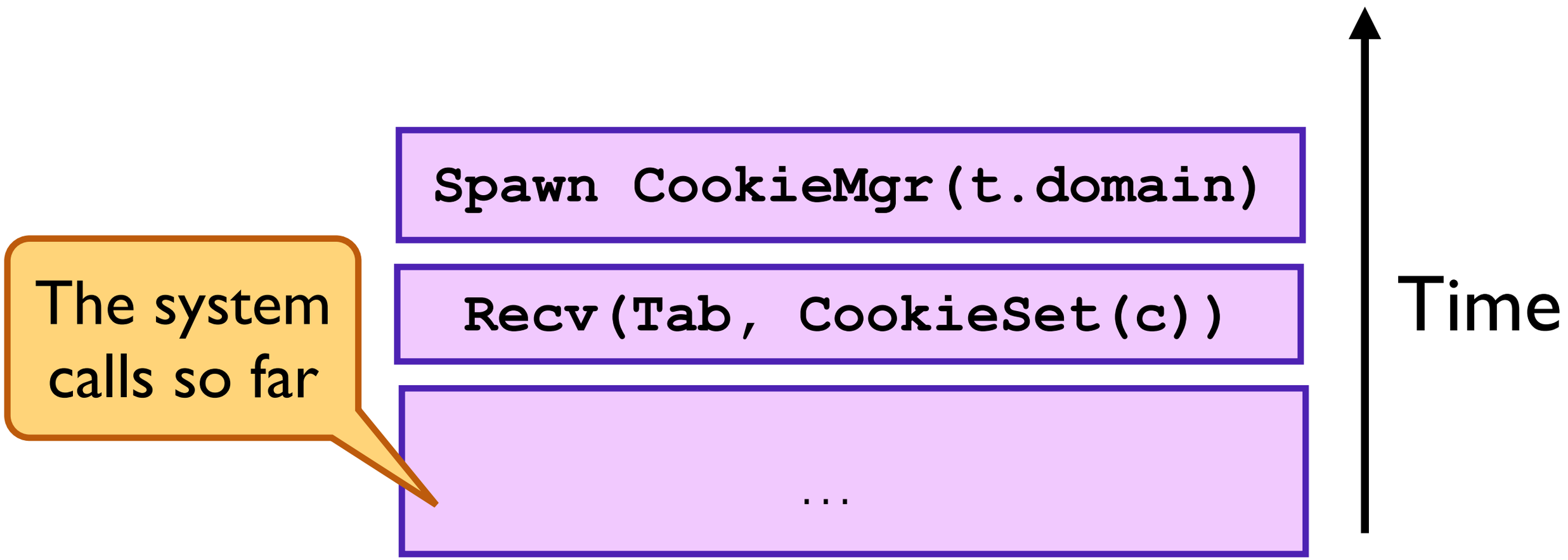

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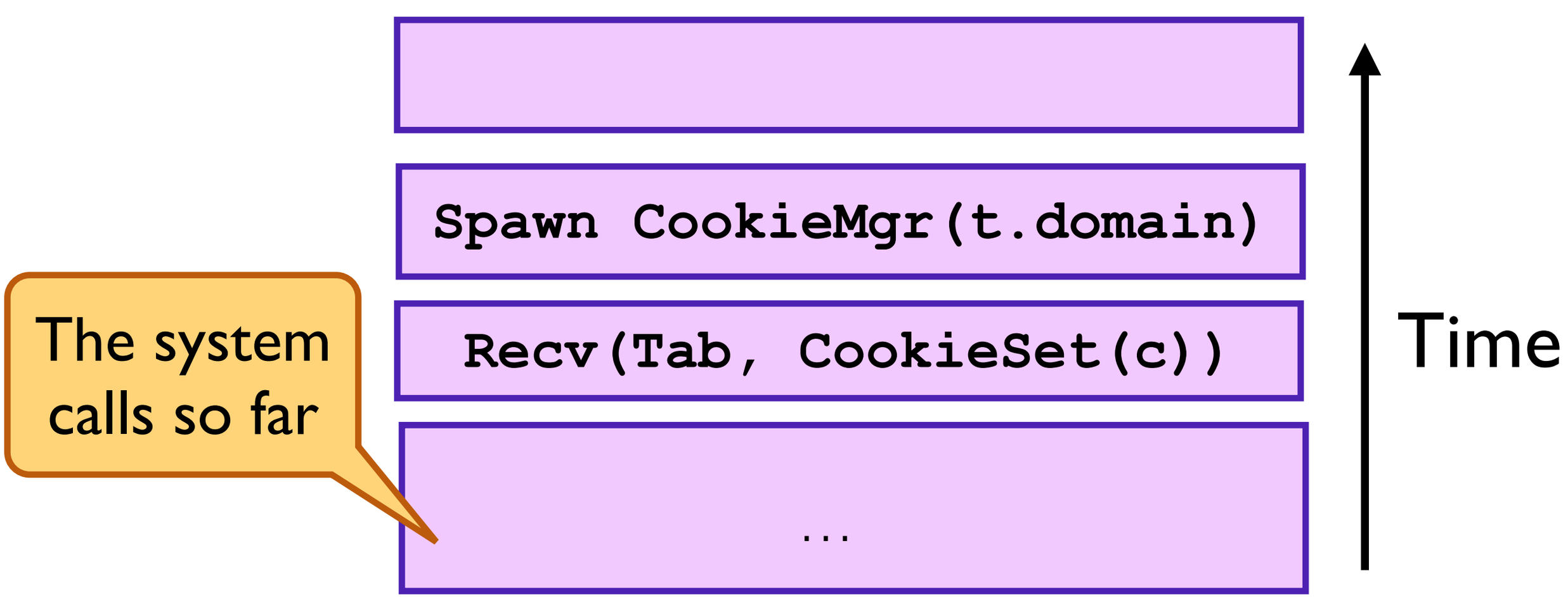

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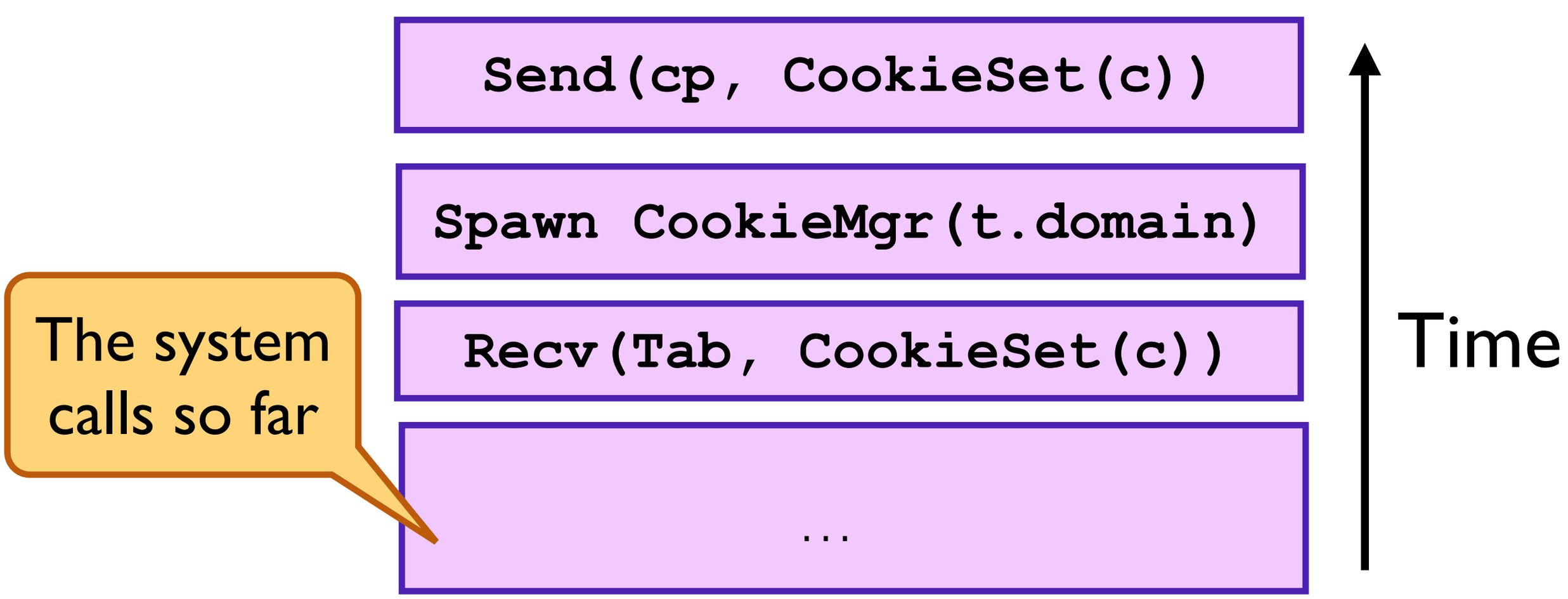

Example: Web browser kernel

```
Components = Tab | CookieMgr | ...
Messages = CookieSet | CookieGet | ...

Handlers:
  When [Tab t] sends CookieSet(c):
    cp <- find CookieMgr(t.domain)
    send(cp, CookieSet(c))

  When [Tab t] sends CookieGet(c):
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Example: Web browser kernel

Specify cookie integrity

```
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Example: Web browser kernel

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Example: Web browser kernel

```
forall d c,
```

For any domain **d** and cookie **c**

```
Components = Tab | CookieMgr | ...
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Example: Web browser kernel

```
forall d c,

   [Send(CookieMgr(d), CookieSet(c))]
```

The kernel sends the cookie manager for domain **d** a cookie **c**

```
Components = Tab | CookieMgr | ...
Messages = CookieSet | CookieGet | ...

