Automating Formal Proofs for Reactive Systems

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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

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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
Clang/LLVM	181
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Proof Assistant Based Verification

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Proof Assistant

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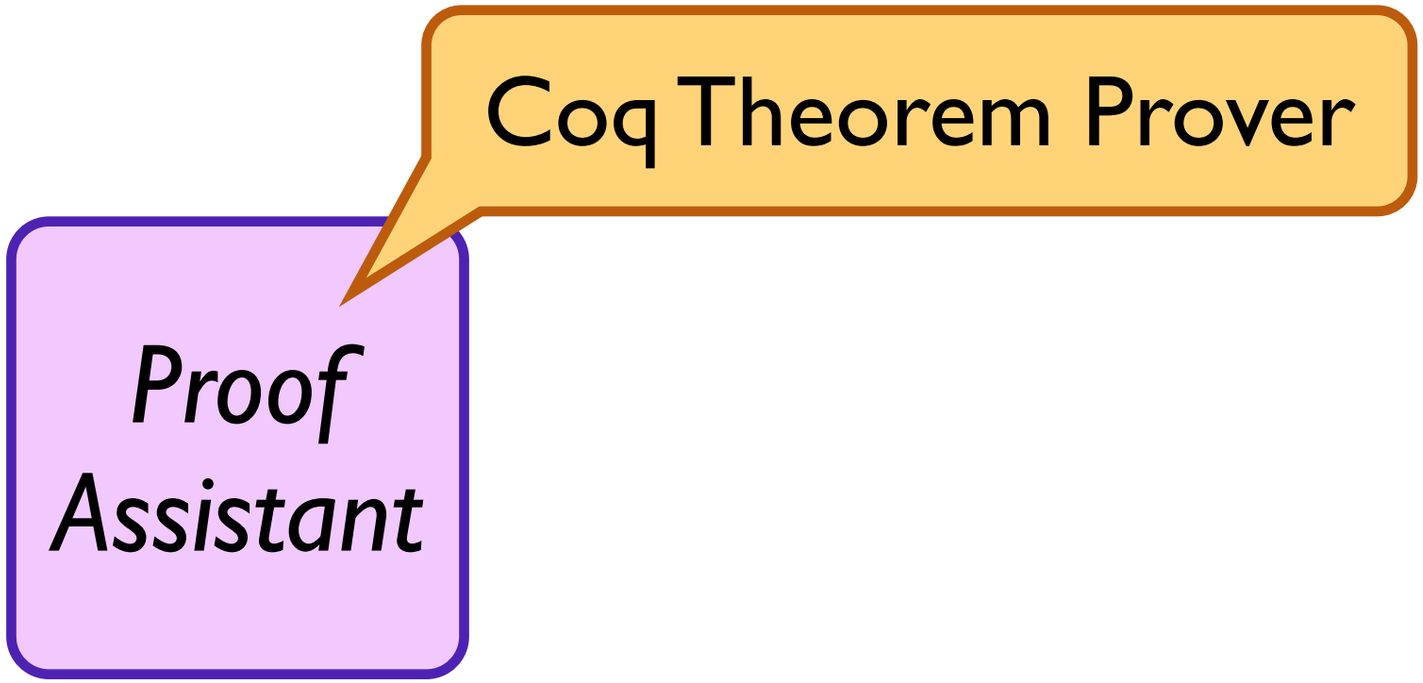

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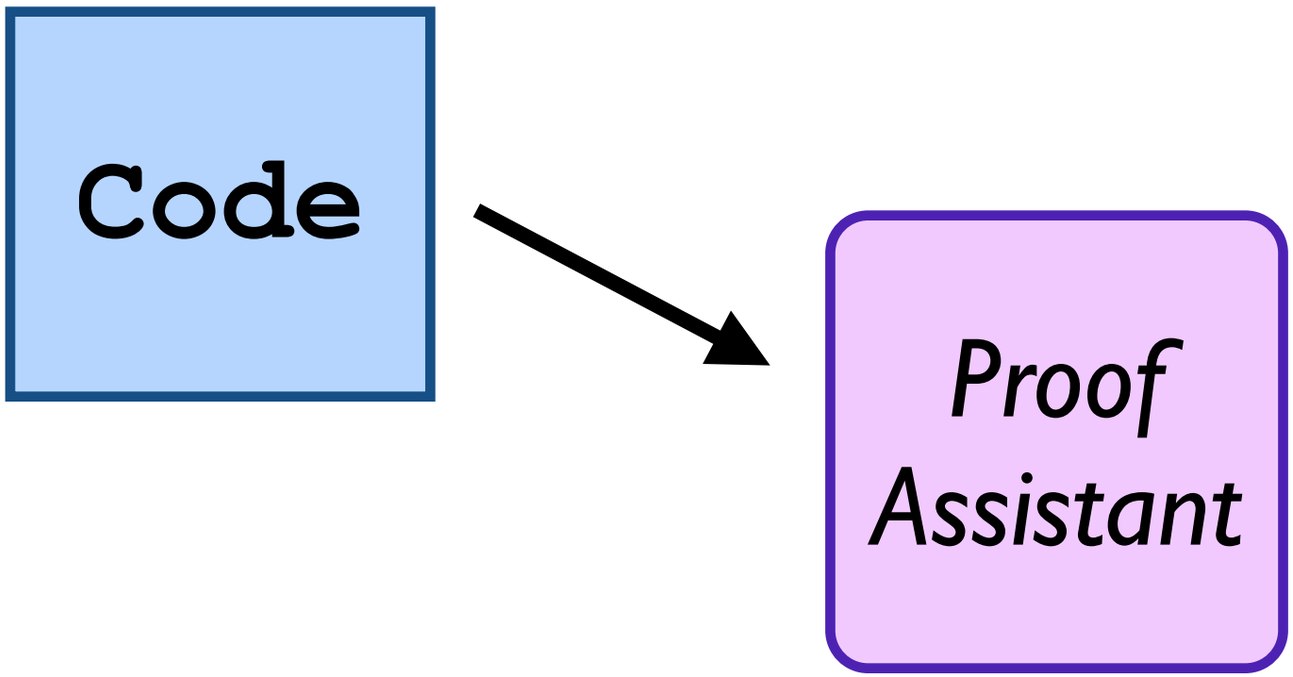

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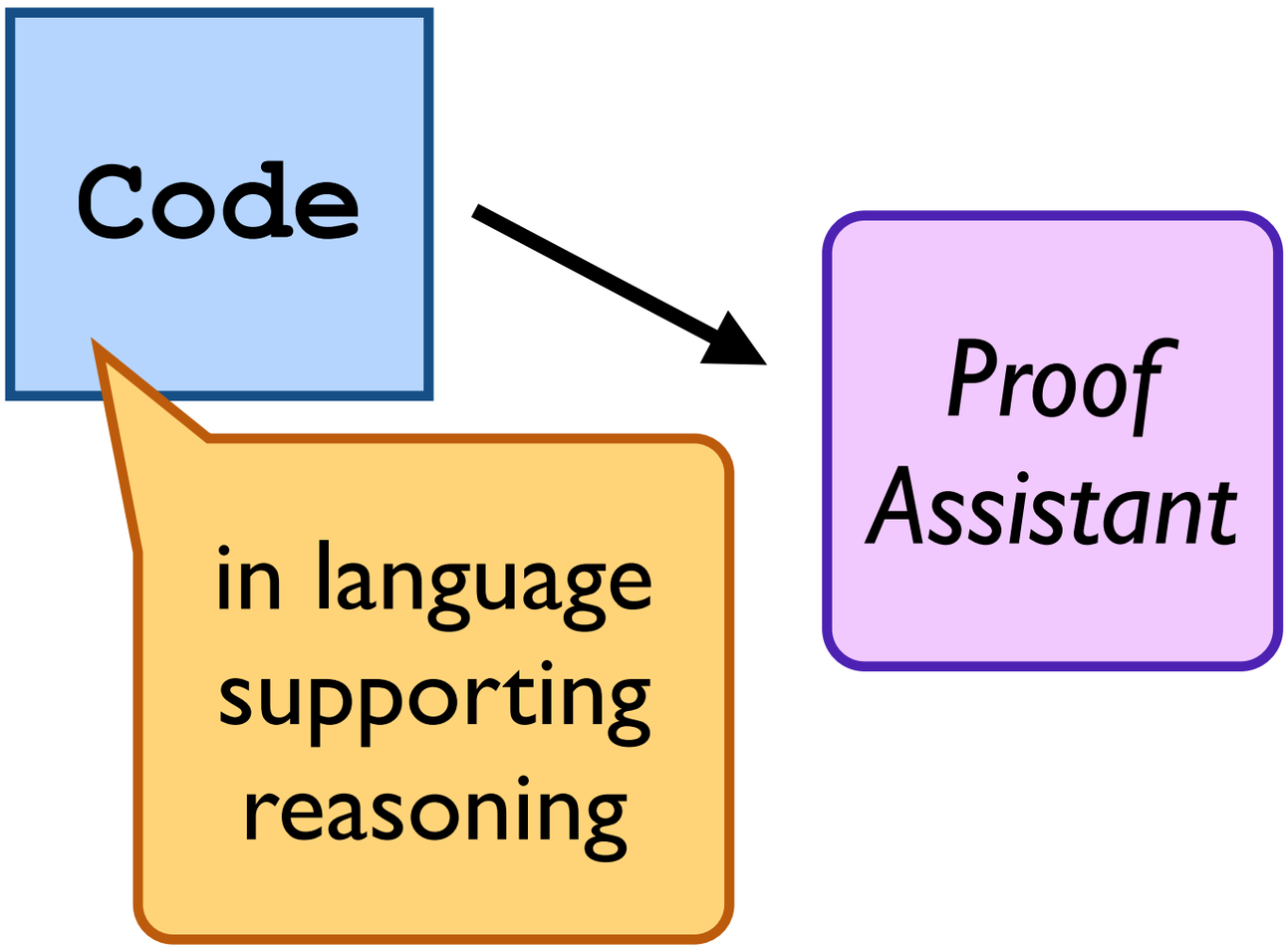

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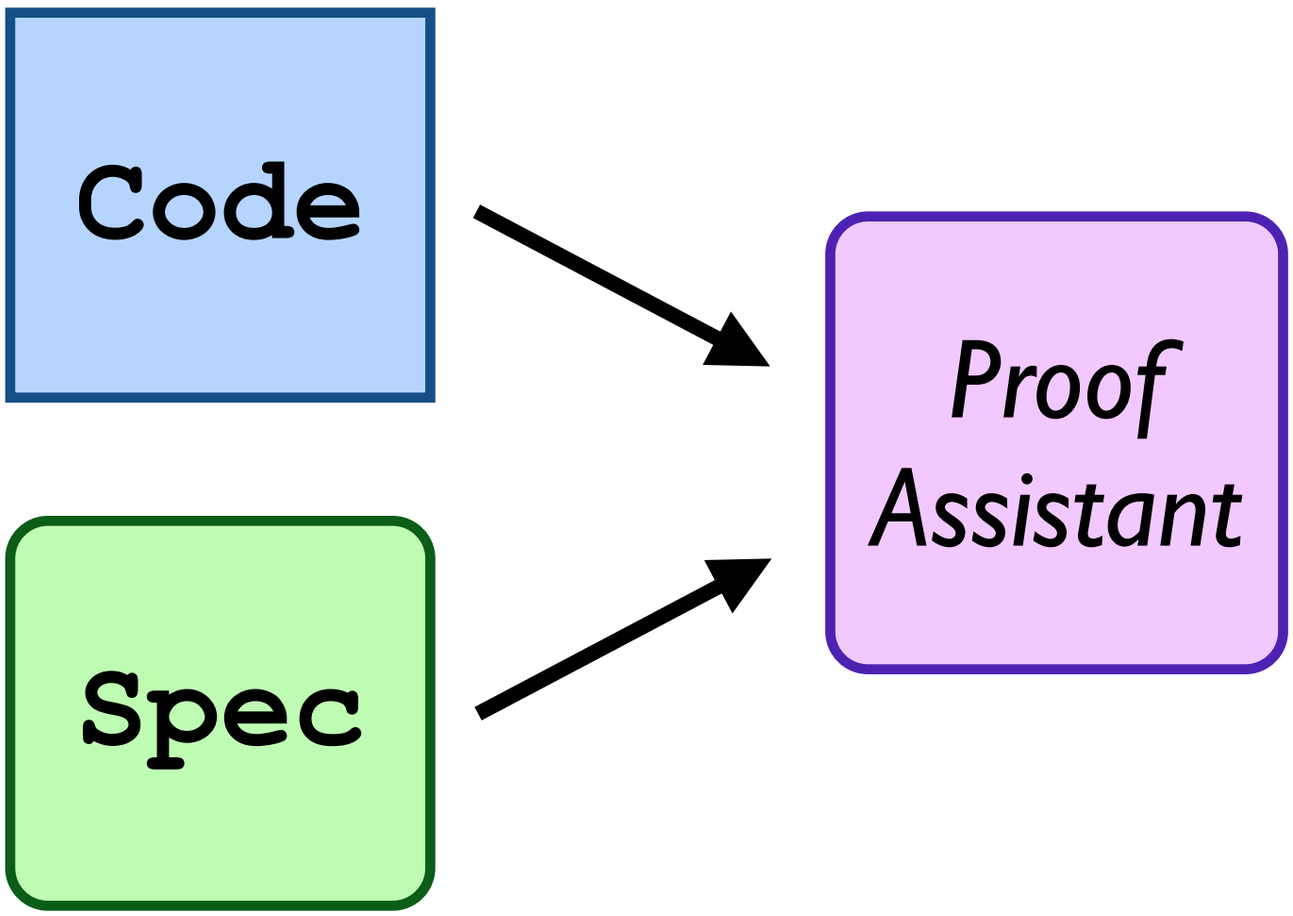

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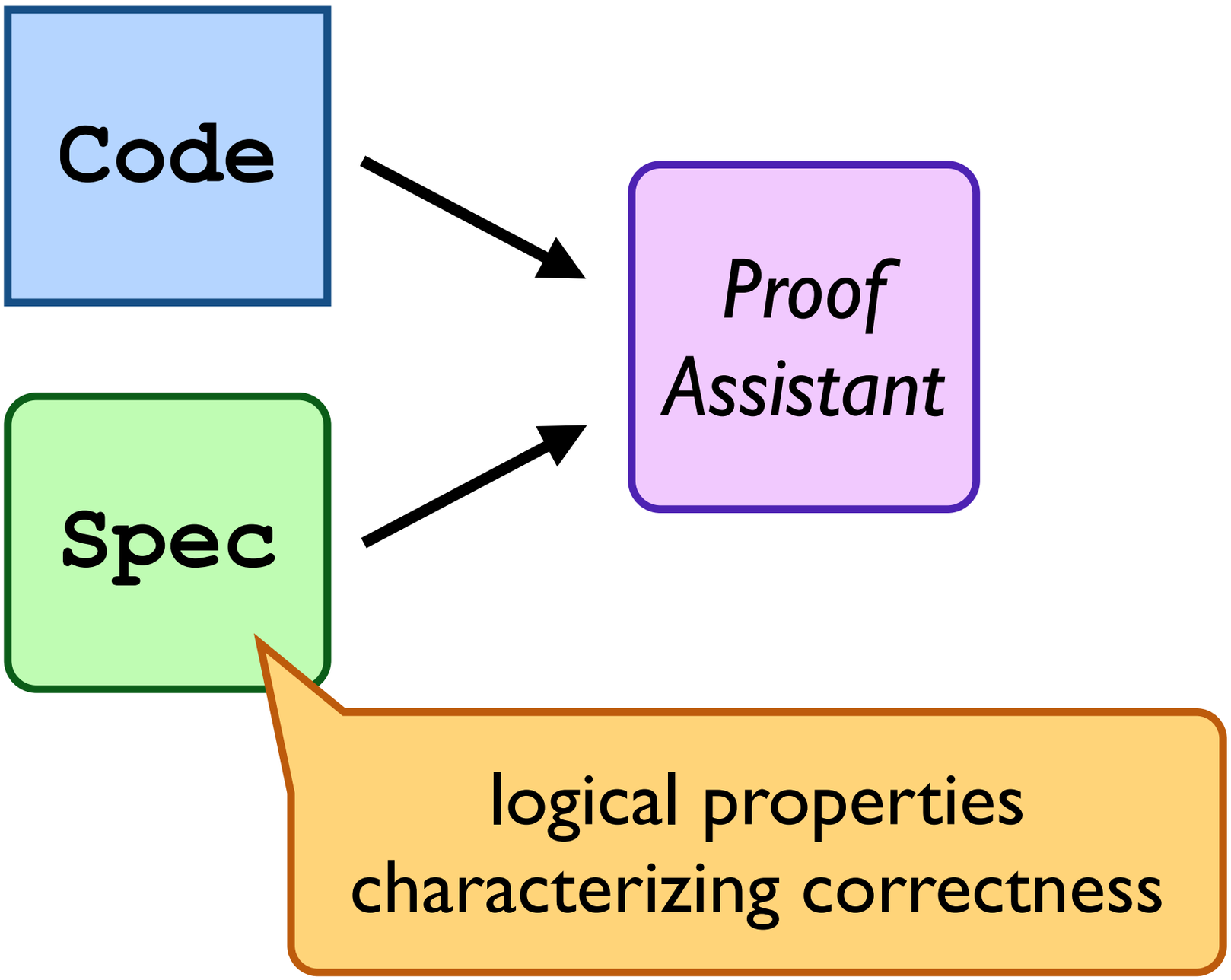

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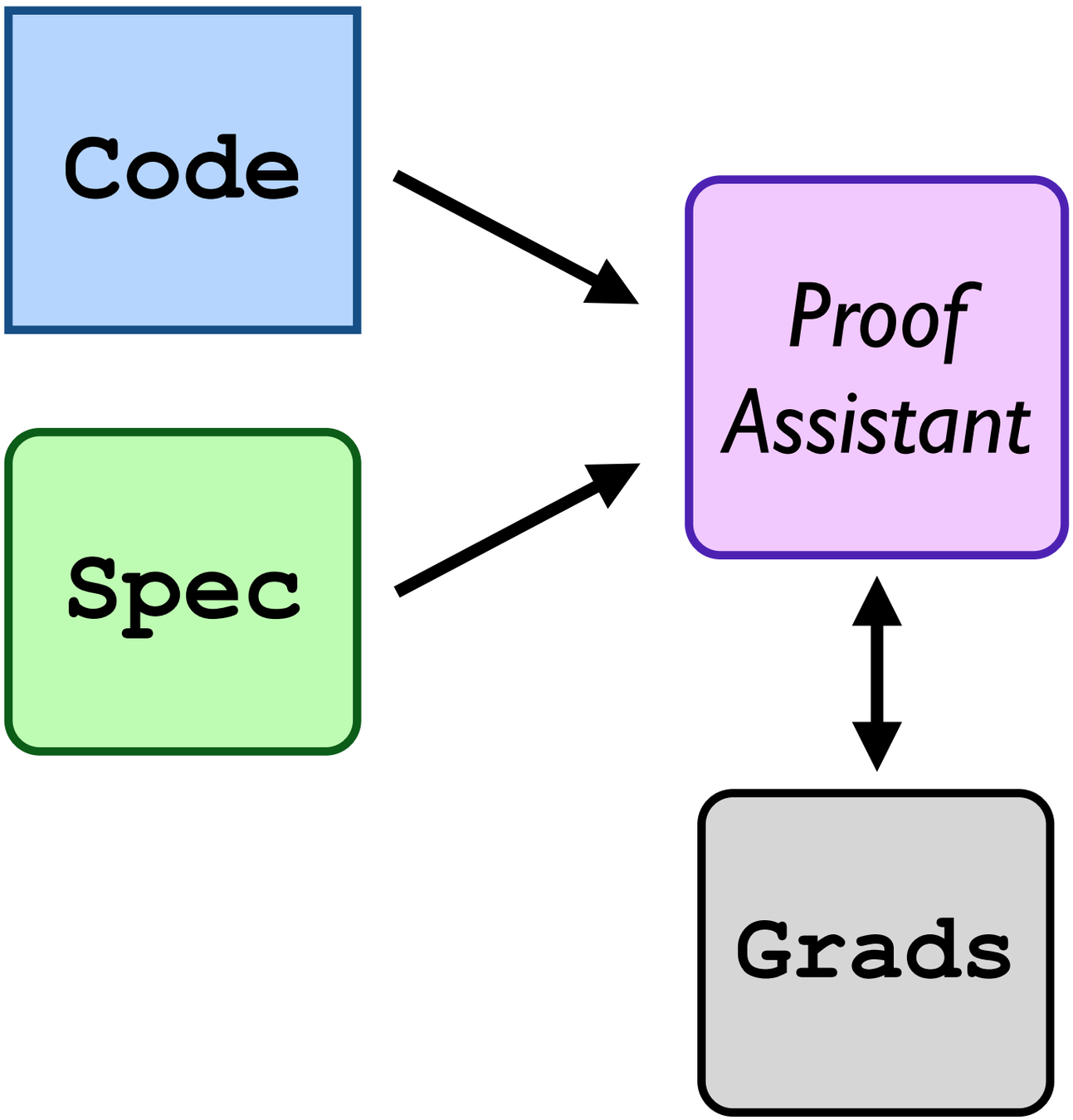