Handlers:
   When [Tab t] sends CookieSet(c):
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Example: Web browser kernel

```
forall d c,

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

Only if

```
Components = Tab | CookieMgr | ...
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```

Example: Web browser kernel

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

```
Compon
Messag                                    ...

Handlers:
   When [Tab t] sends CookieSet(c):
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   When [Tab t] sends CookieGet(c):
      ...
```

The kernel already received a cookie **c** from a tab of domain **d**

Example: Web browser kernel

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

```
C
M                                                  ...

H
  When [Tab t] sends CookieSet(c):
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```

A Enables B

iff

every sys call **B** is preceded by sys call **A**

Example: Web browser kernel

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forall d c,
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REFLEX Benefits:

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Proofs fully automated

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Proof Automation

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Prove kernel code satisfies properties

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by induction on sys call sequences kernel can produce

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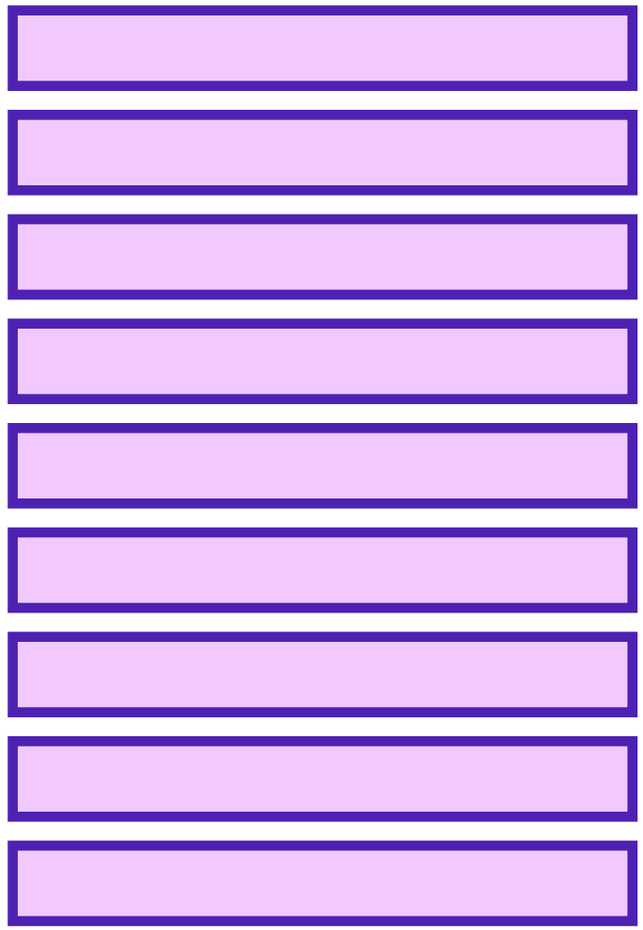

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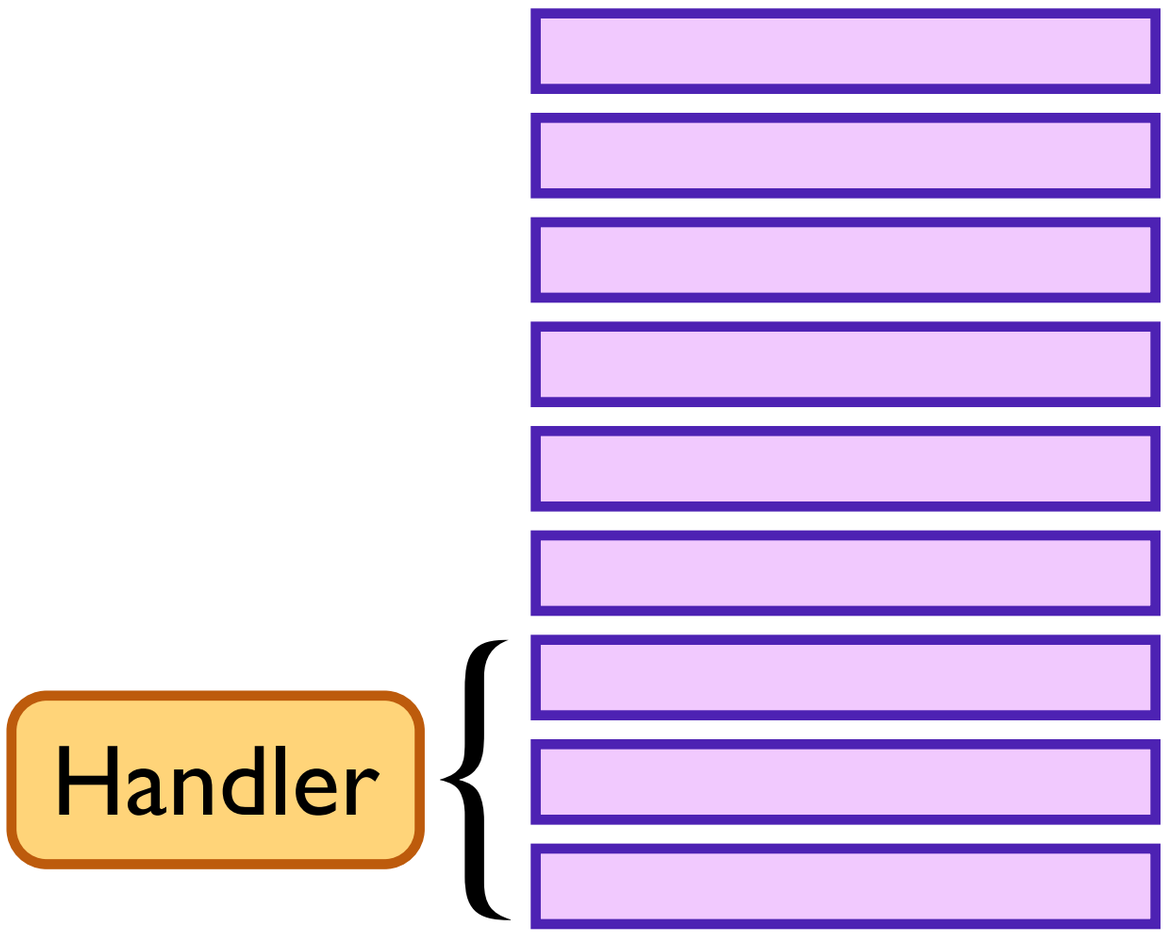

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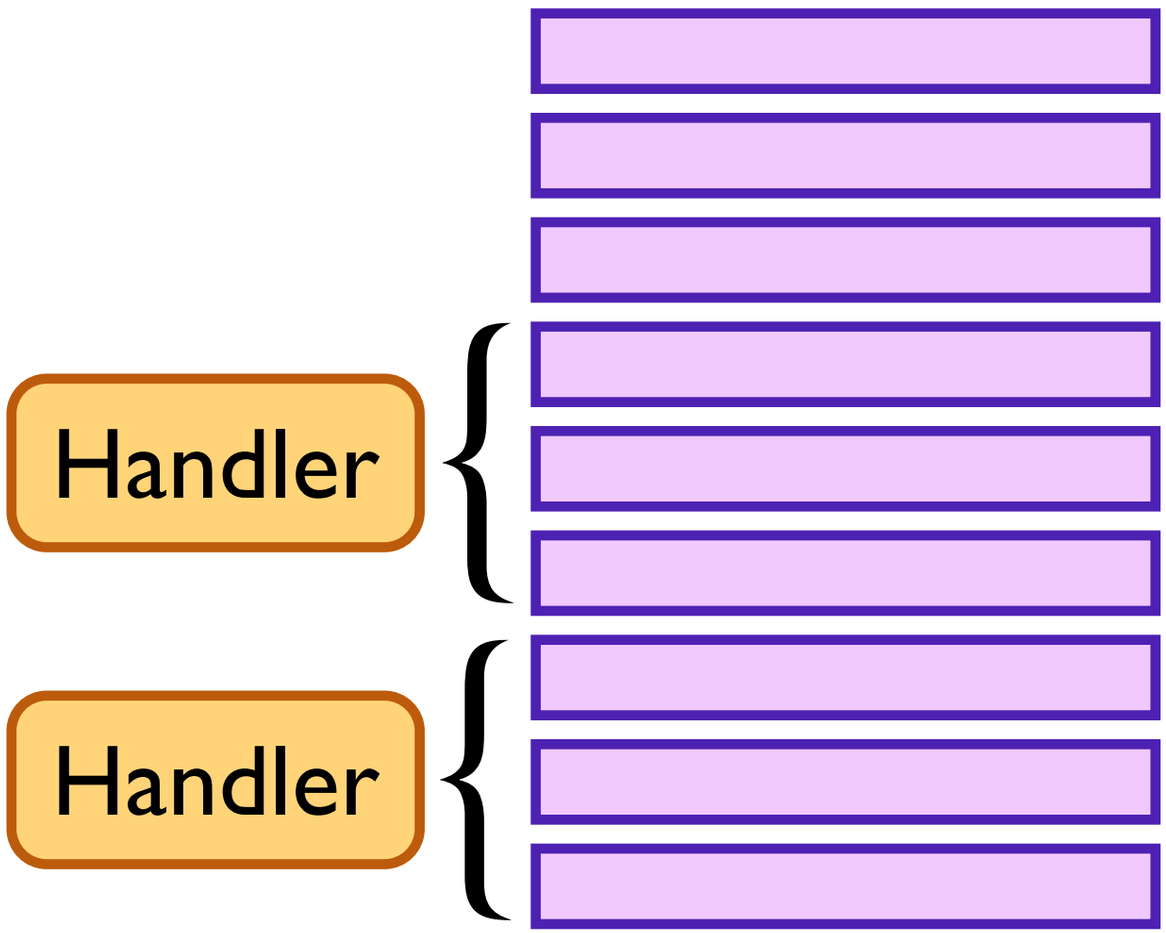

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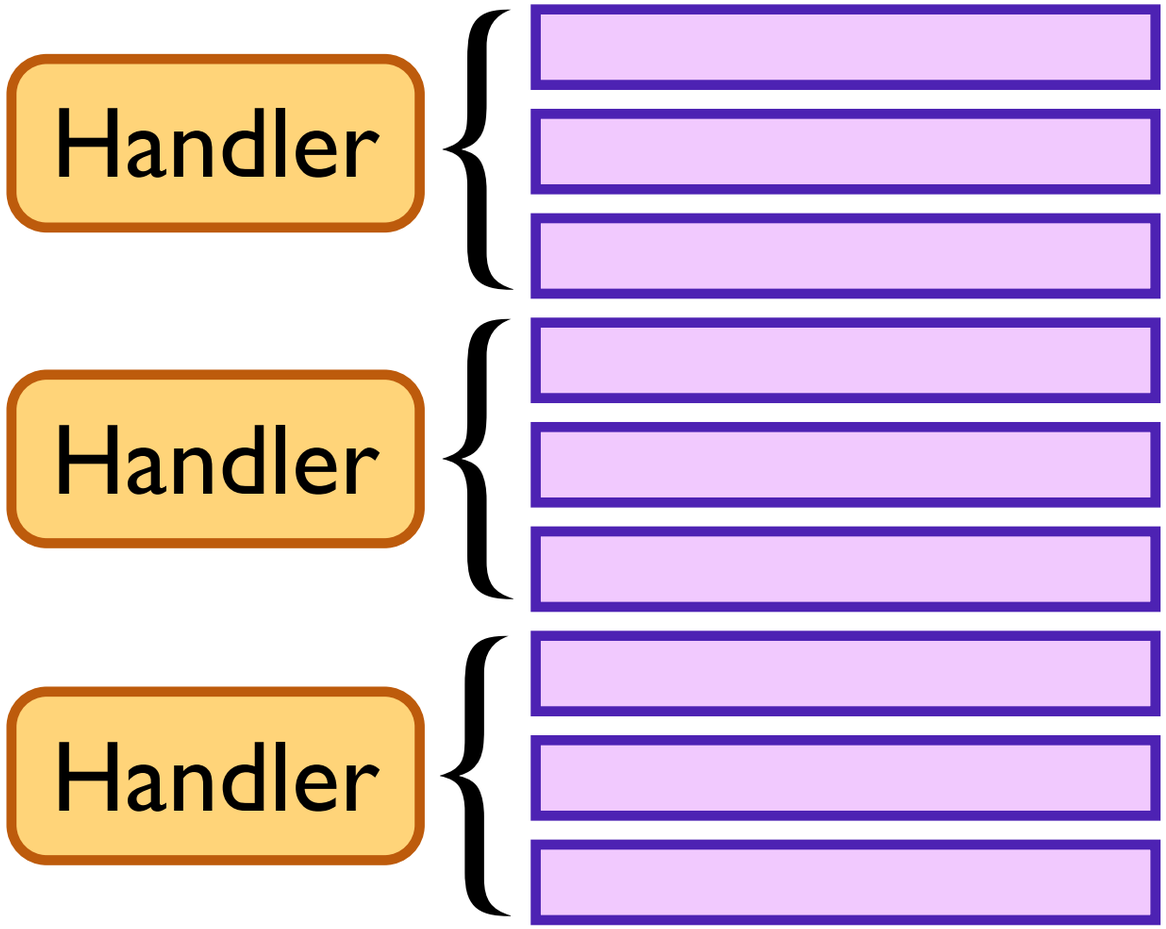

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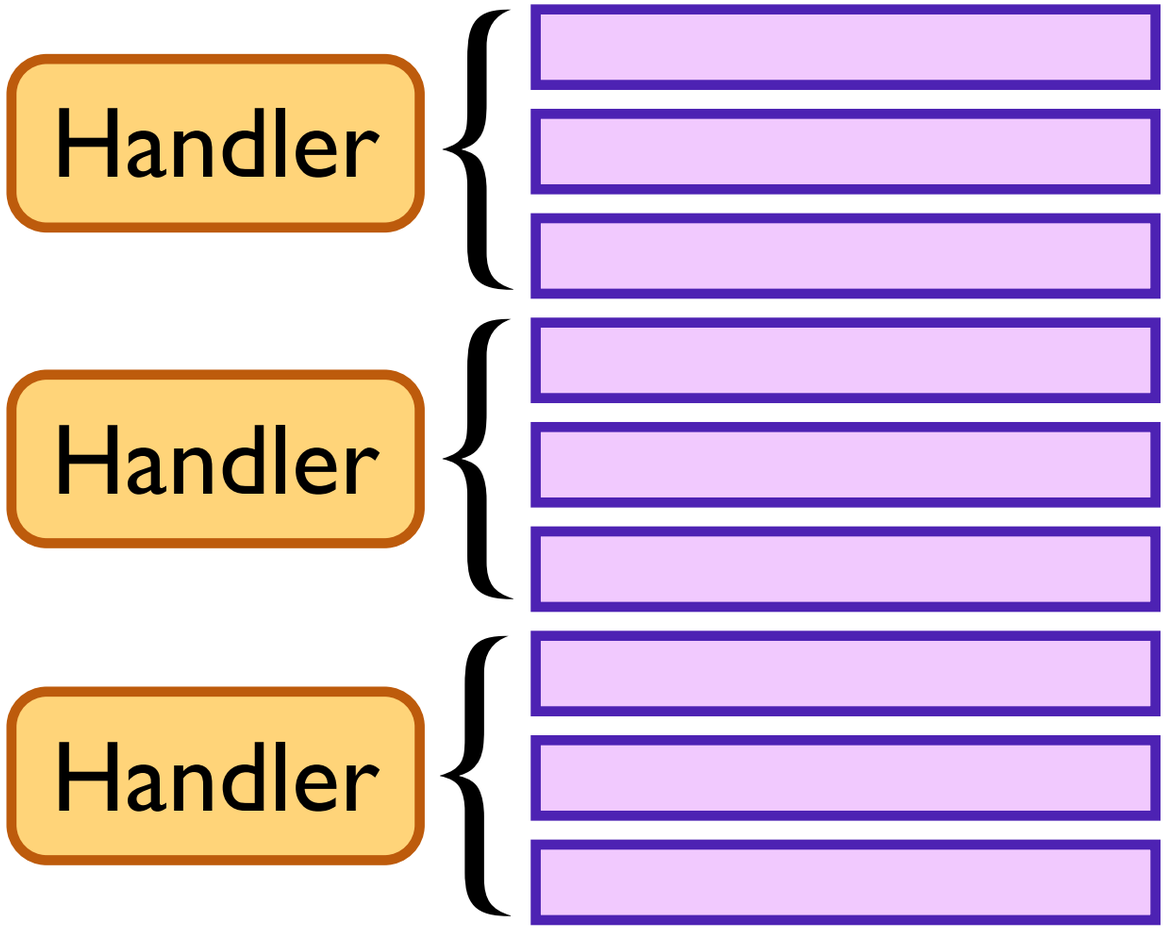

Handlers create structure for induction

Proof Automation

Prove kernel code satisfies properties

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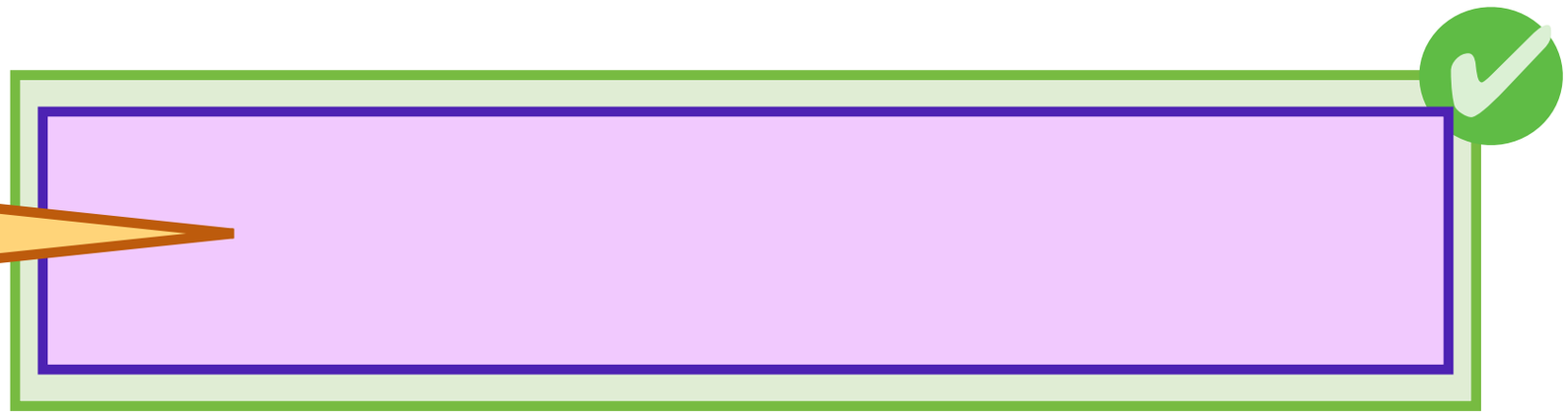
Induction hypothesis: property holds up to this point



Proof Automation

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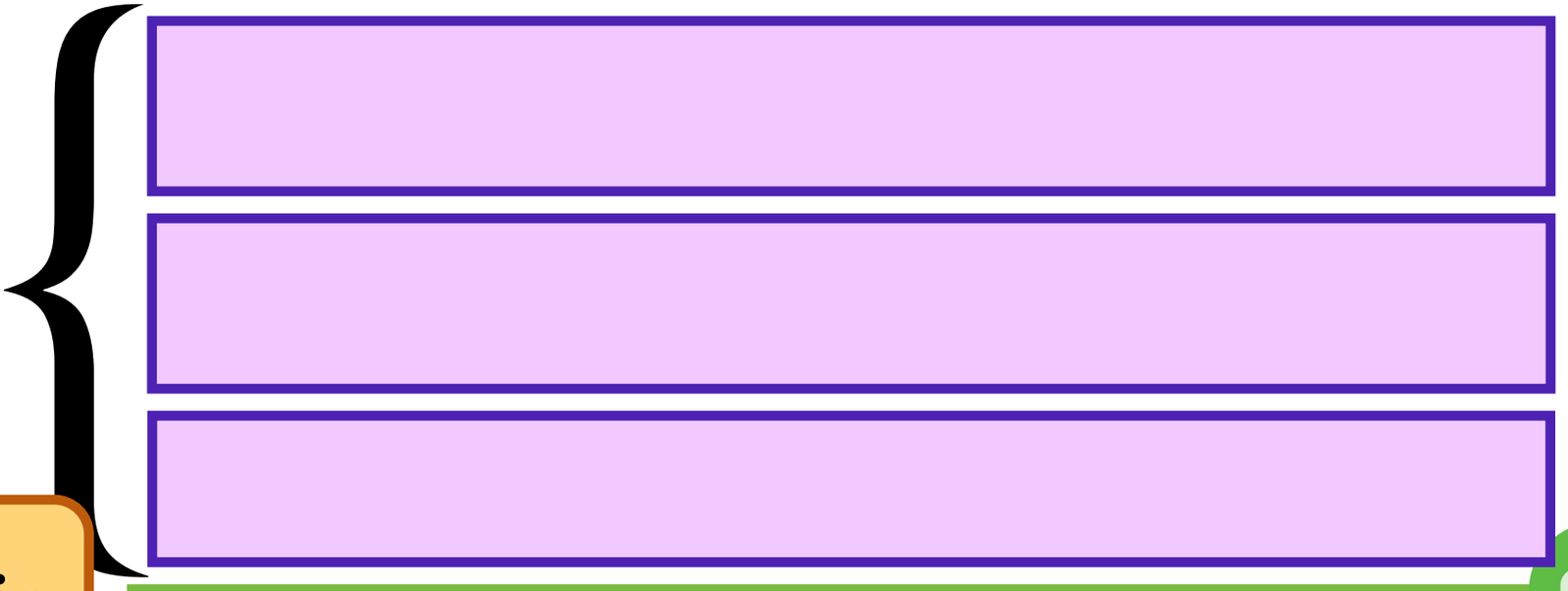
Run a single handler



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Proof Automation