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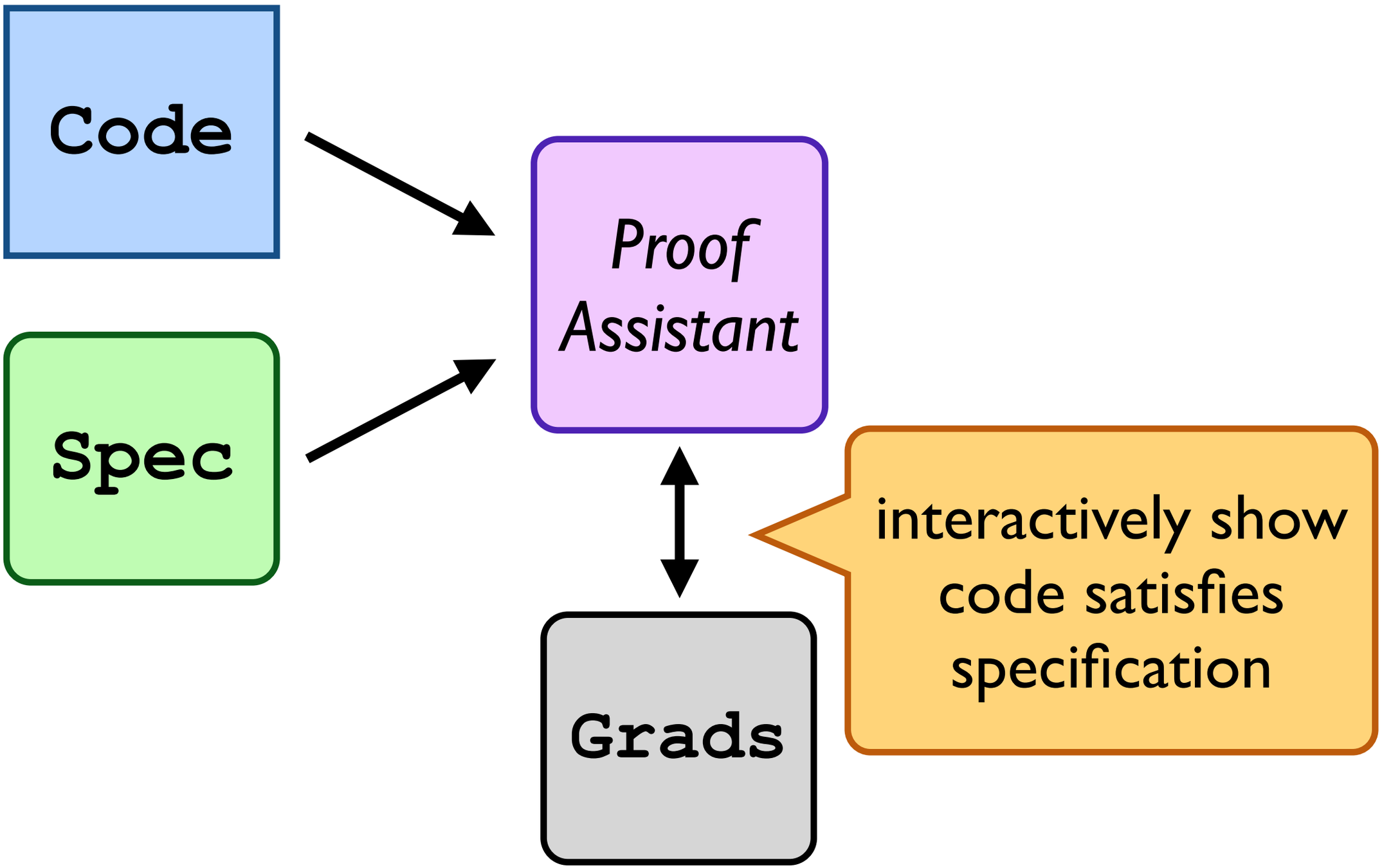

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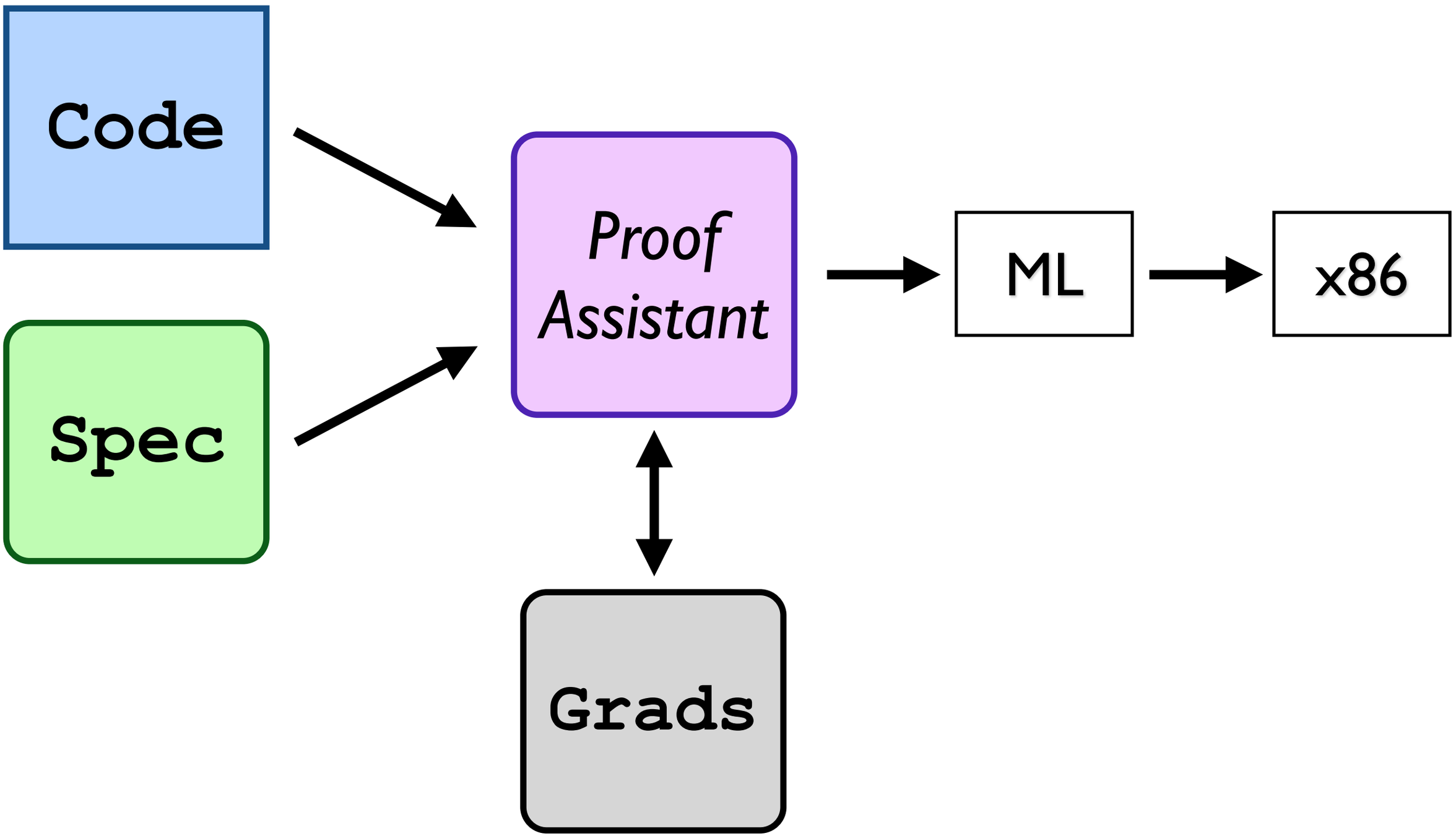

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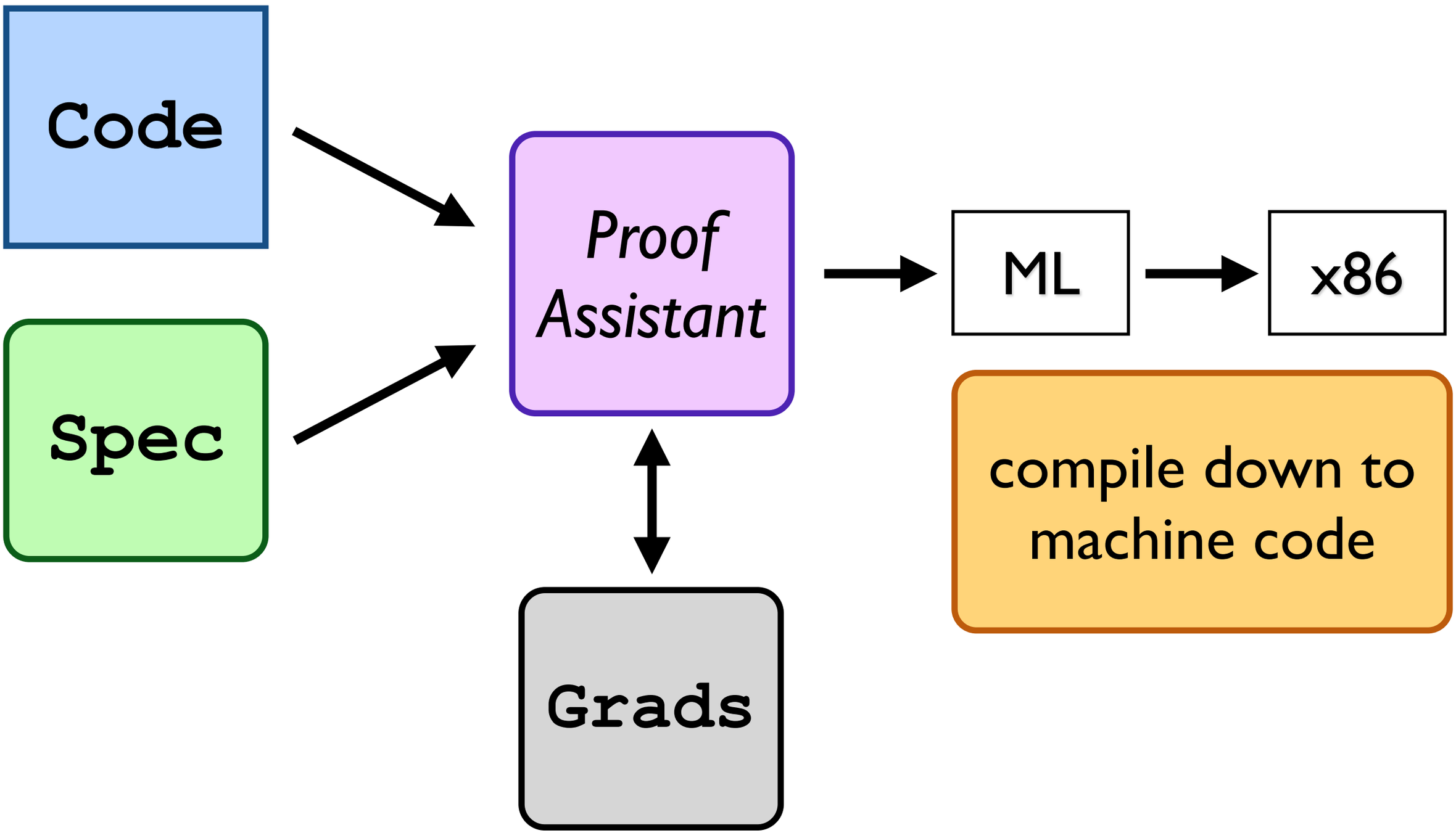

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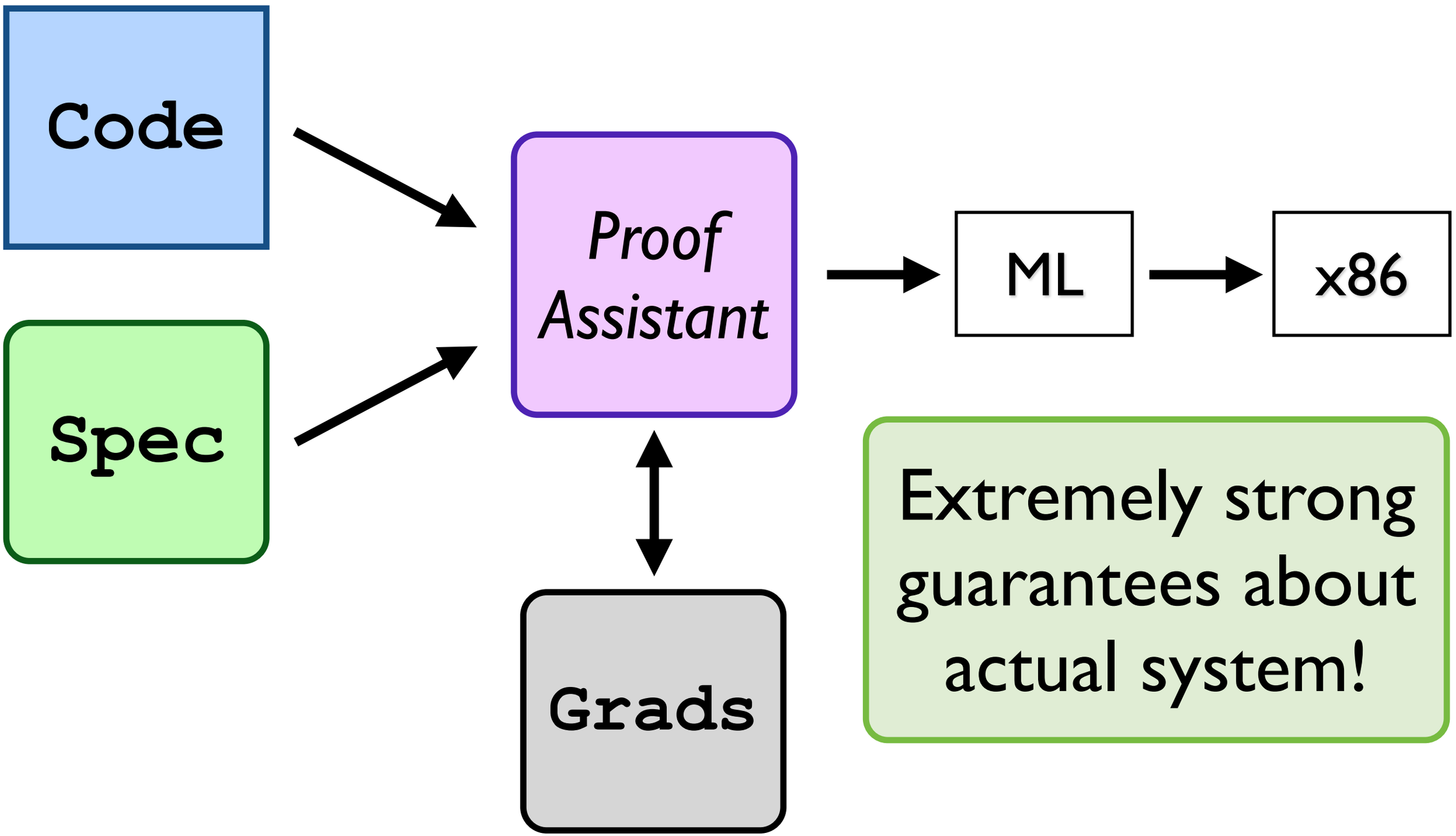

Proof Assistant Based Verification

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

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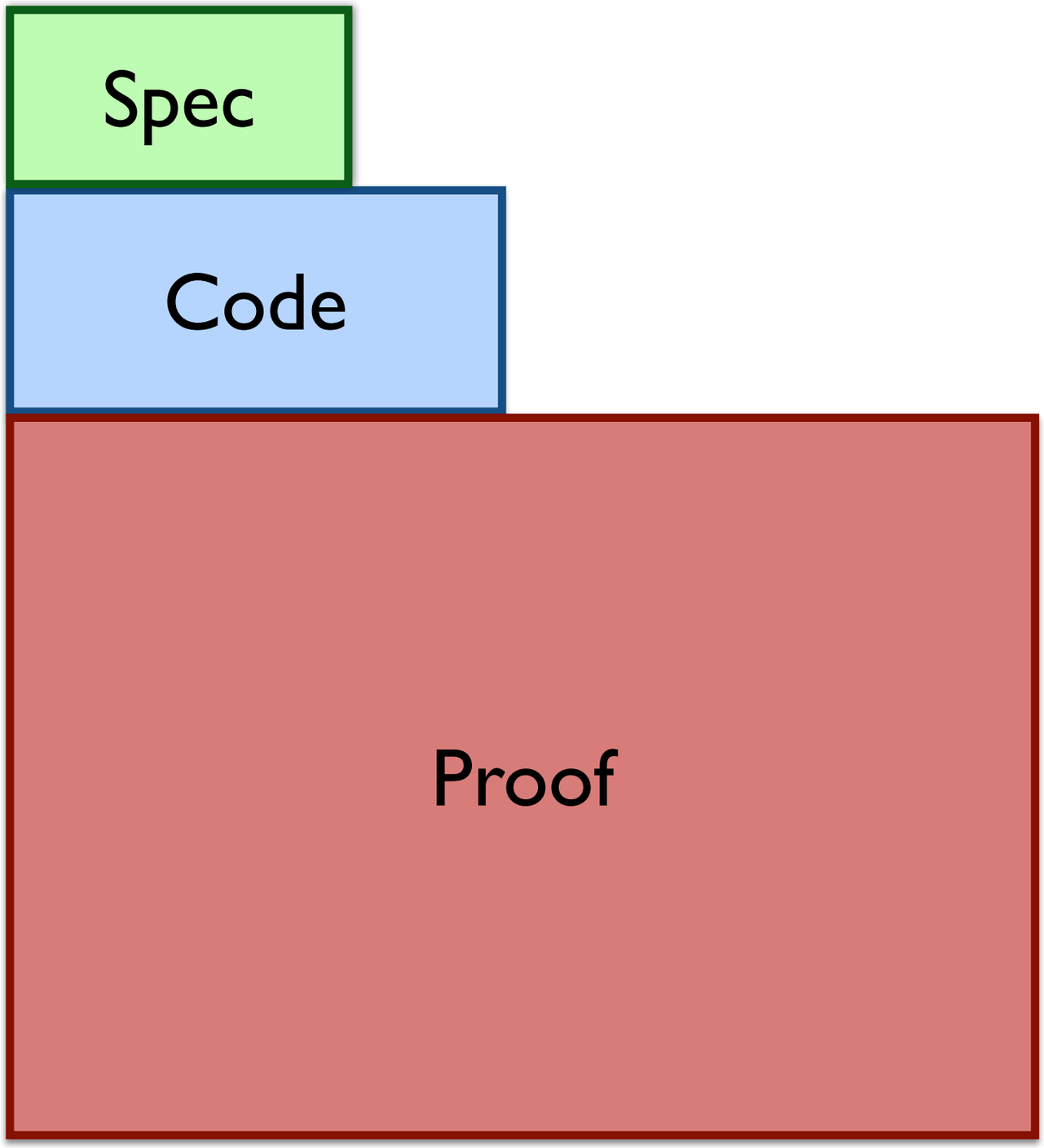
[Klein et al. SOSP 09]

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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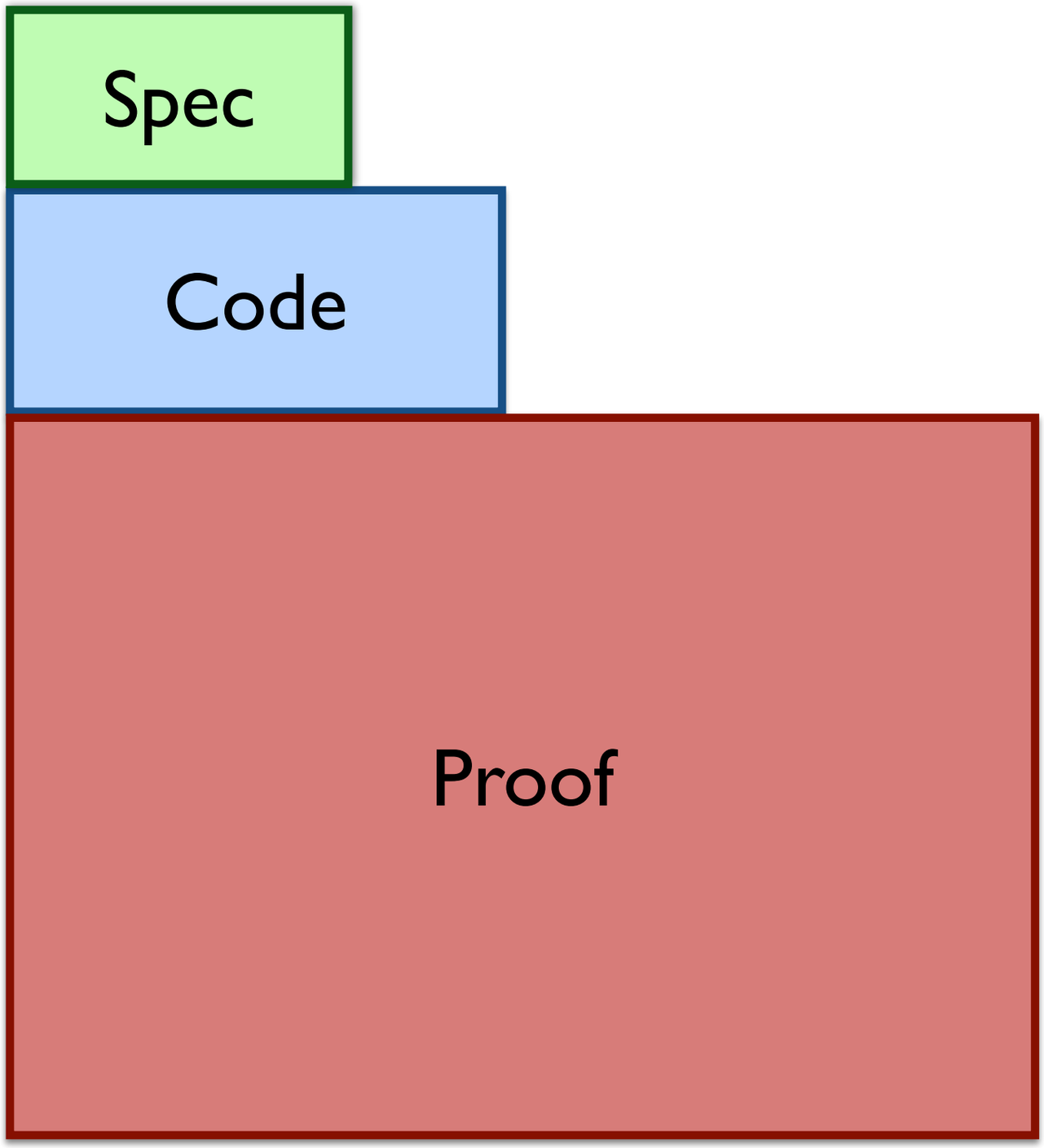
9,000 lines of C code

20 person-years for verification

Manual Proof Burden



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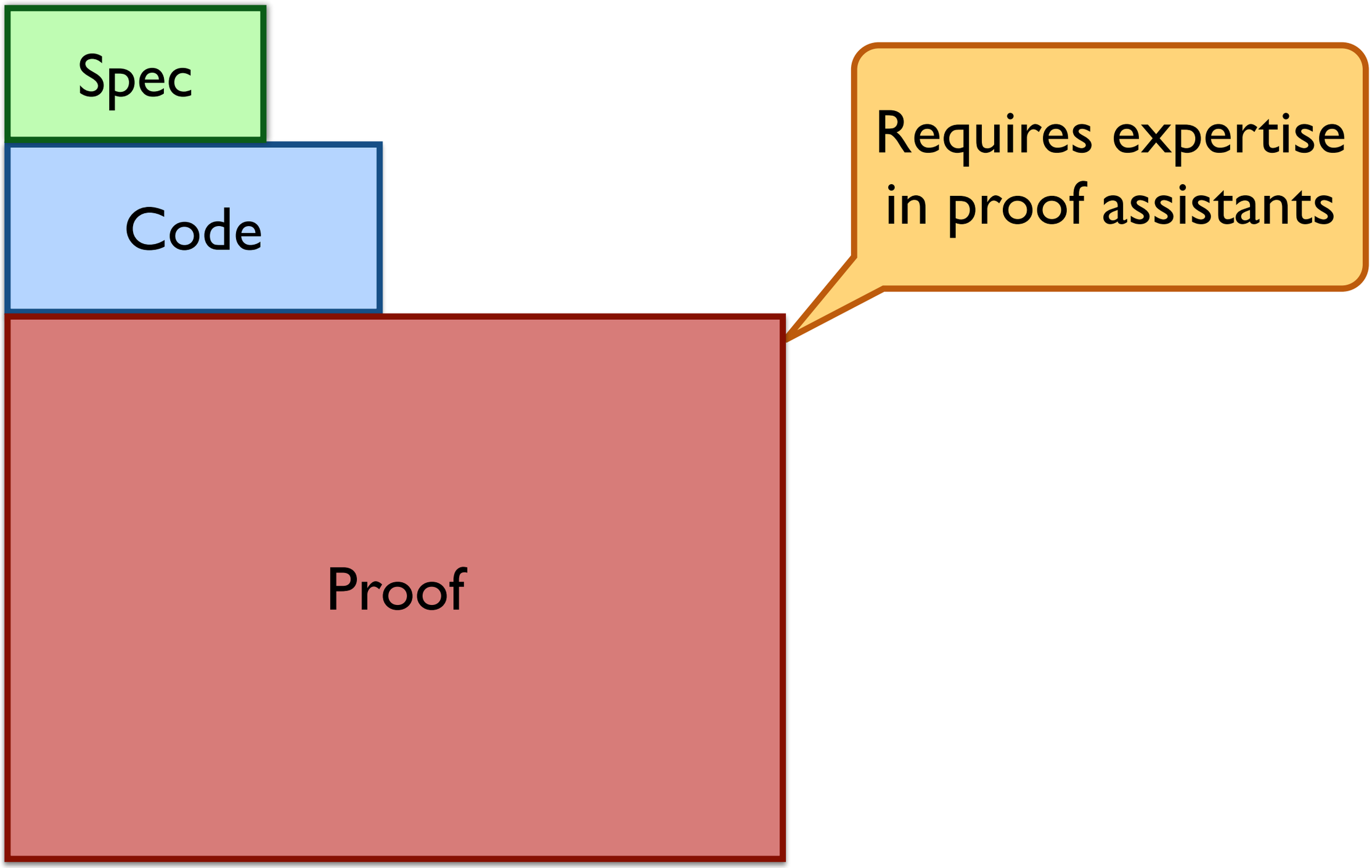

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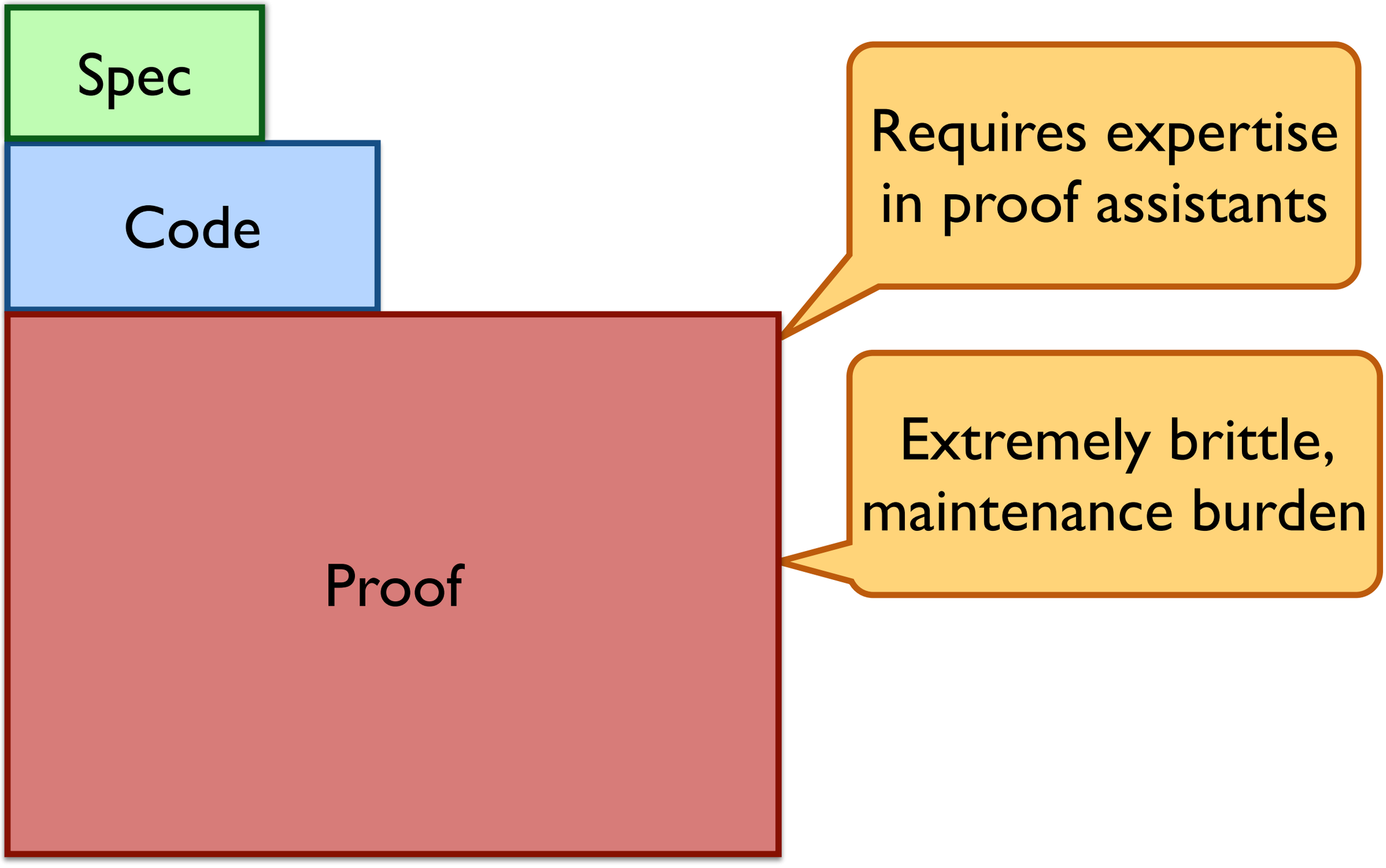
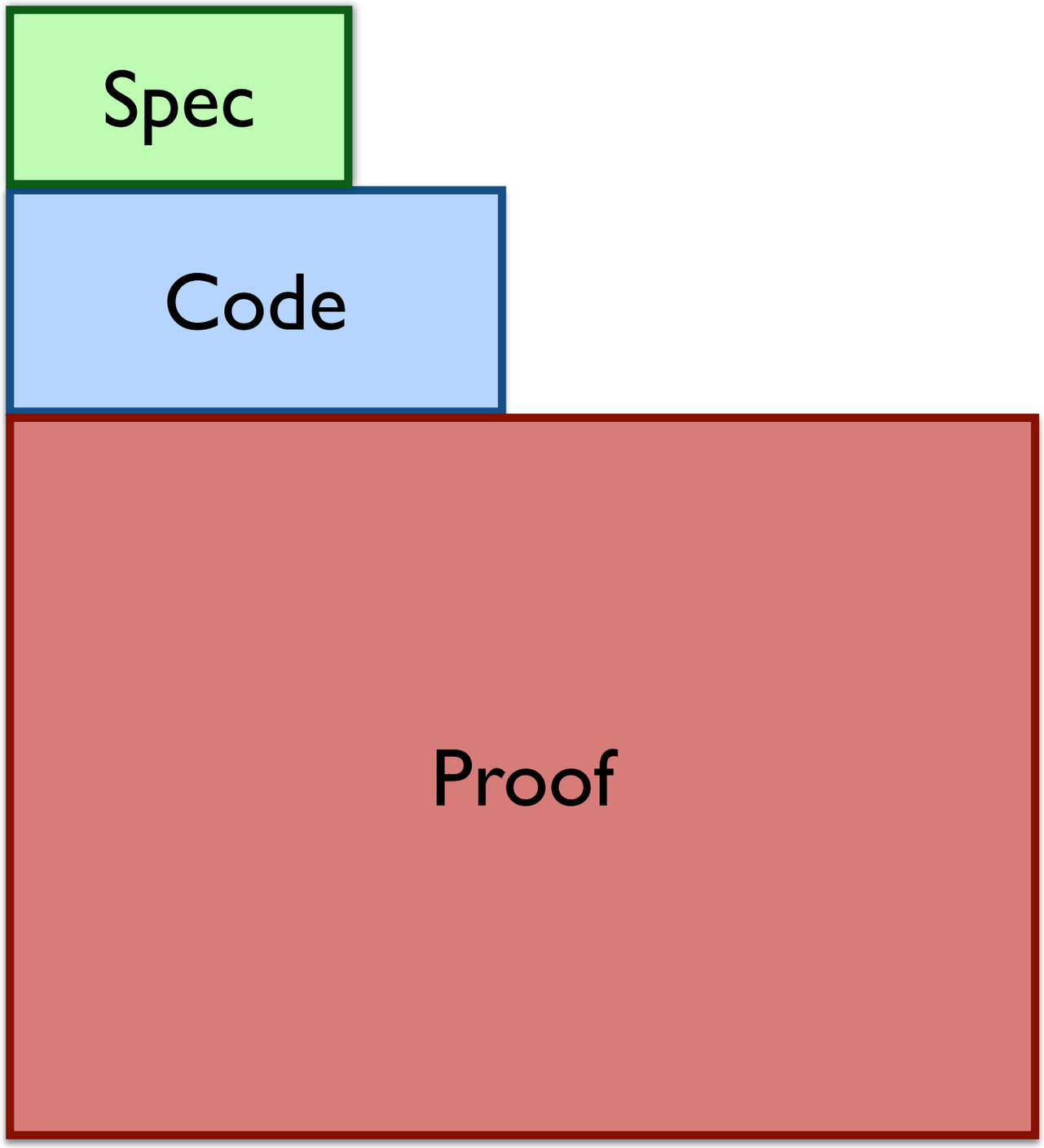


Manual Proof Burden



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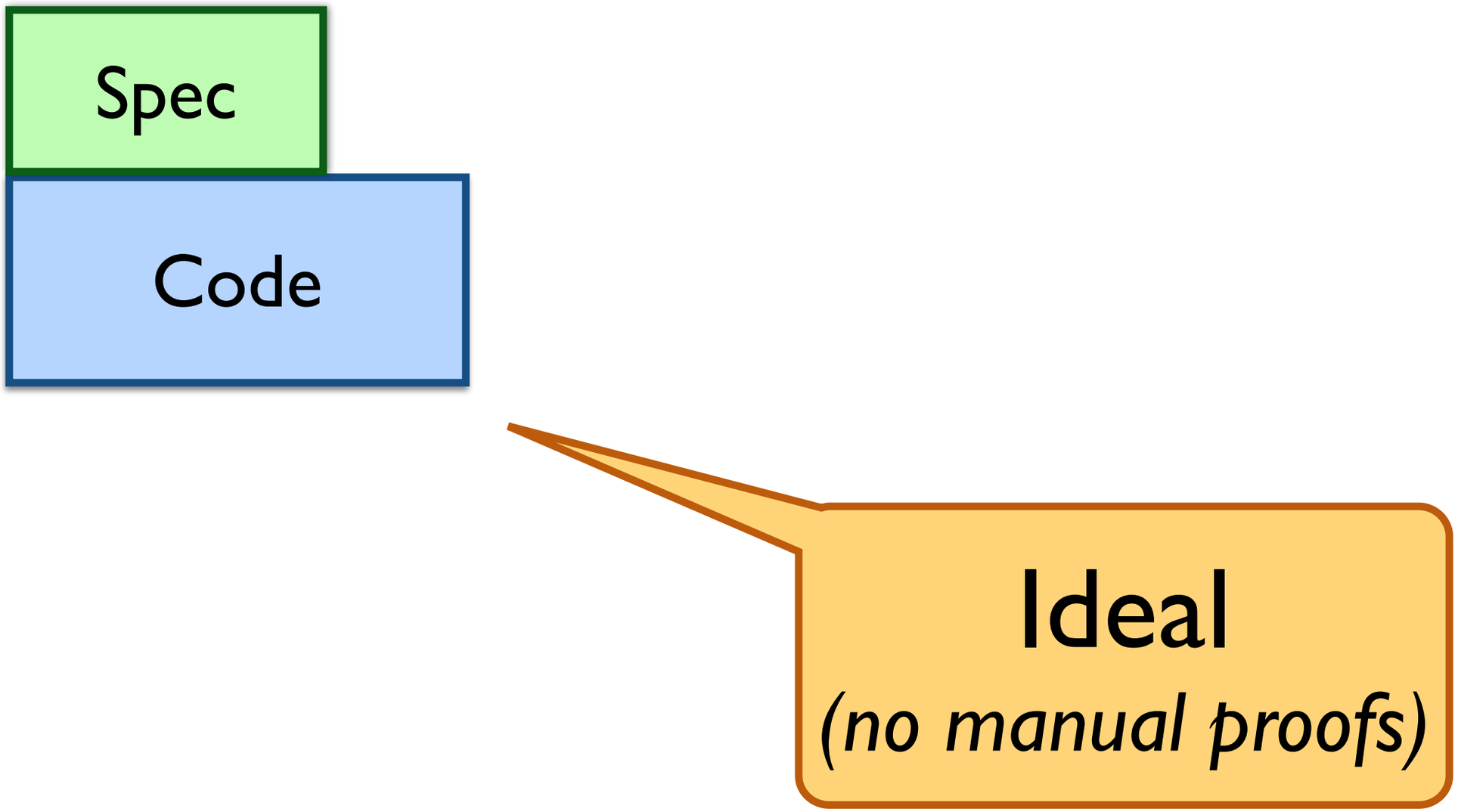

Single application domain

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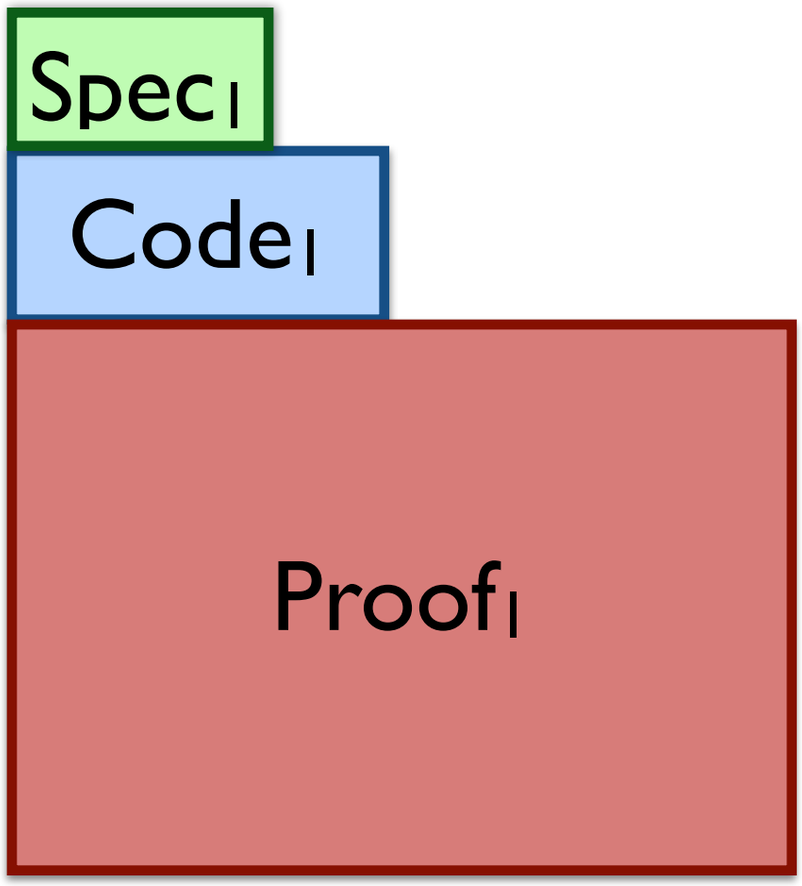