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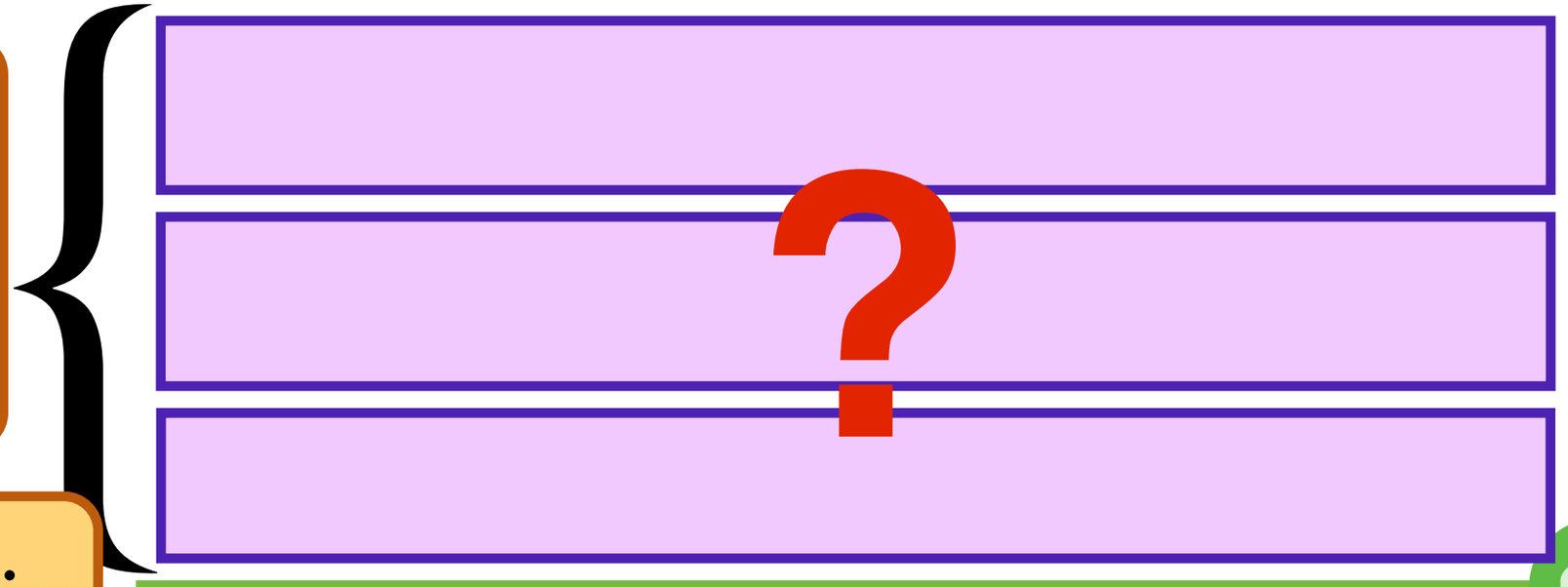
Proof obligation: does property still hold?



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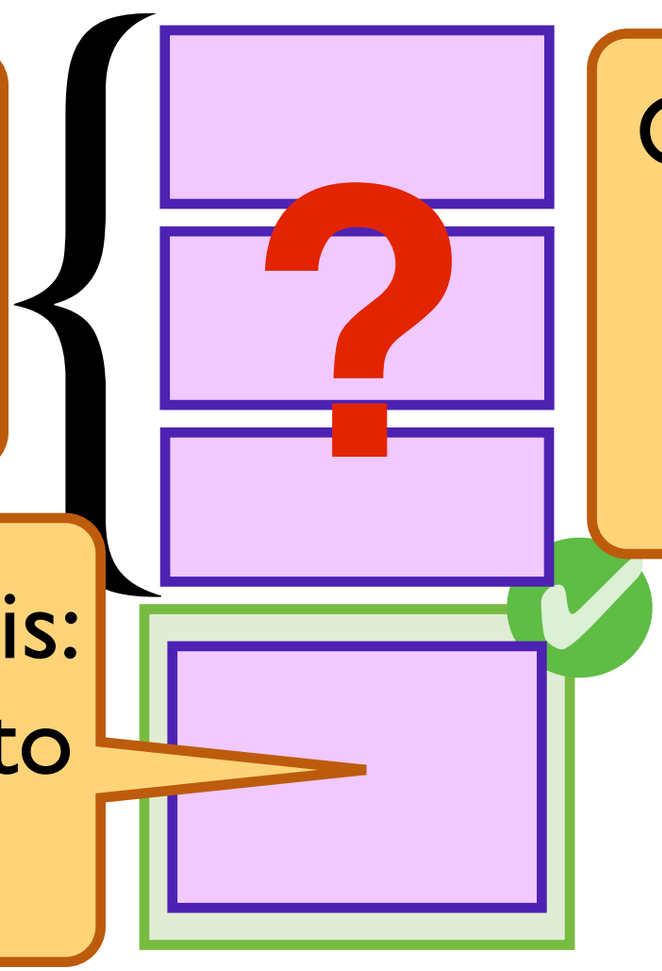

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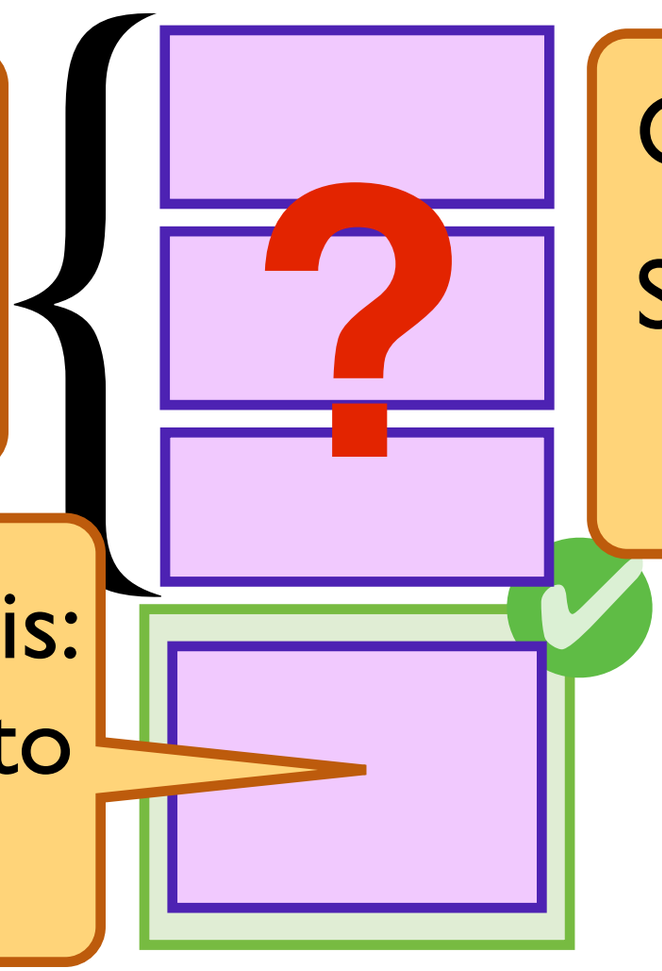

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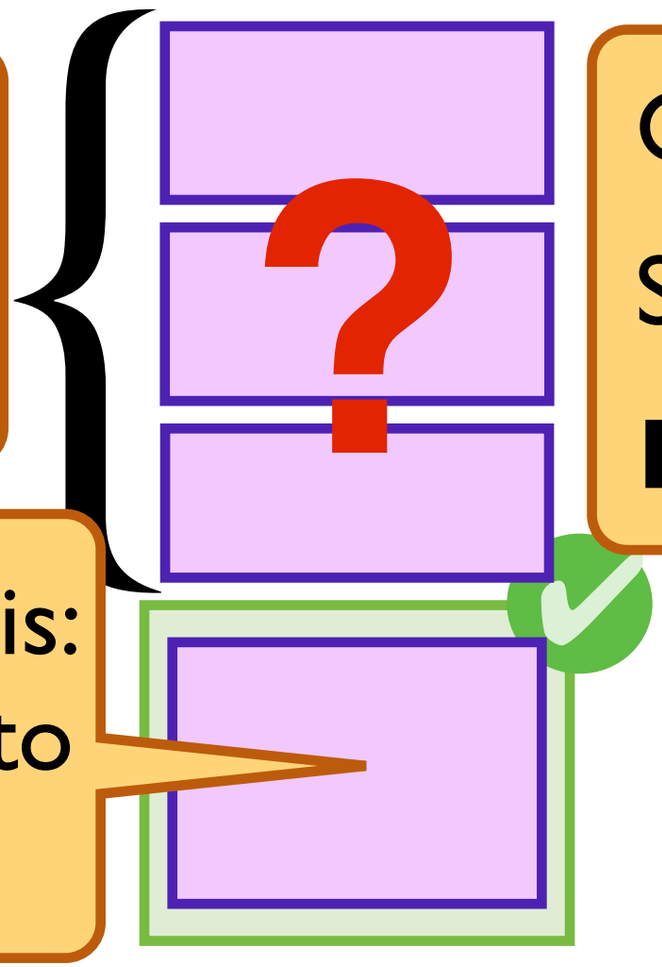

Case analysis on handler

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Prove automatically

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Proof Automation

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Single domain insights:

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Small number of carefully designed property primitives