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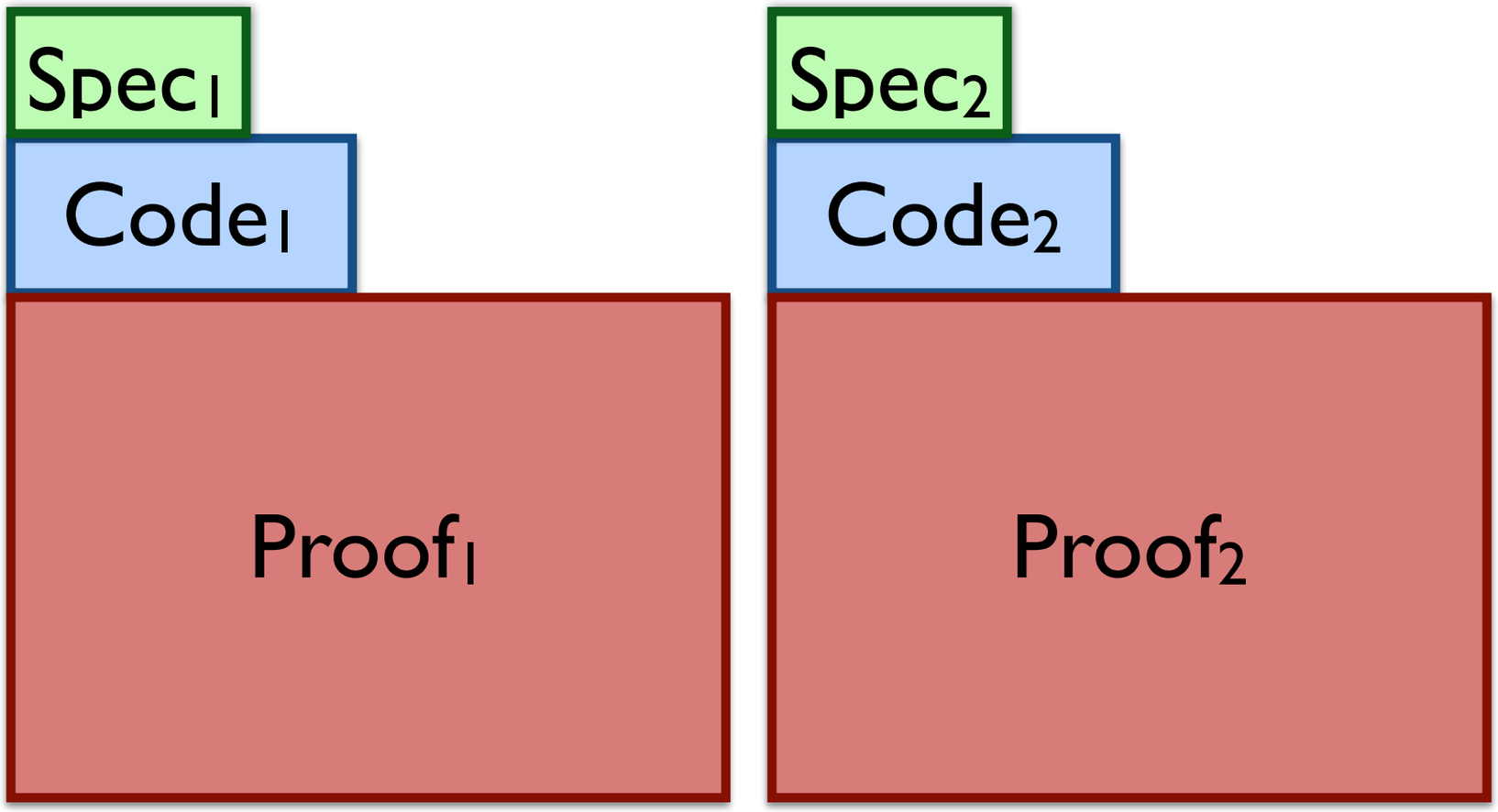

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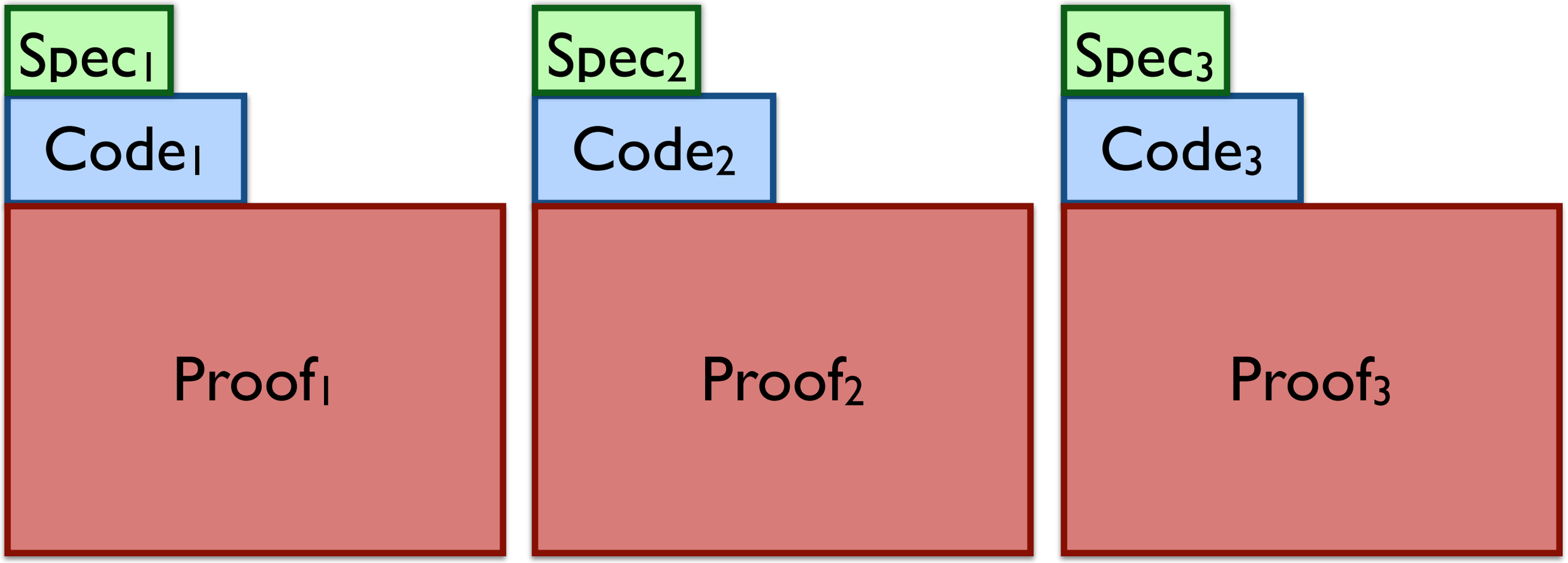
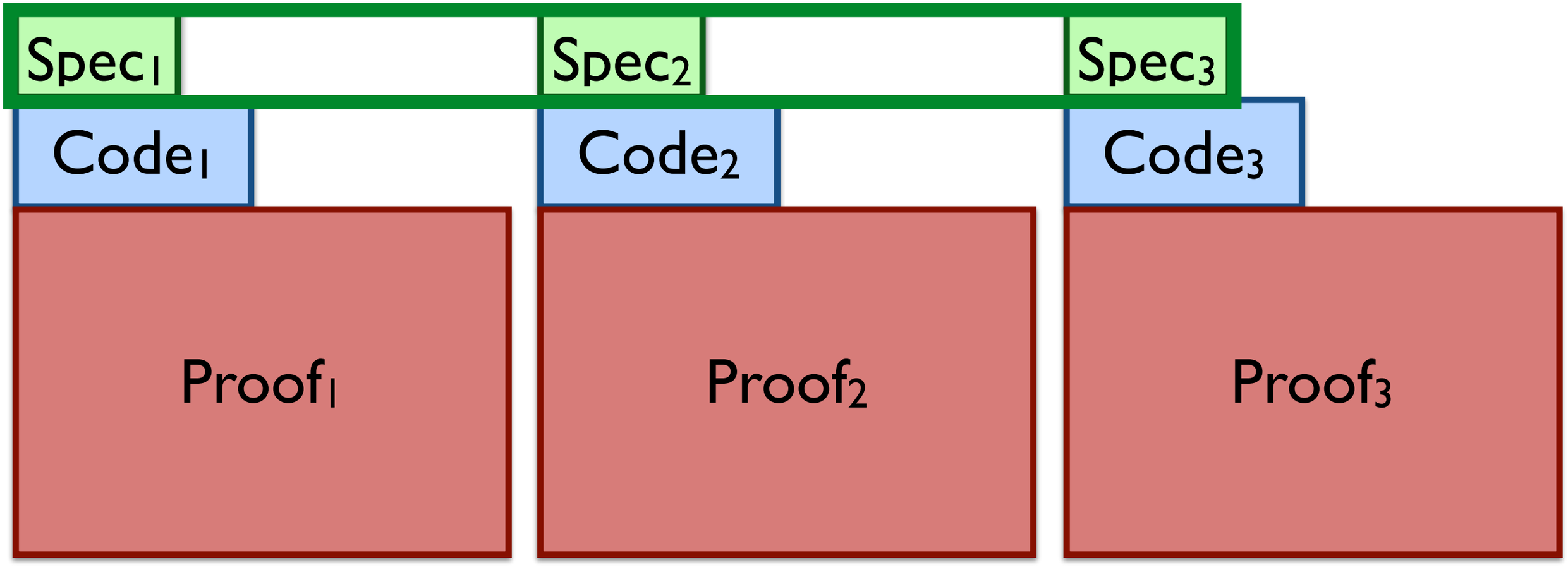


Single application domain

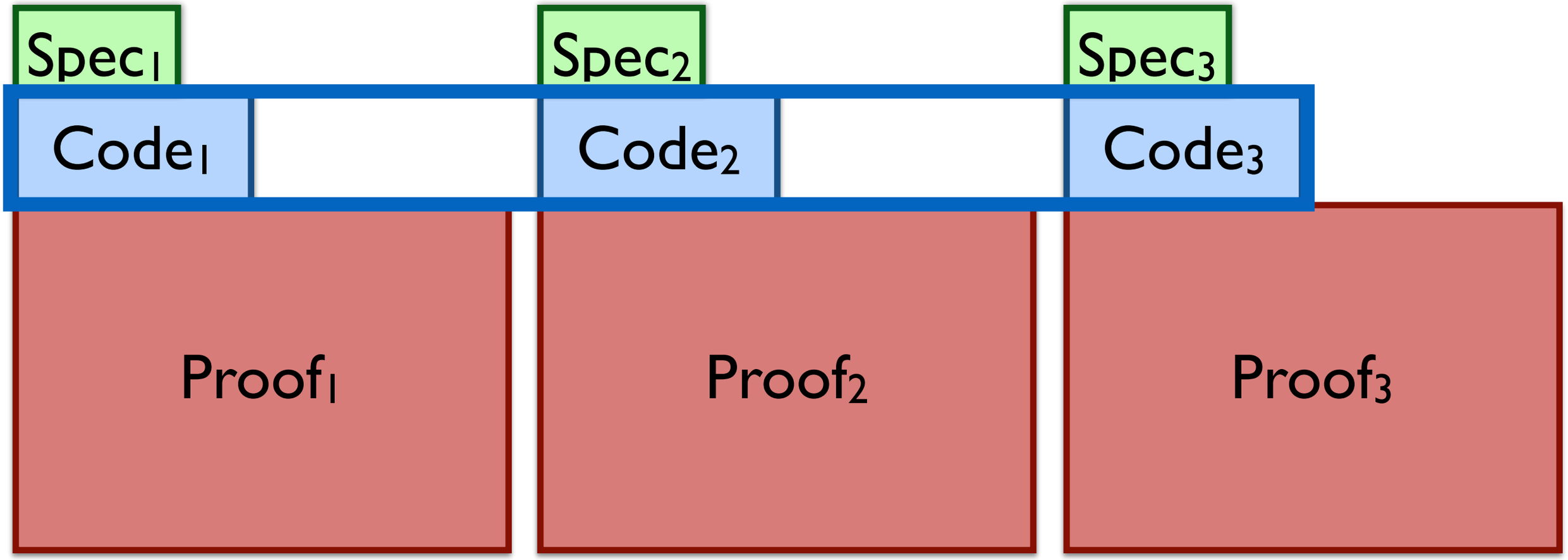
Similar properties



Single application domain

Similar properties

Similar architecture

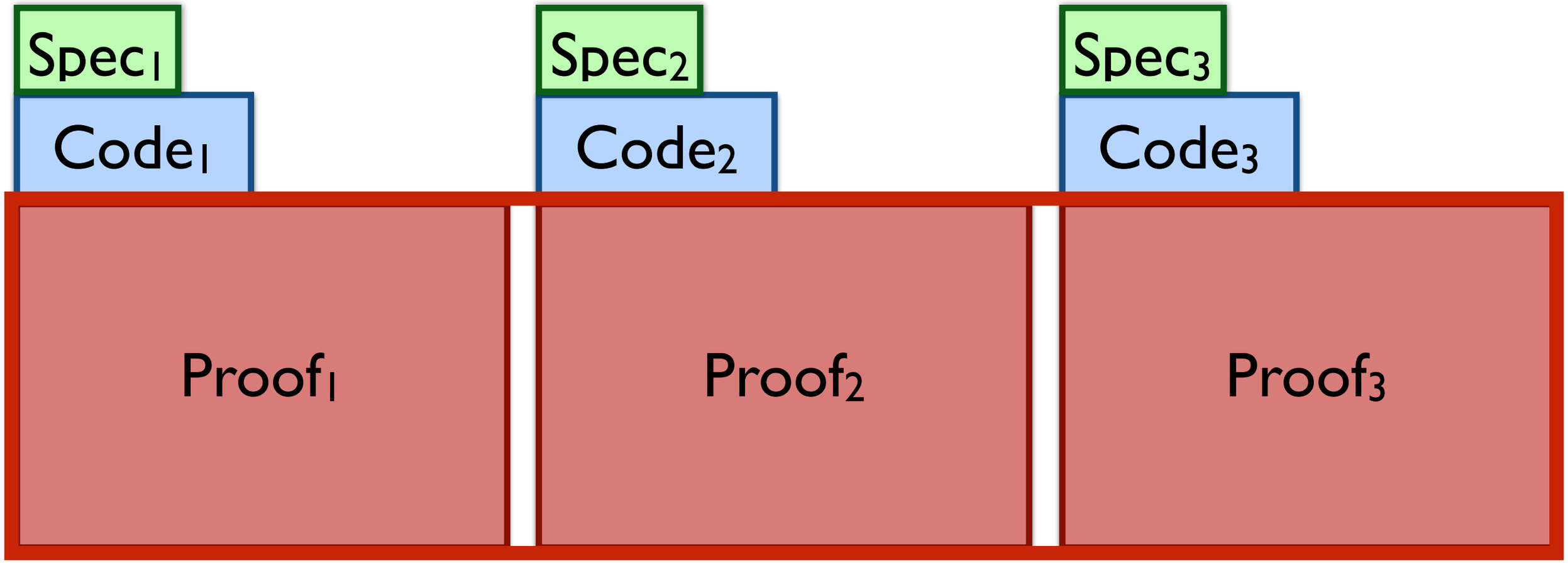


Single application domain

Similar properties

Similar architecture

Similar reasoning

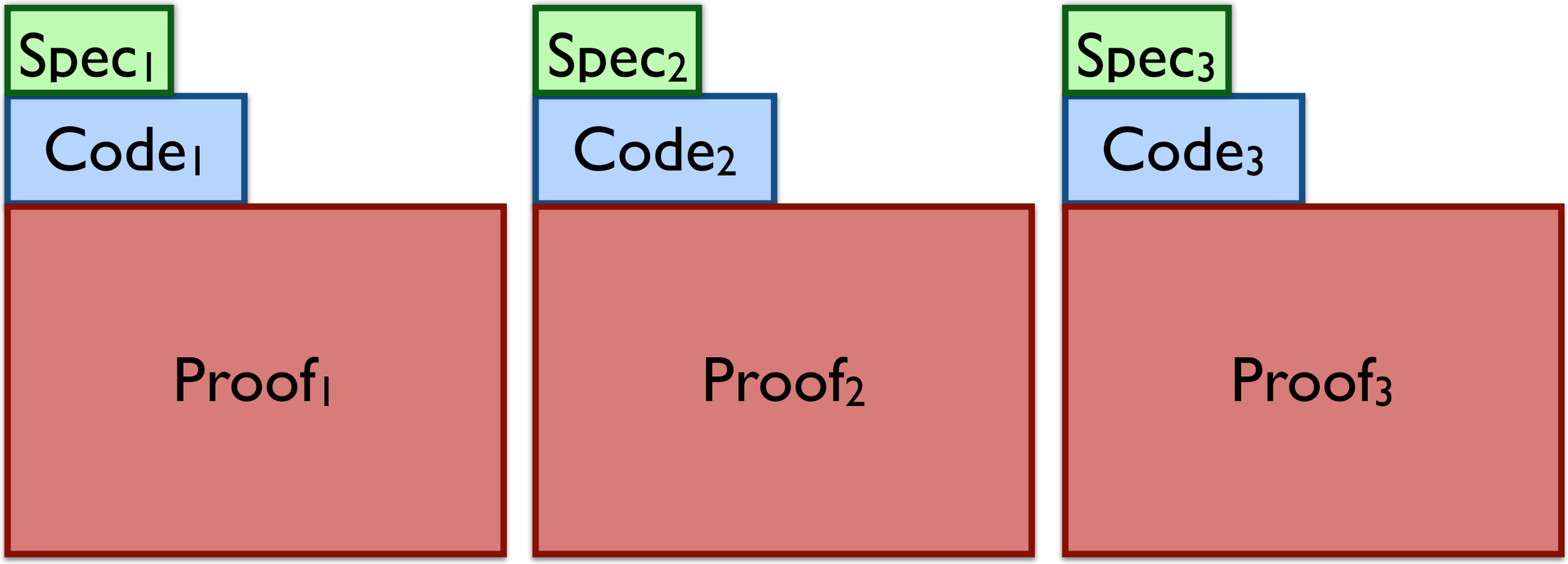


Single application domain

DSL for Specs

Similar architecture

Similar reasoning

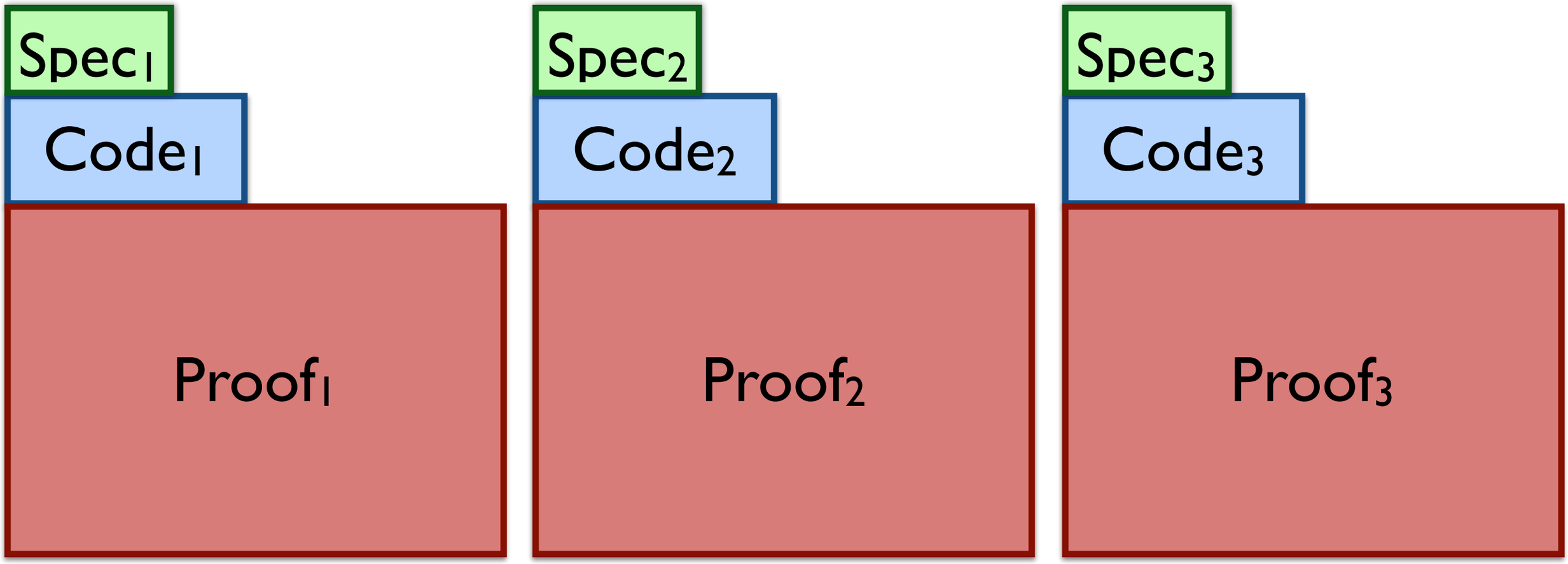


Single application domain

DSL for Specs

DSL for Code

Similar reasoning



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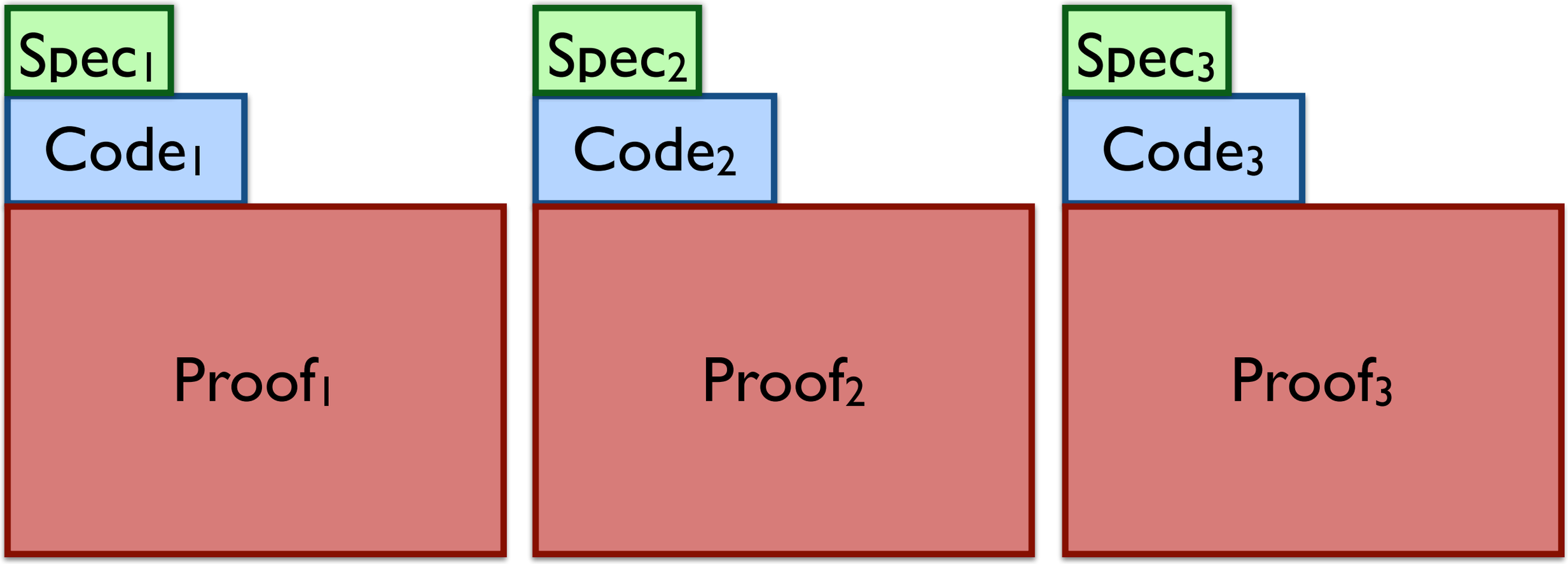
DSL for Specs

DSL for Code

Proof Automation



Single application domain

DSL for Specs

DSL for Code

$Spec_1$

$Code_1$

$Spec_2$

$Code_2$

$Spec_3$

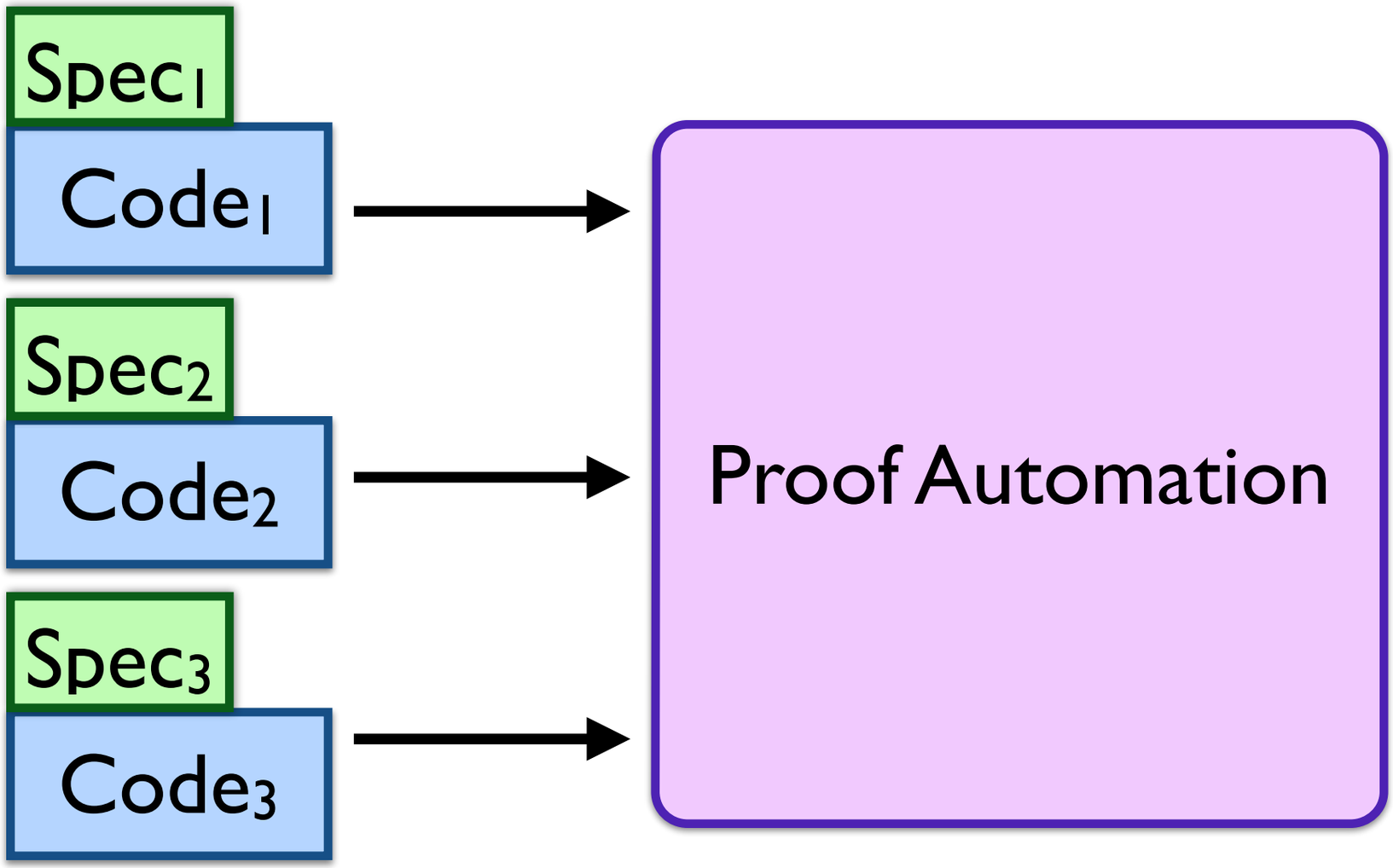
$Code_3$

Proof Automation

Single application domain

DSL for Specs

DSL for Code



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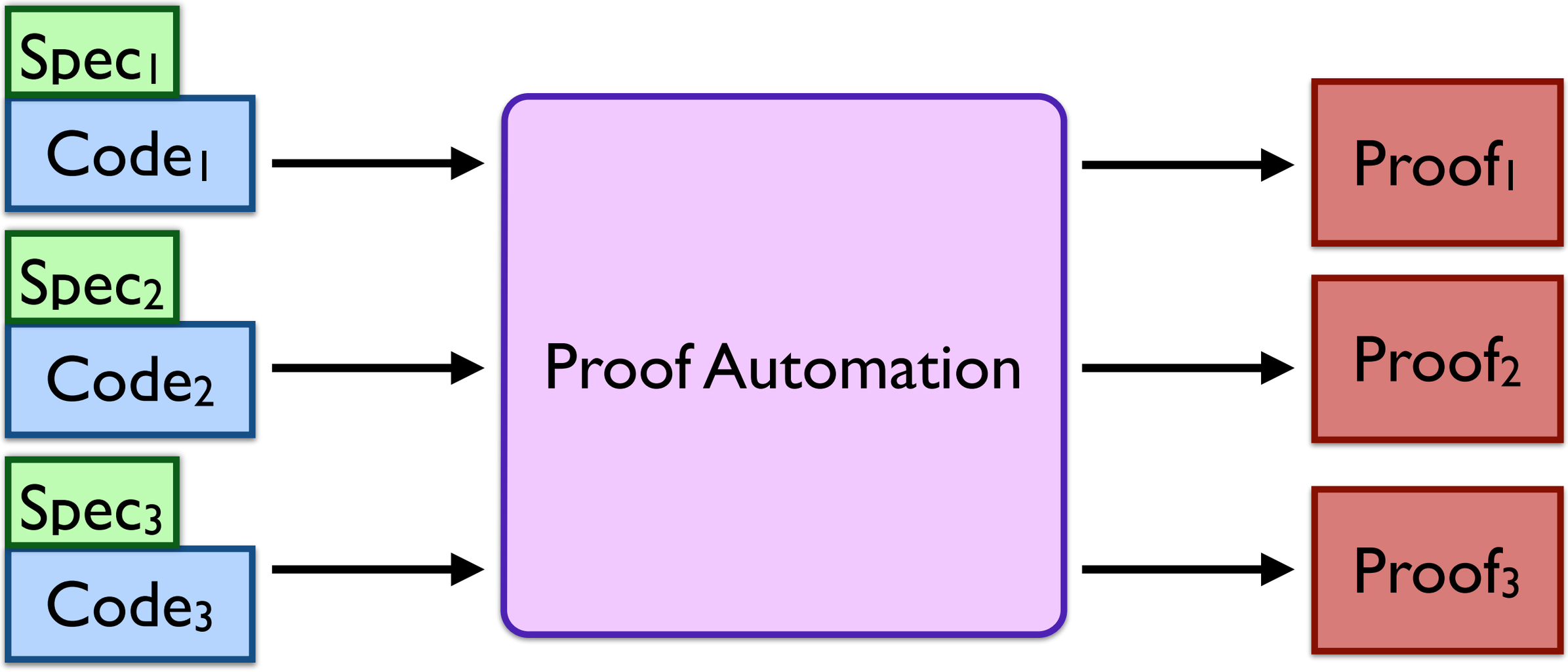
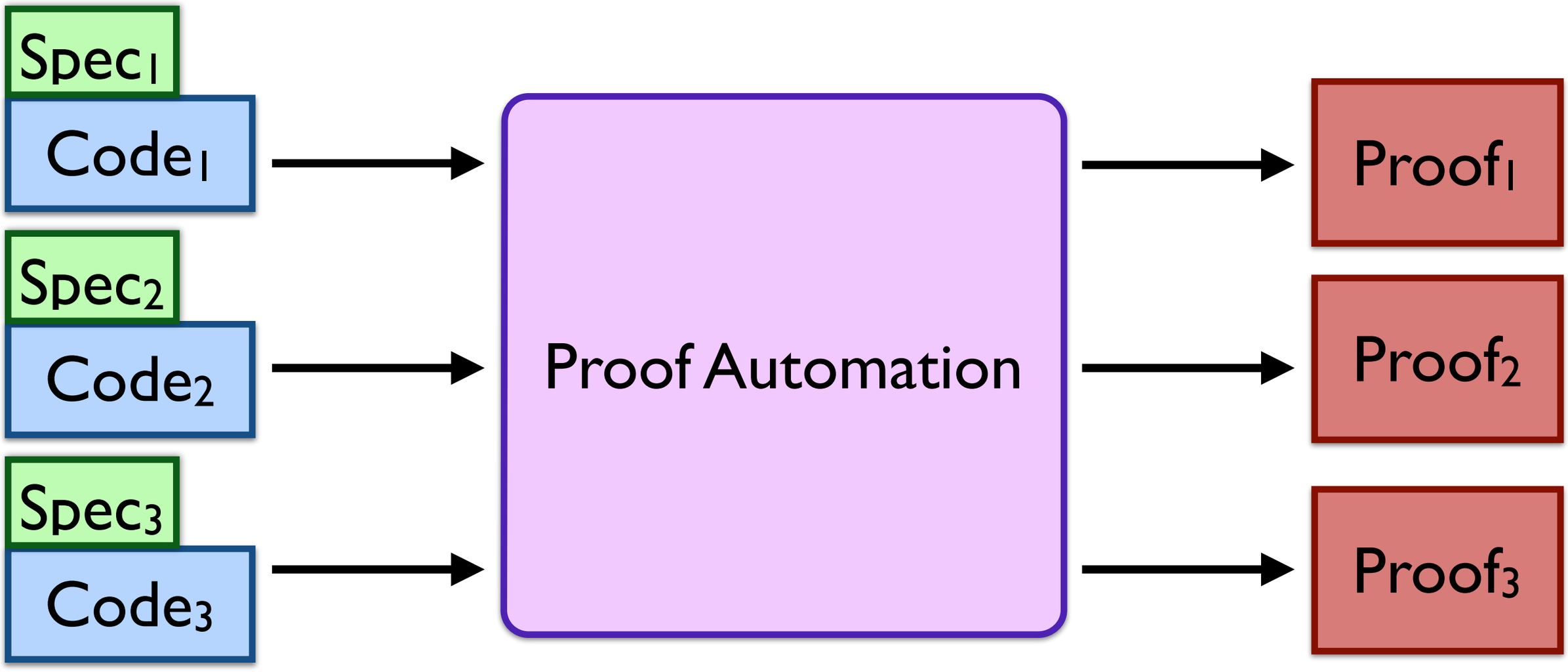
DSL for Code



Reactive systems

DSL for Specs

DSL for Code



Reactive systems

DSL for Specs

DSL for Code

Reactive systems

REFLEX

Reactive systems

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No manual proofs,

Reactive systems

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No manual proofs,

yet proof assistant guarantee.

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Automation incomplete,

Reactive systems

REFLEX

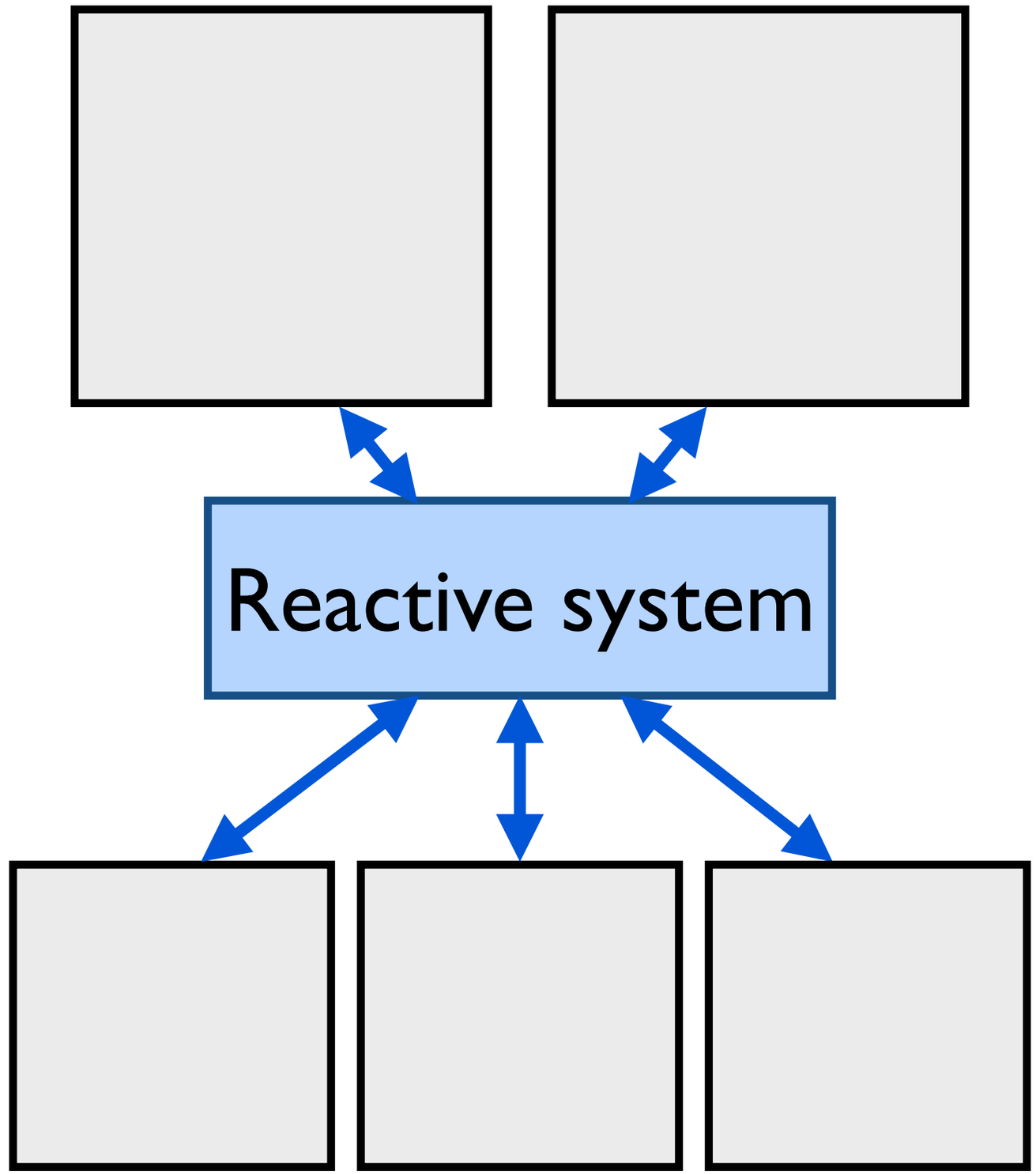
No manual proofs,

yet proof assistant guarantee.