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Domain-specific heuristics for non-local reasoning

Evaluation

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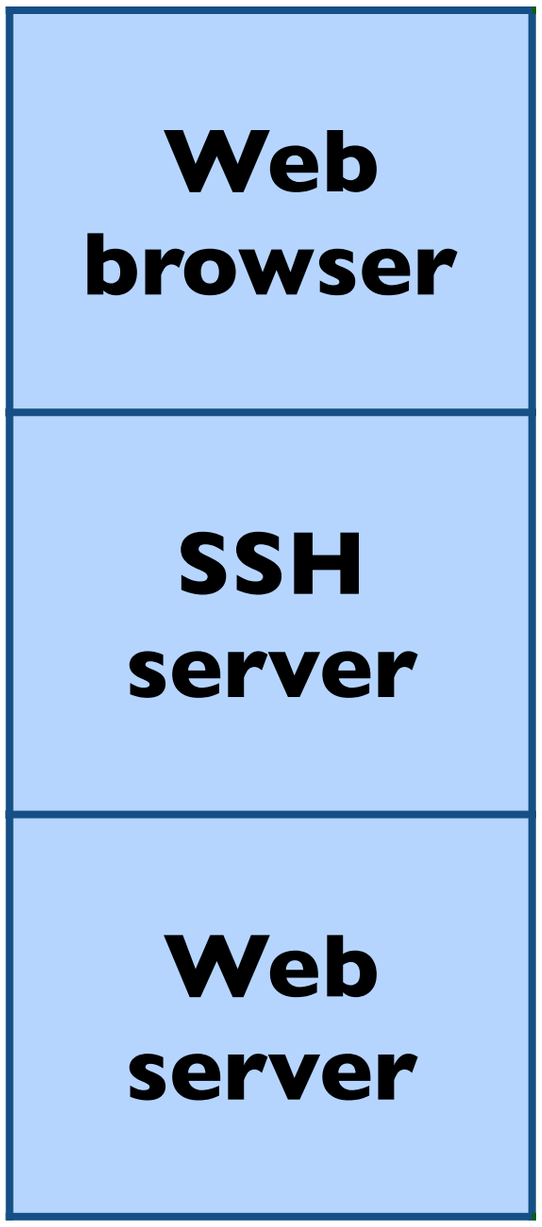

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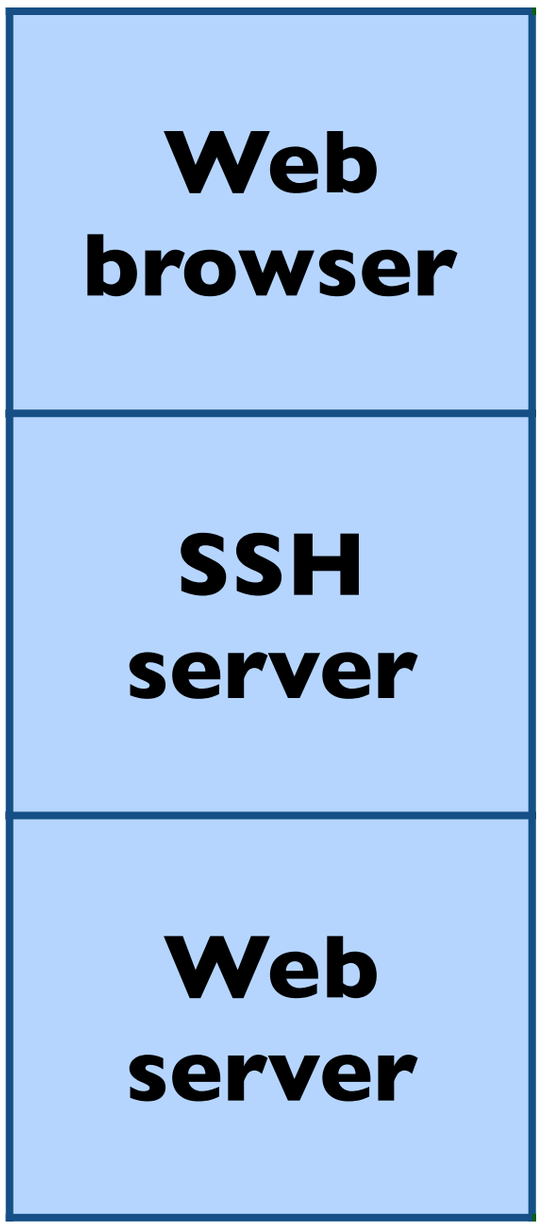

Auto verified 33 properties (80% in < 2 minutes)

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Web browser	**Domains do not interfere, Cookie integrity, …**
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Reflex :

7500 lines of Coq

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

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

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Single reactive system

Development Effort: Framework

Reflex : Many reactive systems