Automation incomplete,

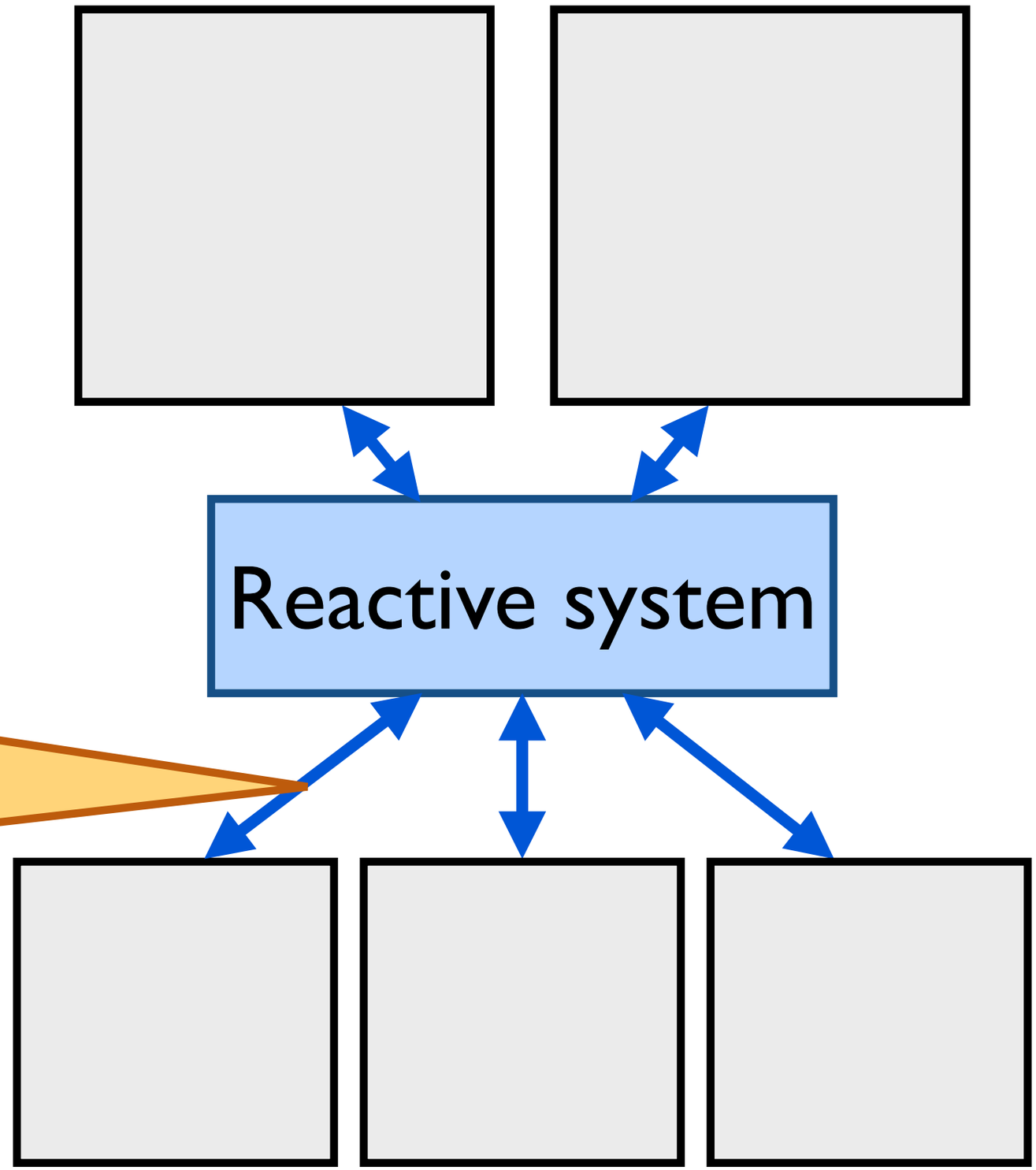
but **verified browser, ssh, web server.**

Reactive systems

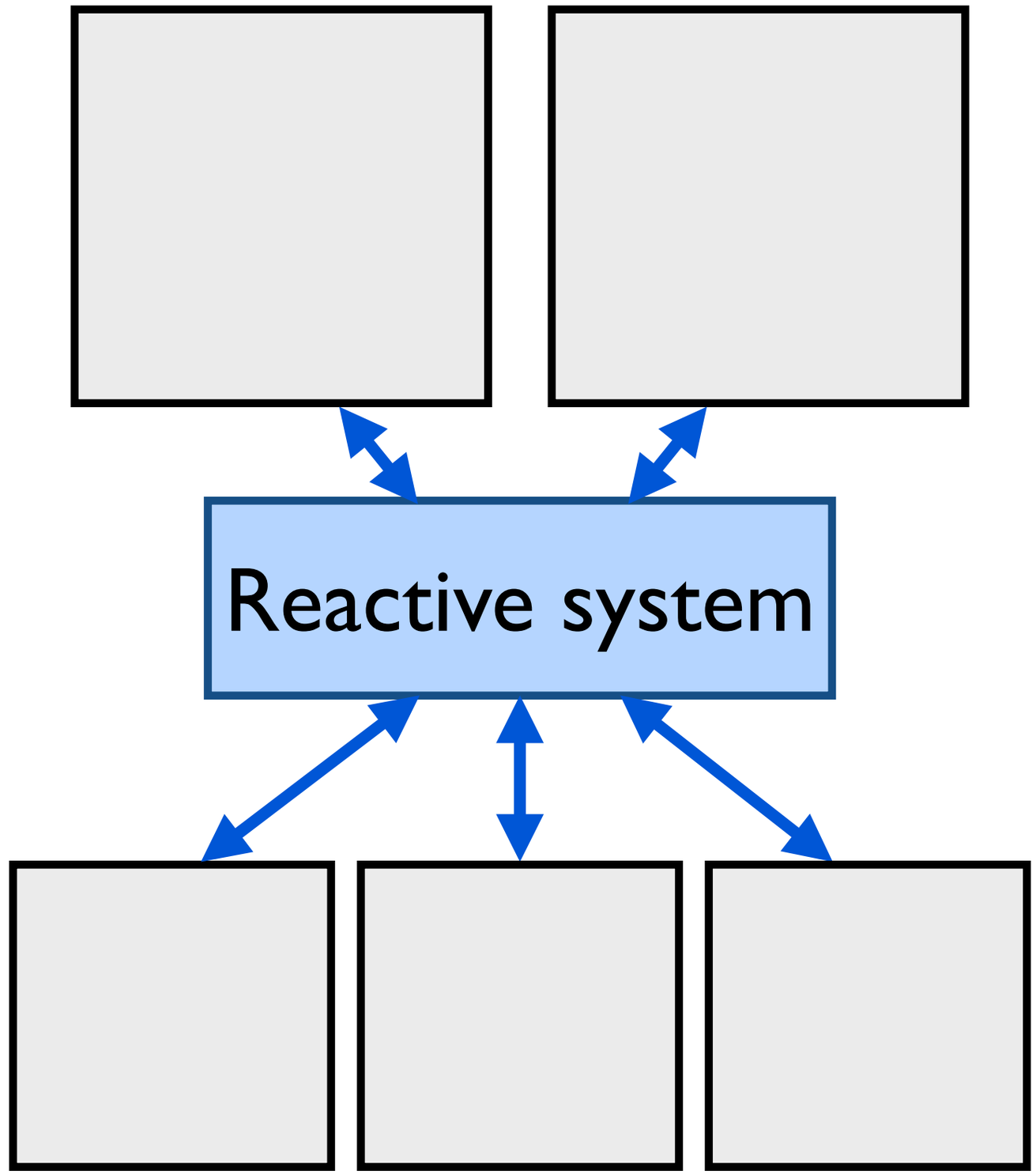


Reactive systems

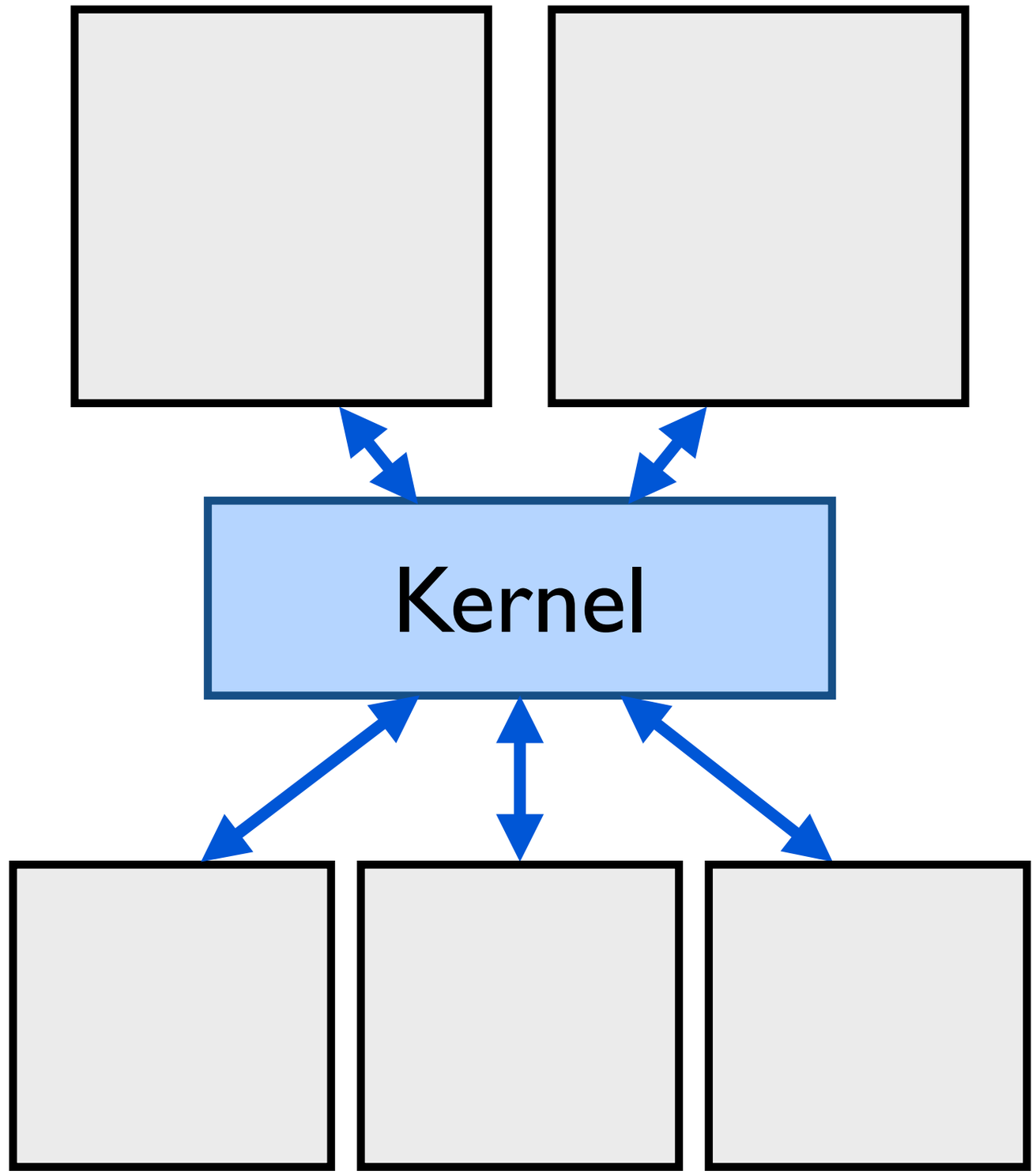
Continuously read messages from components and send messages to components



Reactive systems



Example: Web browser kernel



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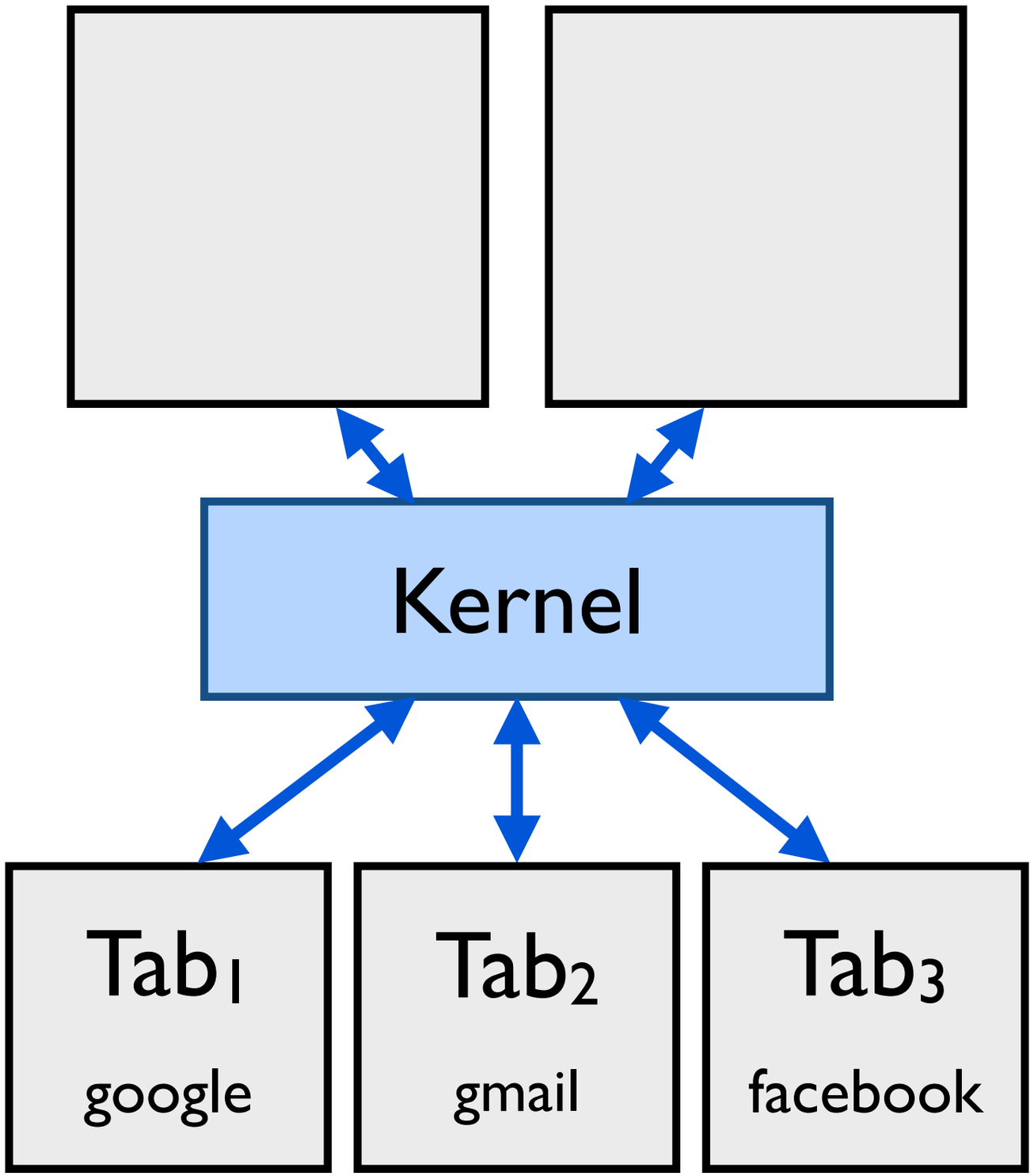

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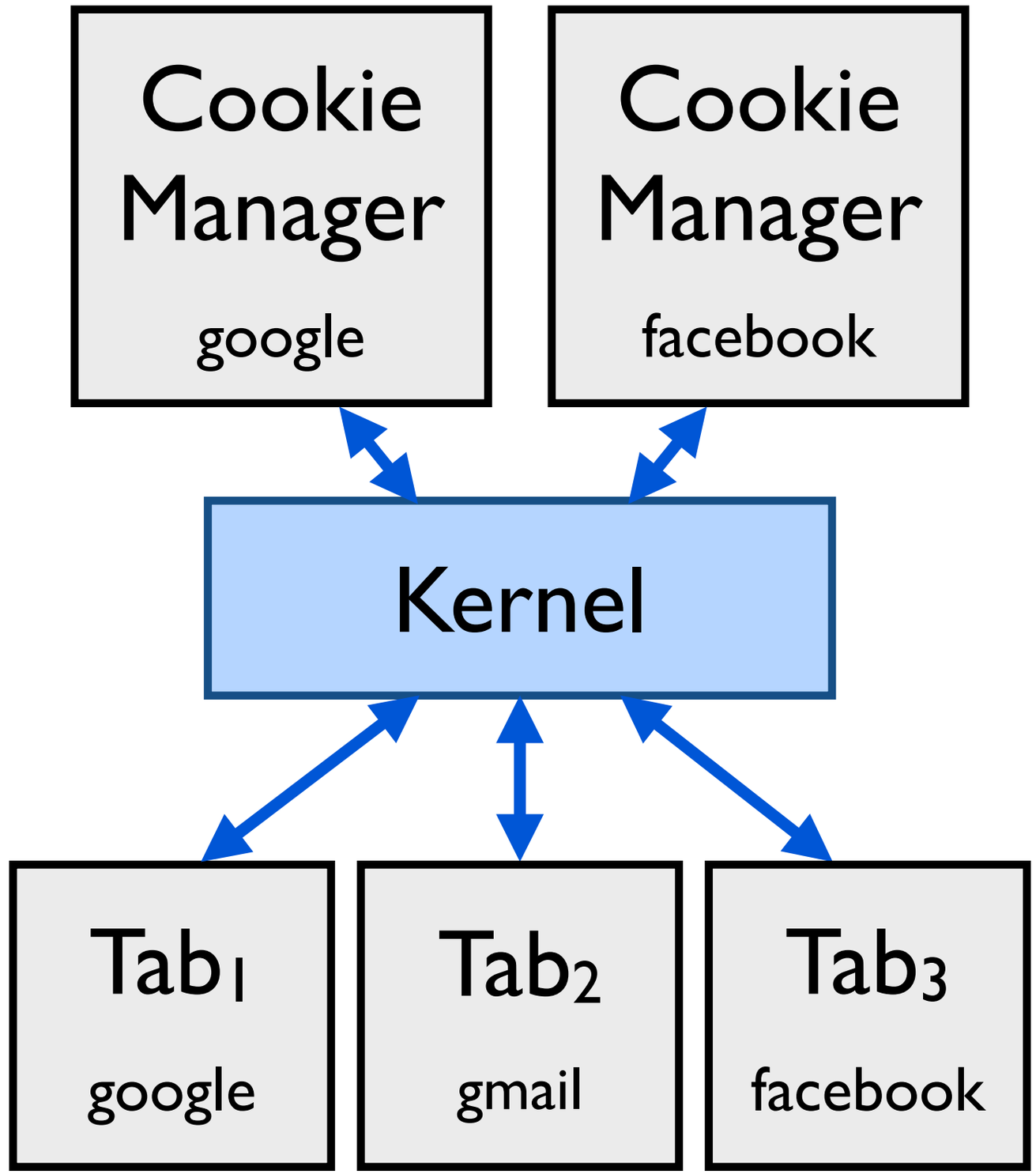

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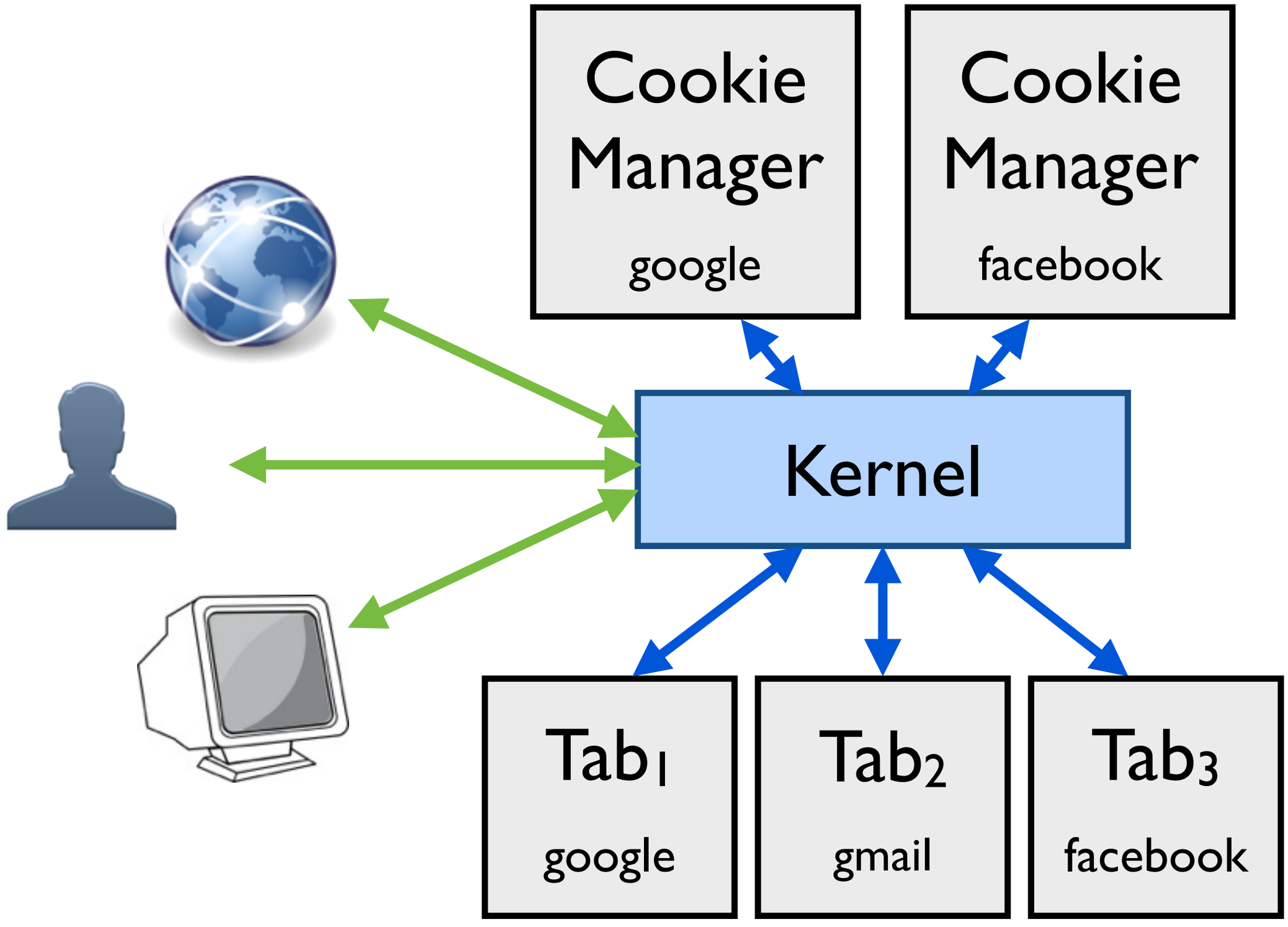

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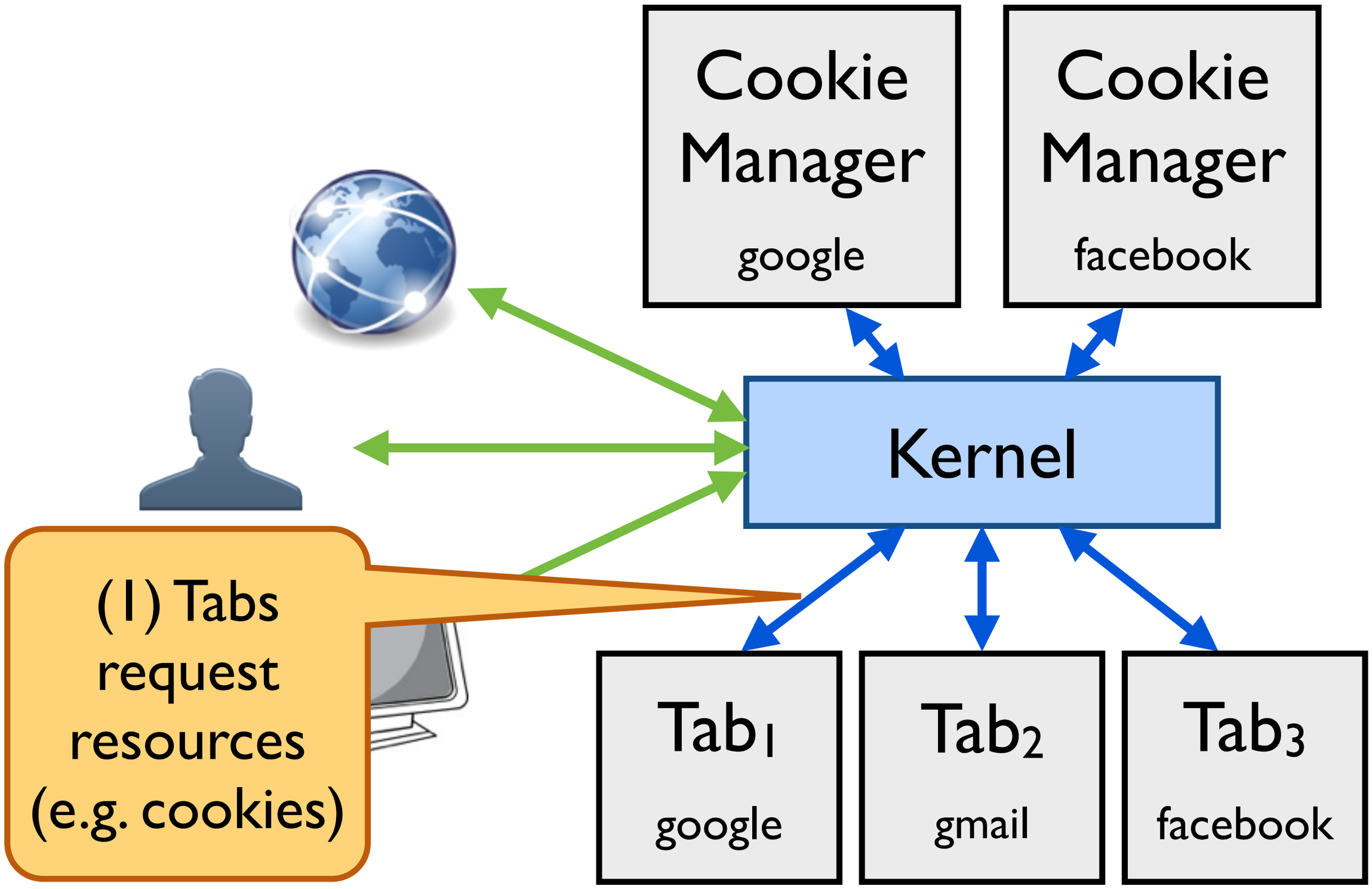

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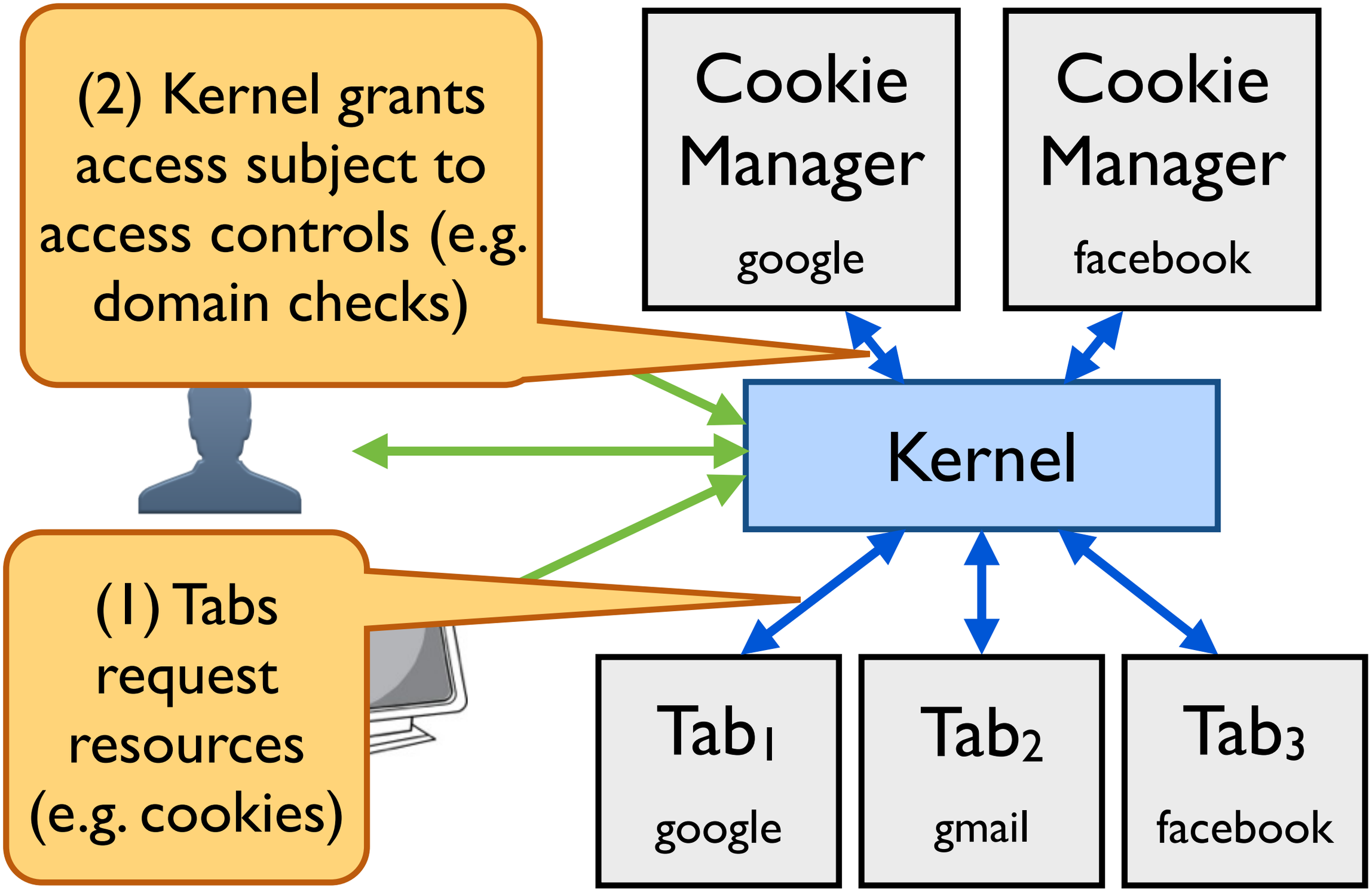

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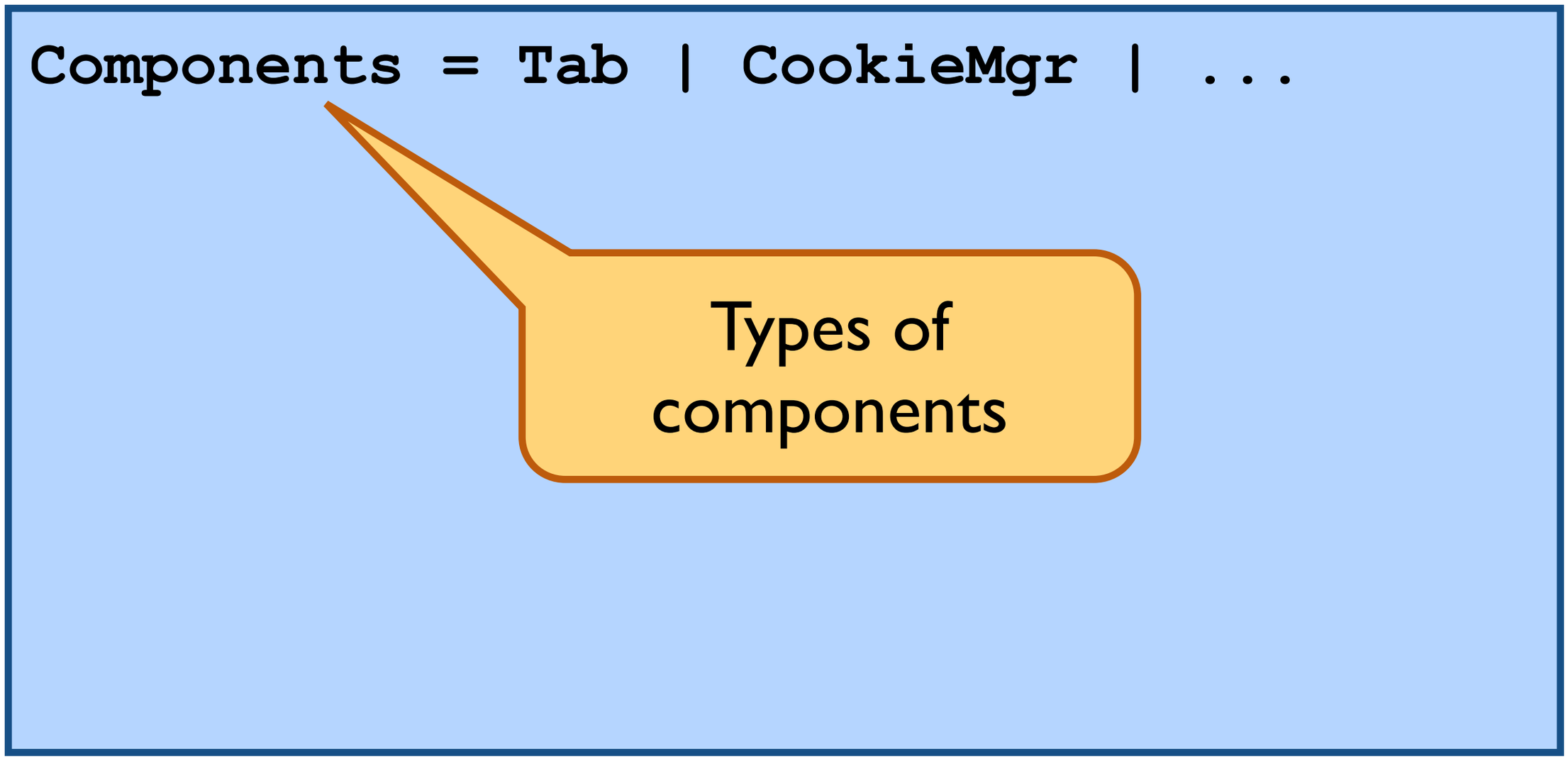

Example: Web browser kernel

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

Properties

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Handlers:
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Specify allowed behaviors

Properties

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   When [Tab t] sends CookieSet(c):
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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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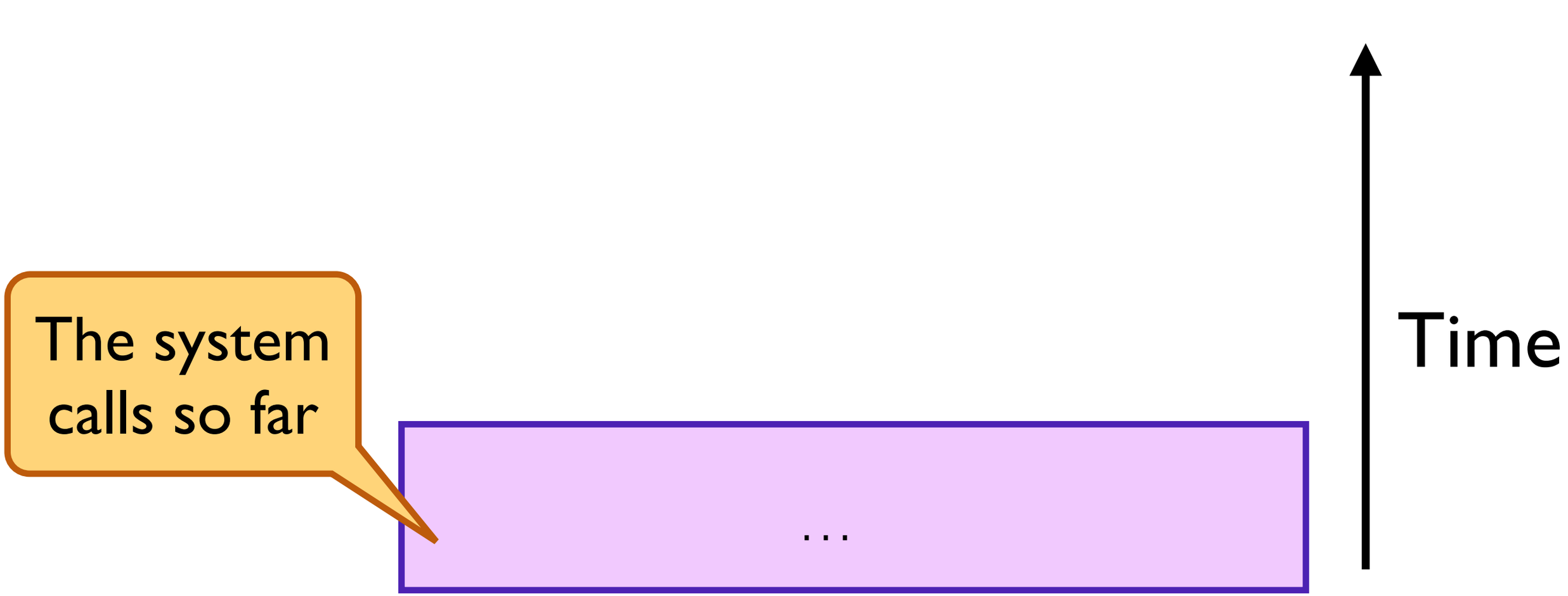

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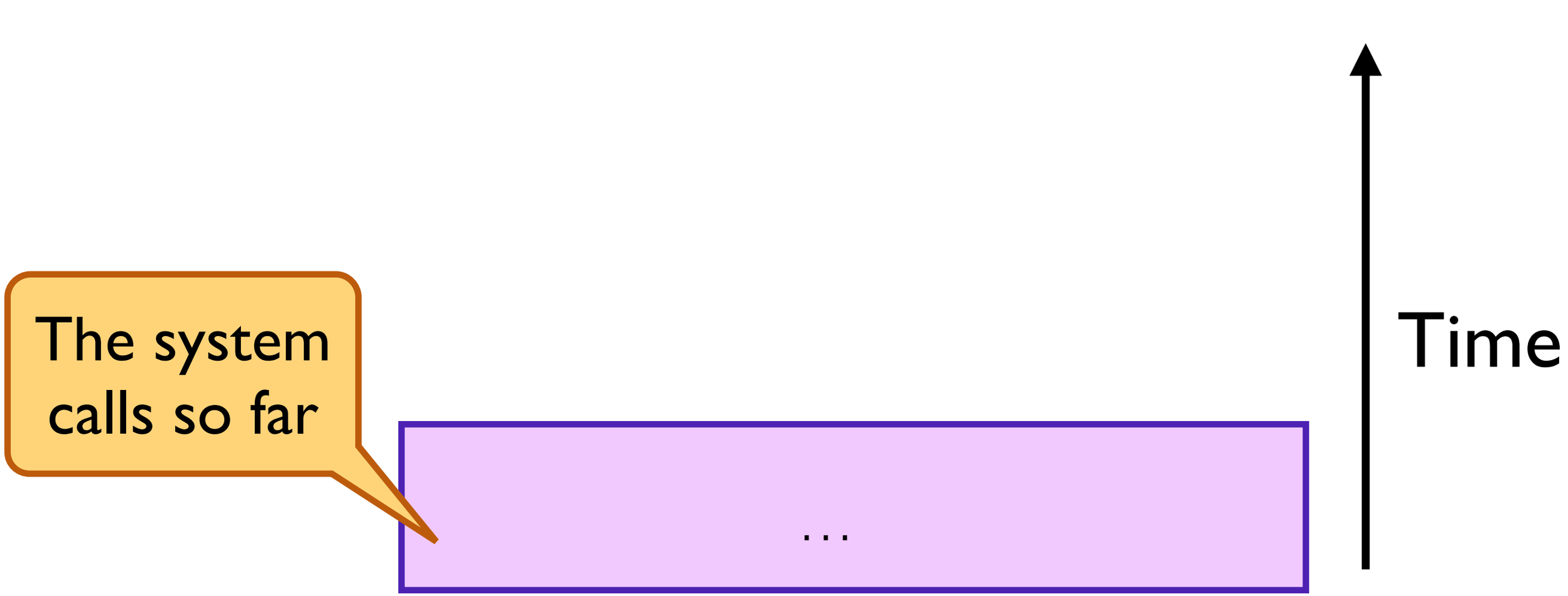