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

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Webkit

OpenSSH

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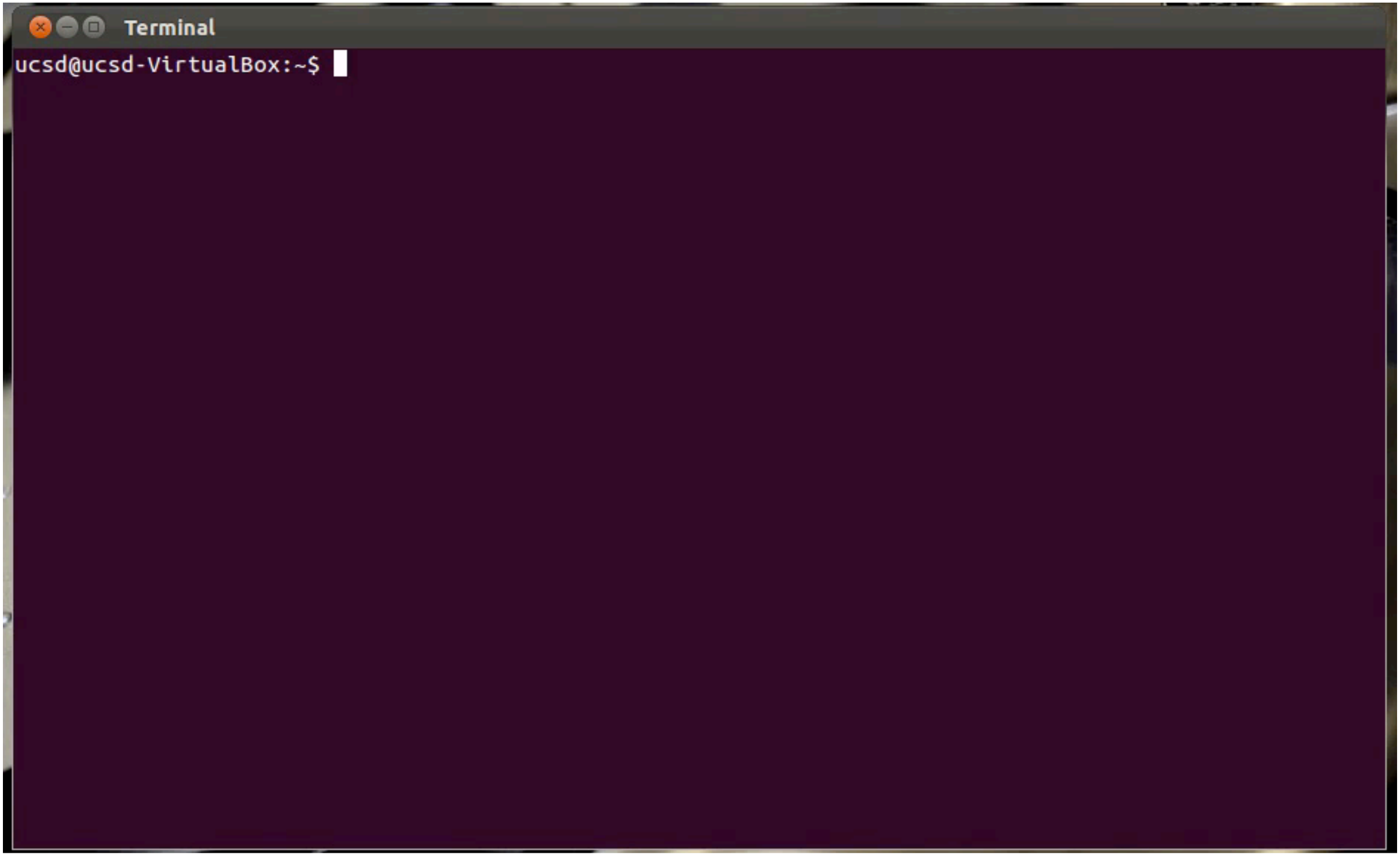
- **Low level incompleteness in automation tactics**

SSH Server Kernel in REFLEX



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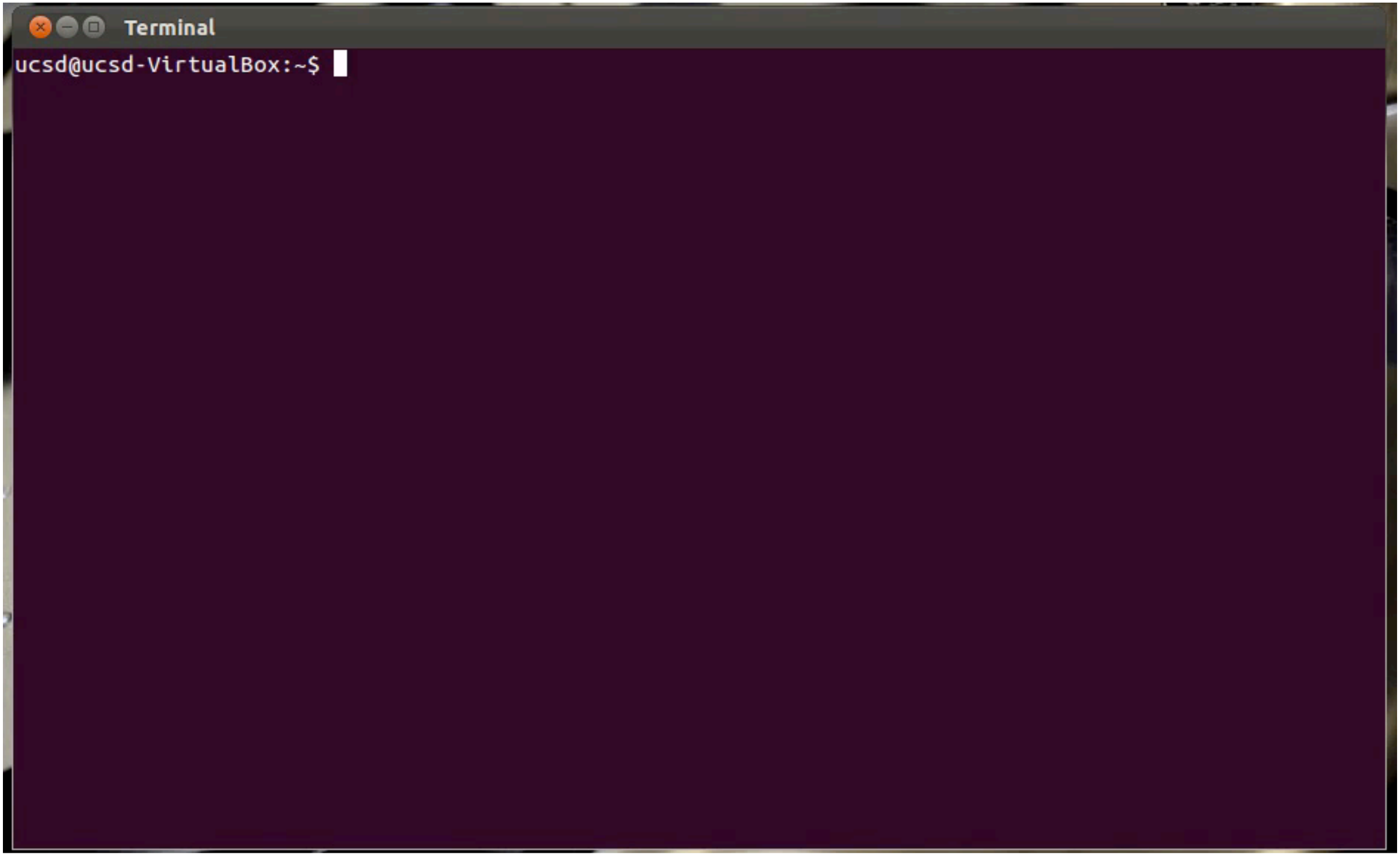
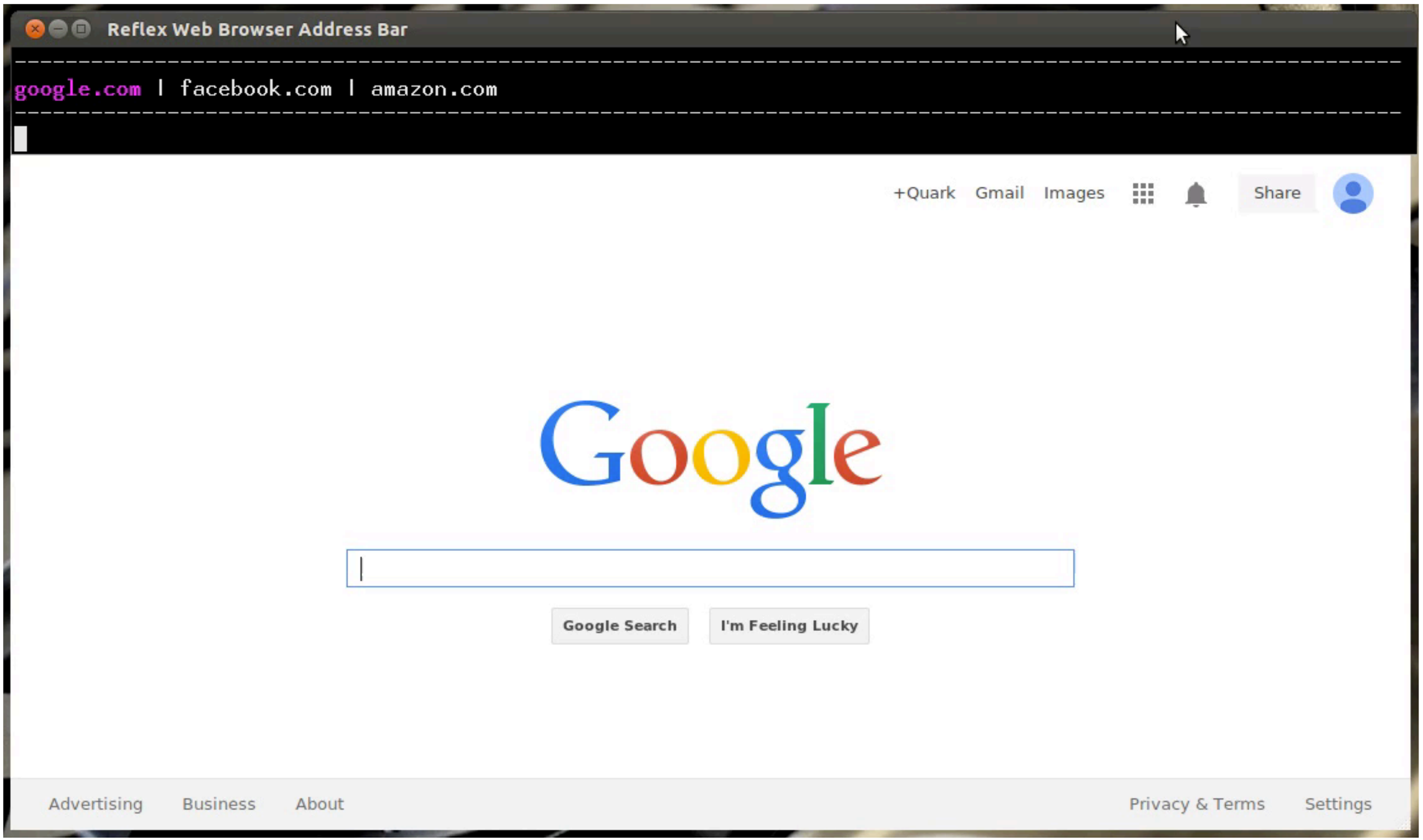


Web Browser Kernel in REFLEX



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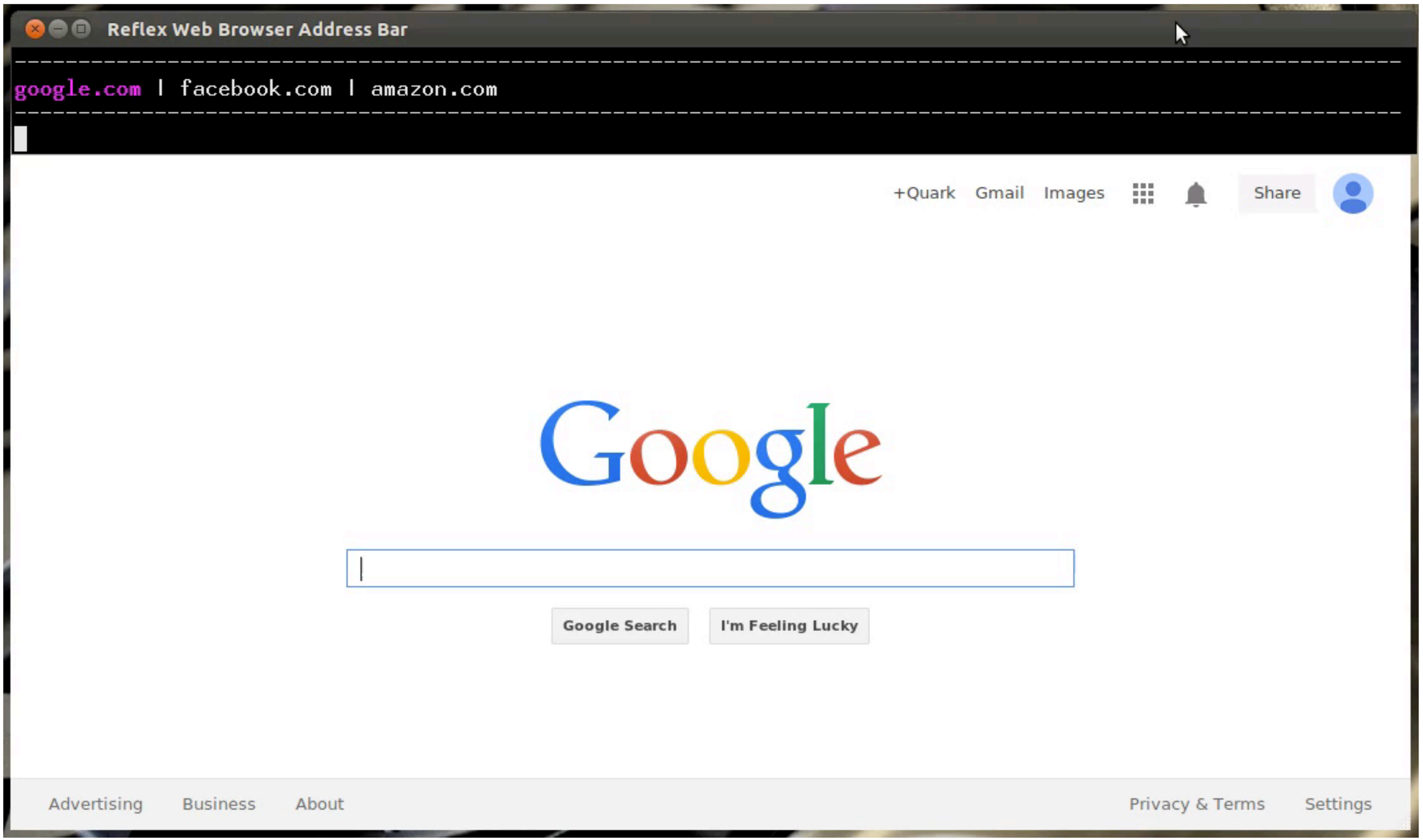

Conclusion

Proof assistant based verification

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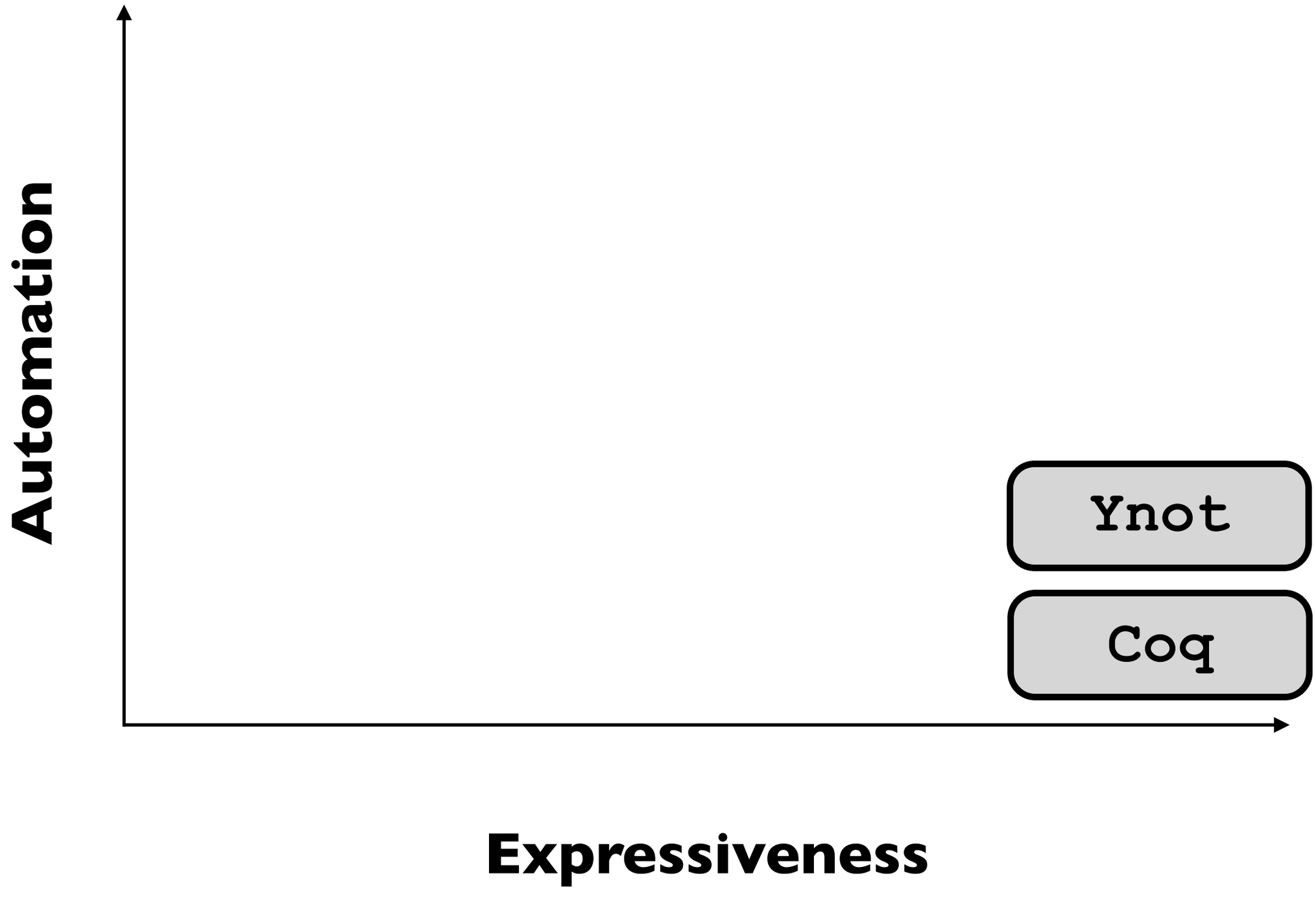

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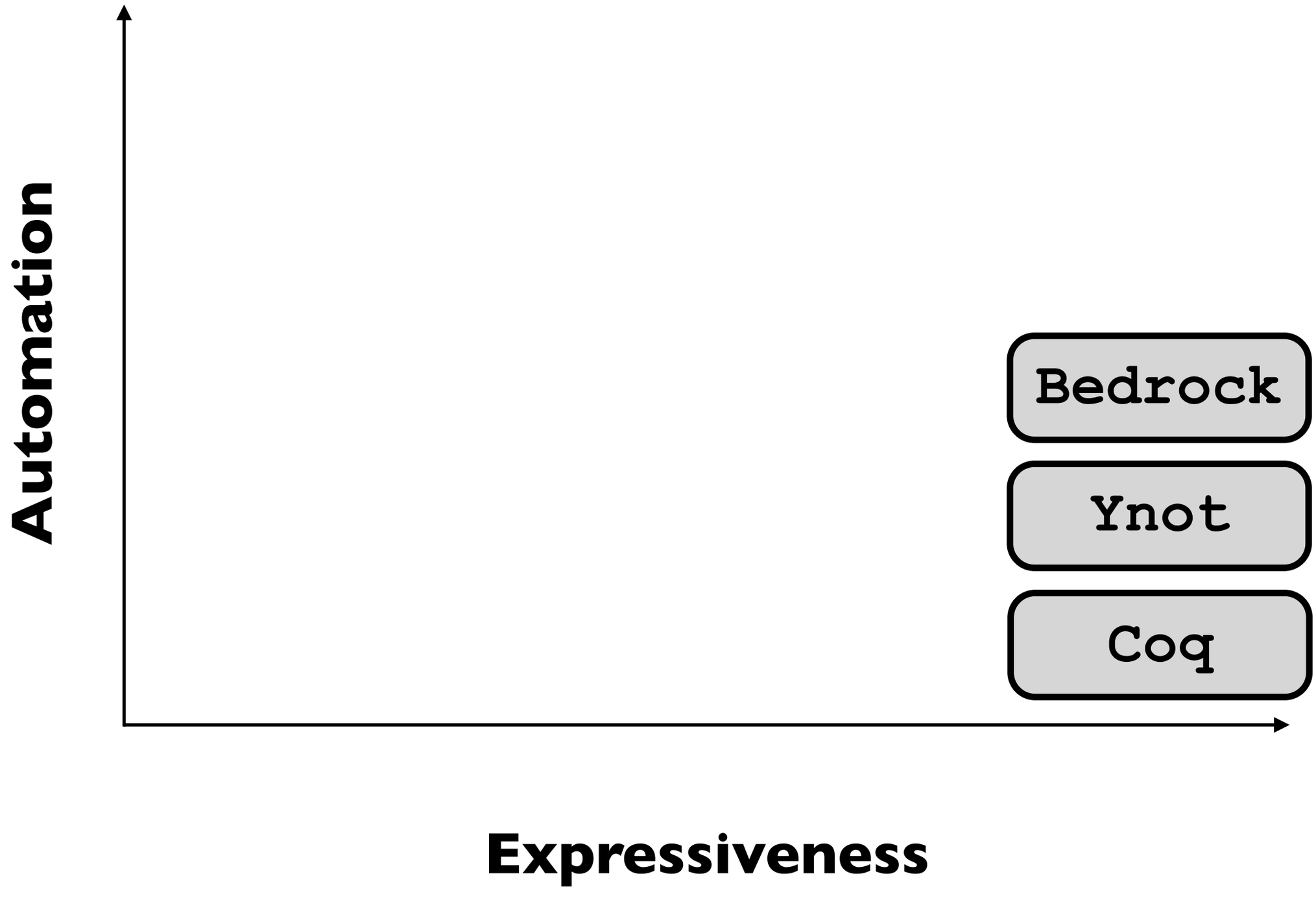

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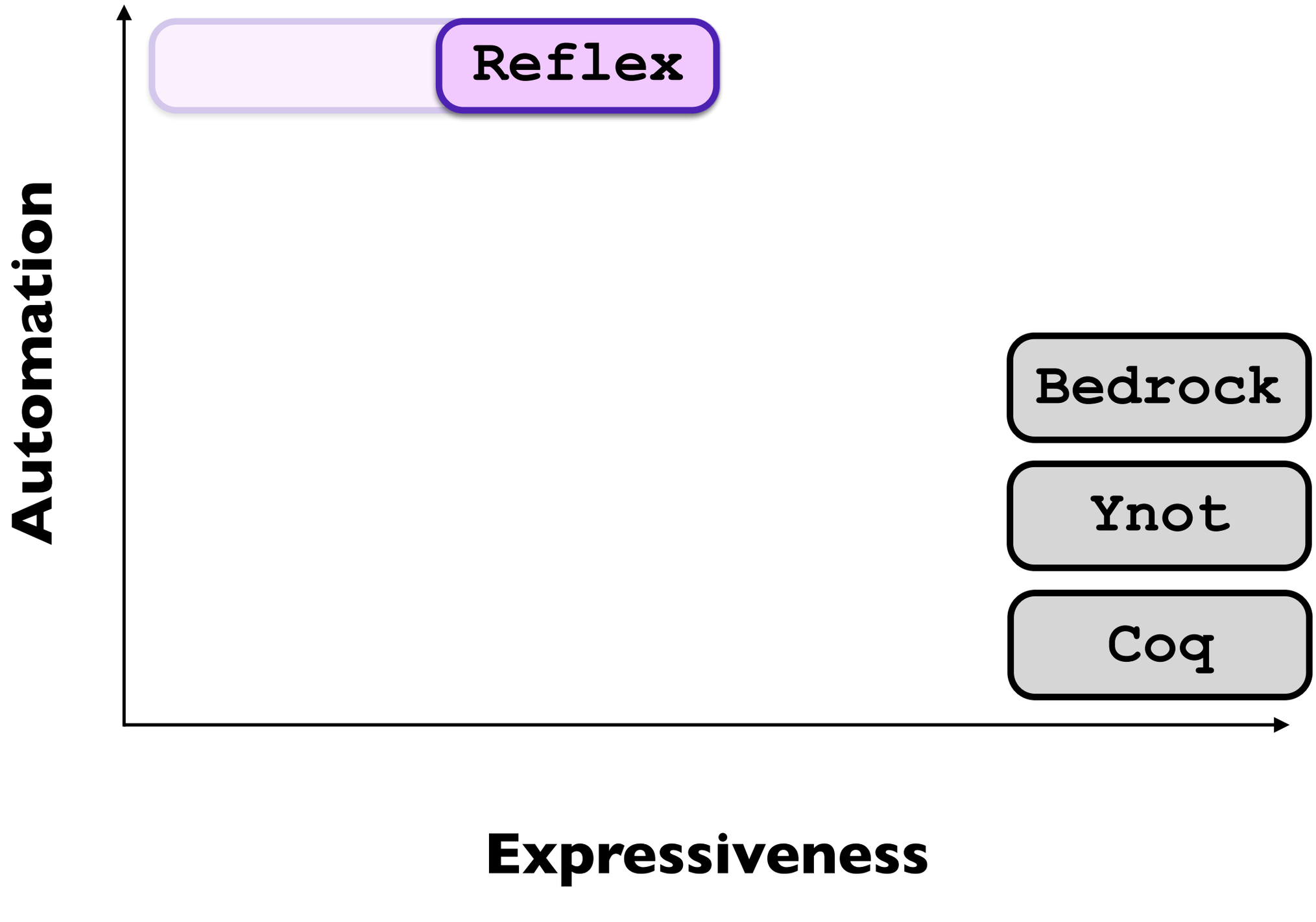

Conclusion

`Reflex`

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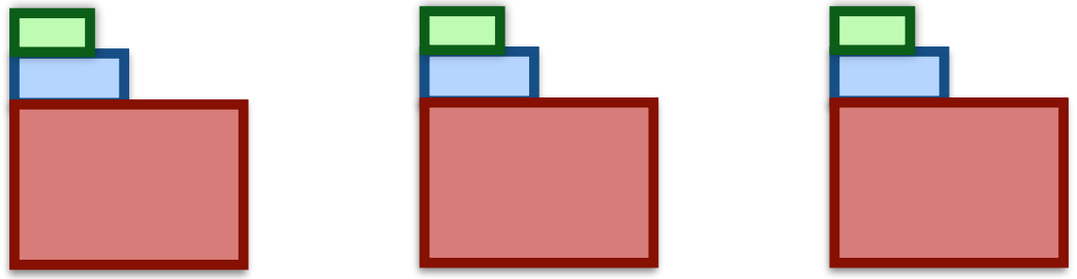

DSL expressive enough for entire domain

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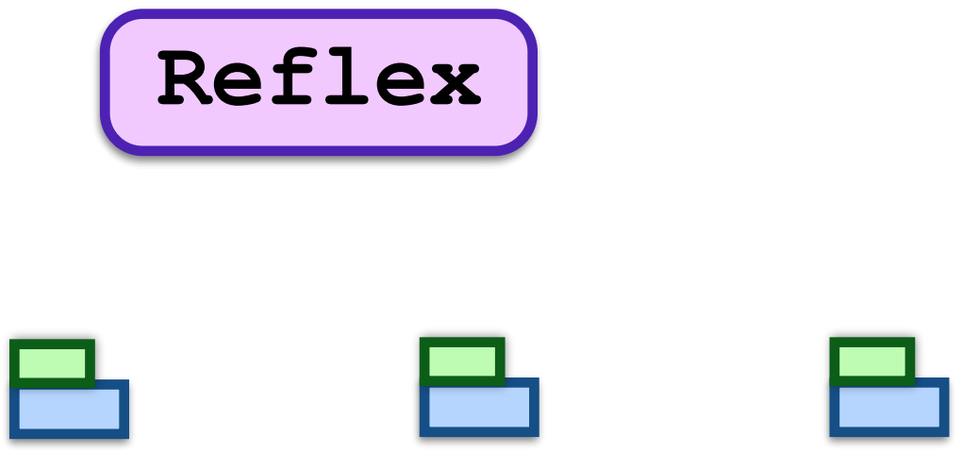

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Automation eliminates manual proof burden

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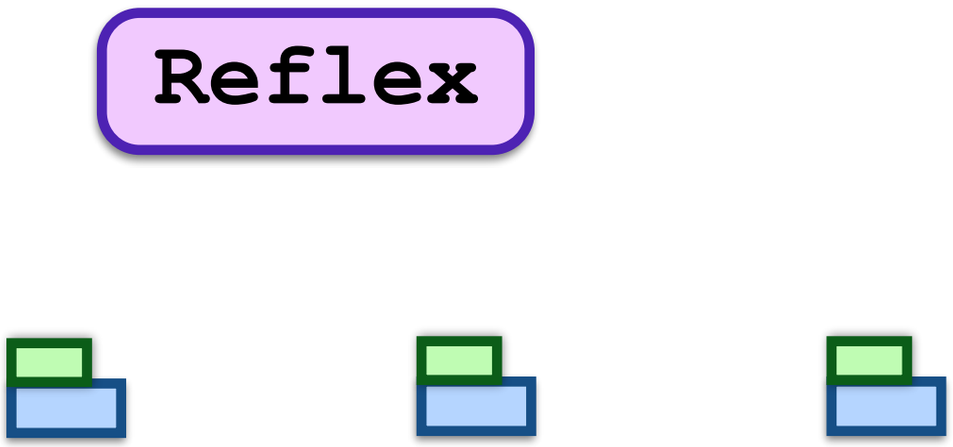

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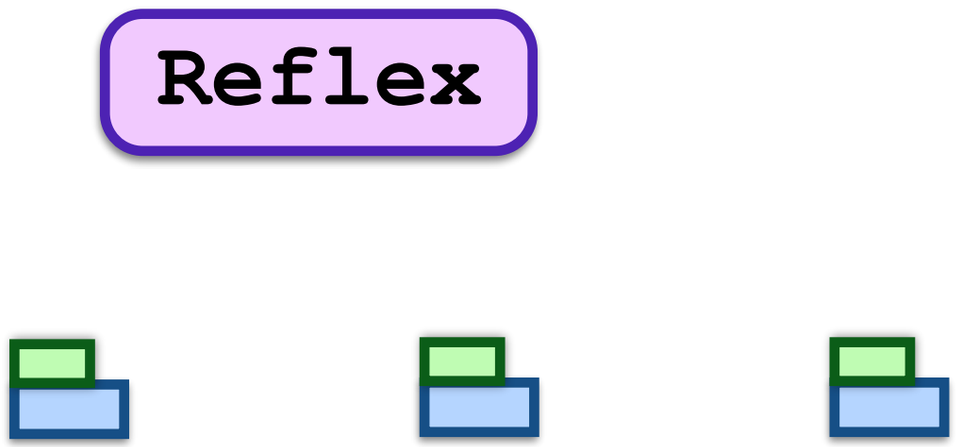
http://goto.ucsd.edu/reflex/

Thank You!



DSL expressive enough for entire domain

Automation eliminates manual proof burden

http://goto.ucsd.edu/reflex/