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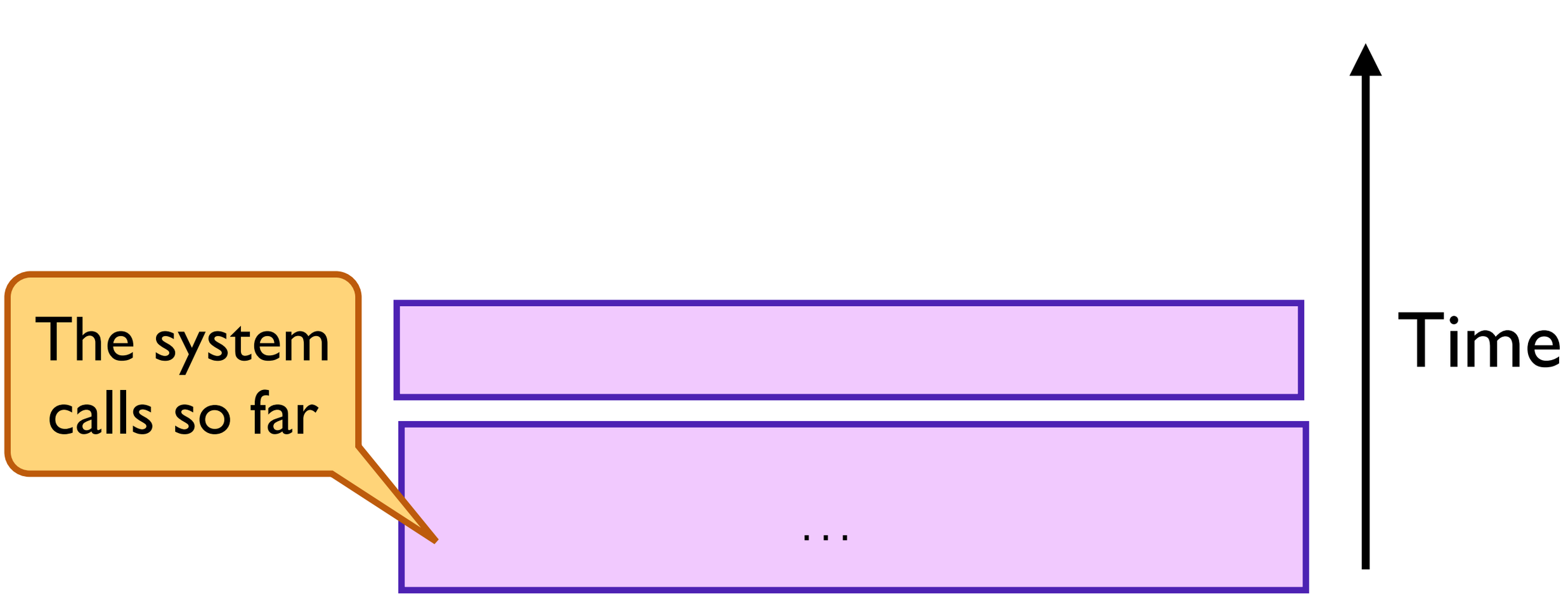

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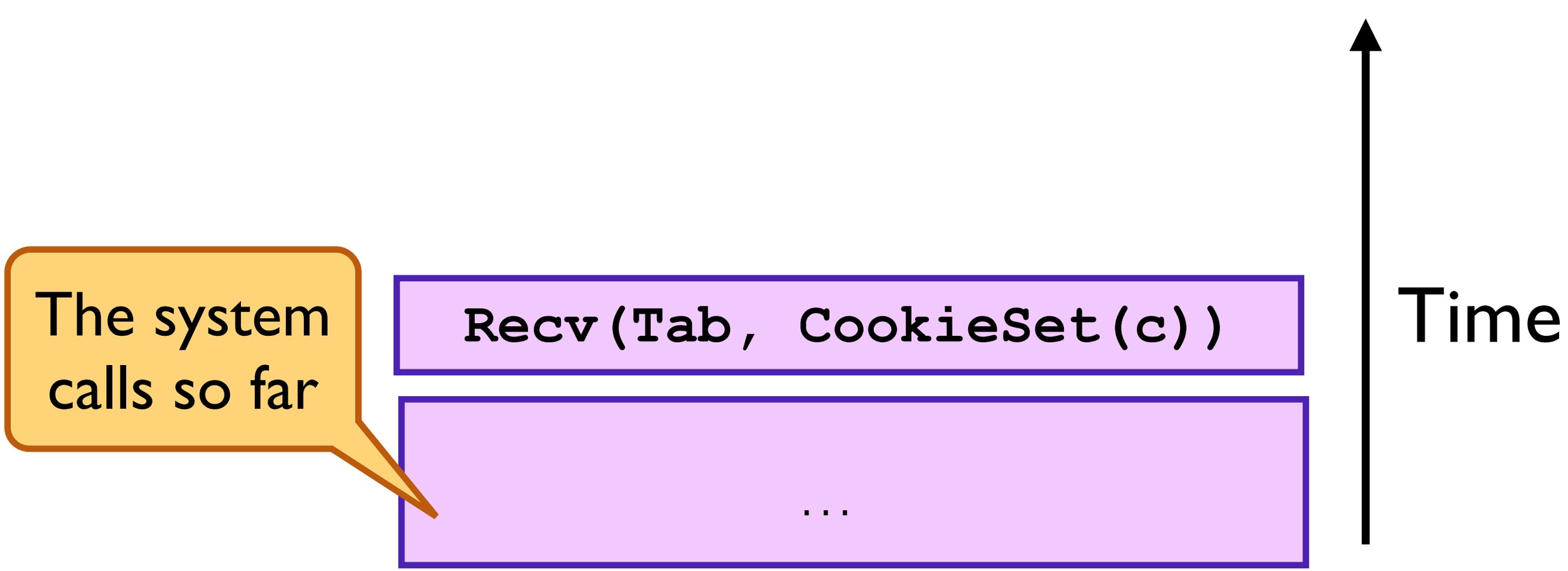

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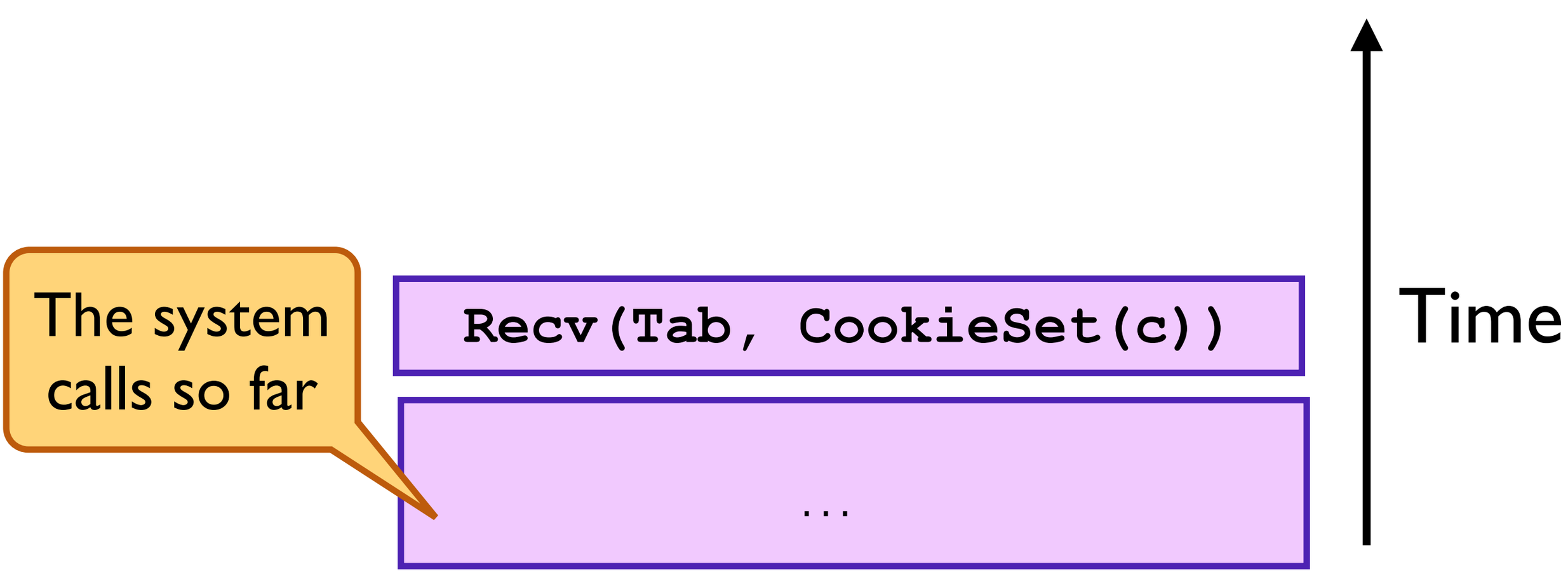

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When [Tab t] sends CookieSet(c):
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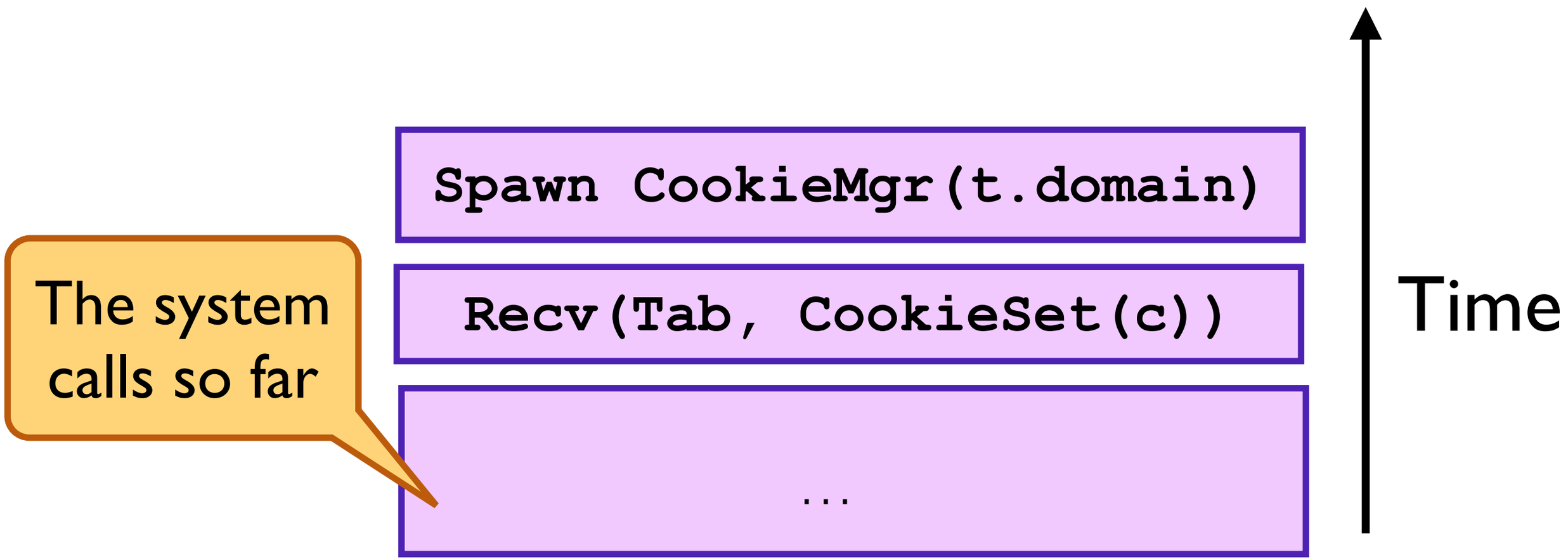
  send(cp, CookieSet(c))
```

Specify allowed behaviors wrt sequence of system calls



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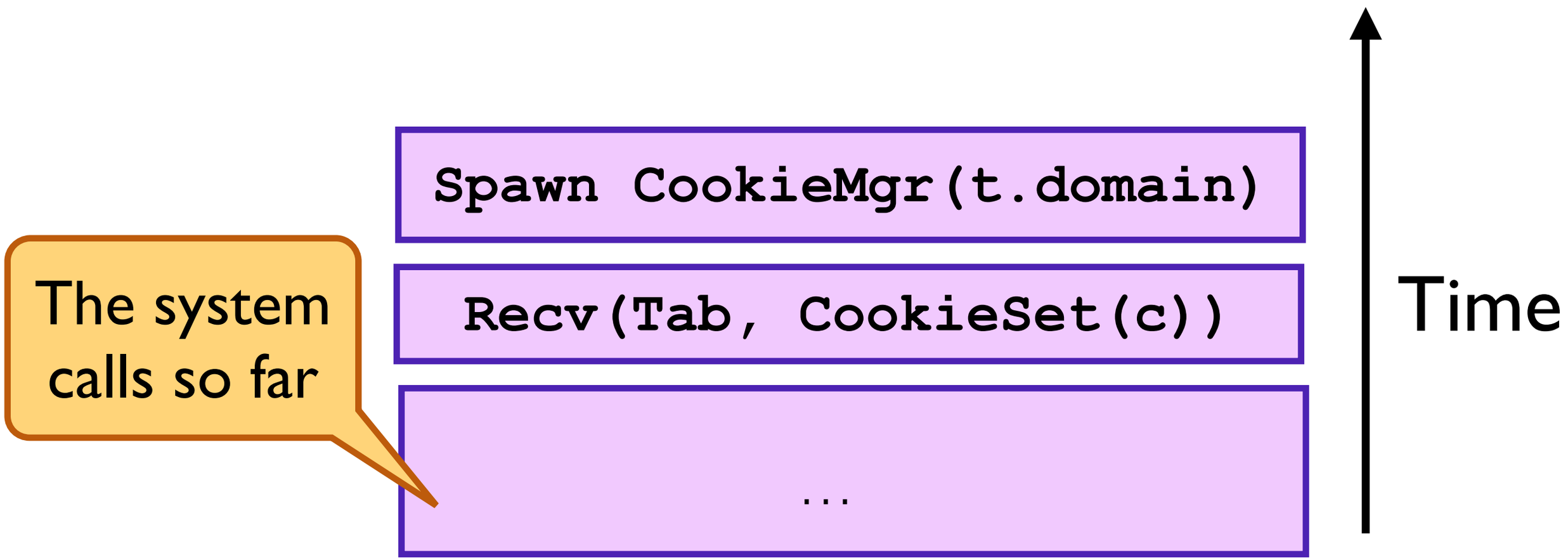

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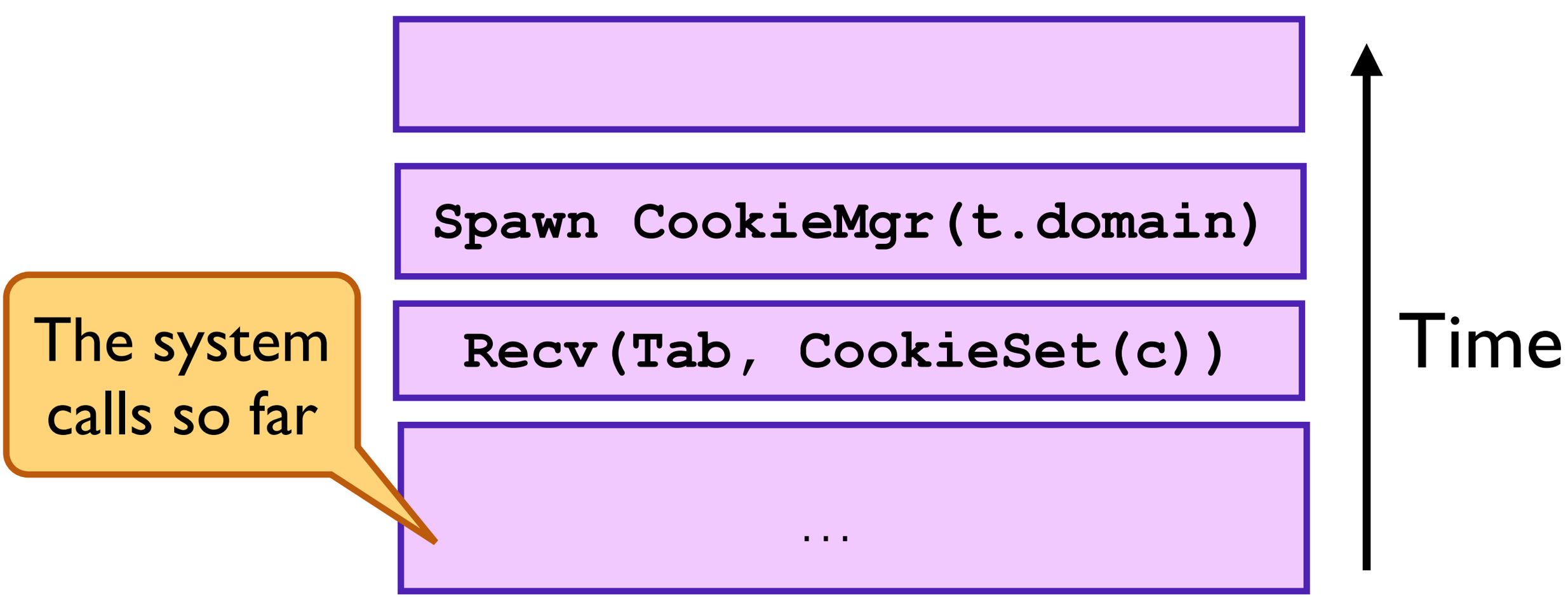

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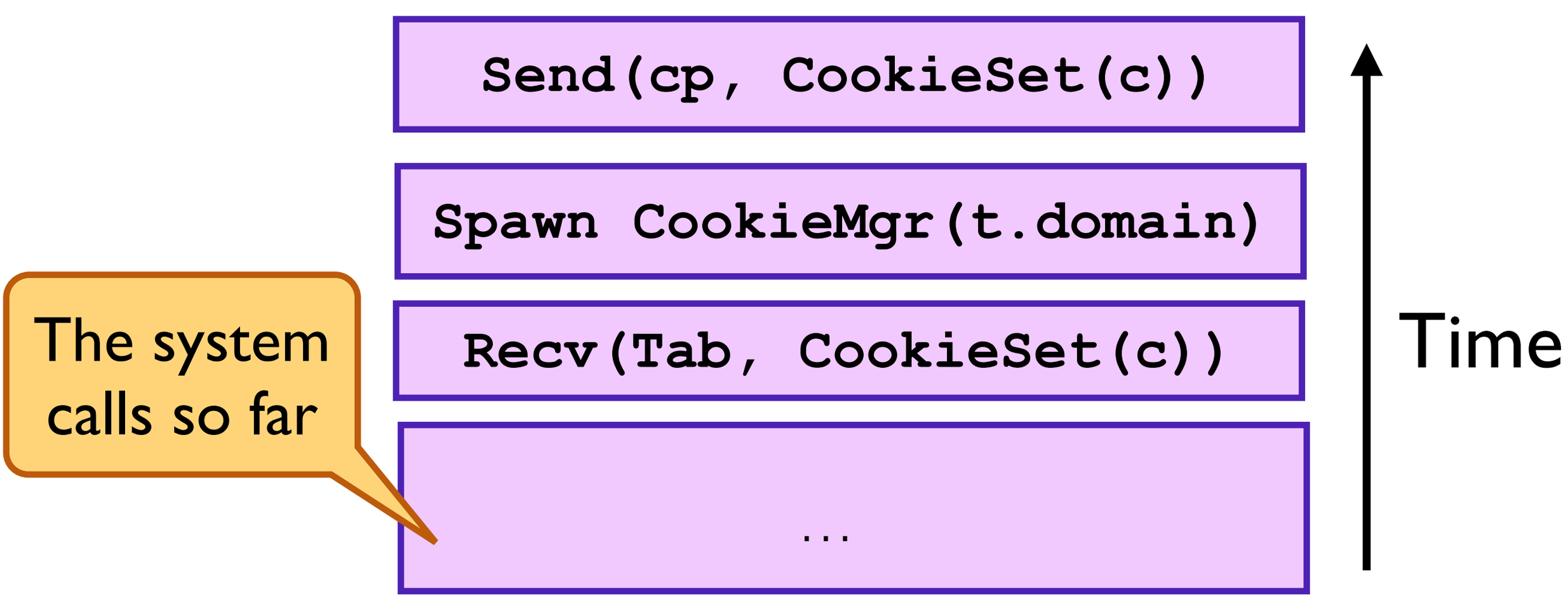

Example: Web browser kernel

```
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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    cp <- find CookieMgr(t.domain)
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    ...
```
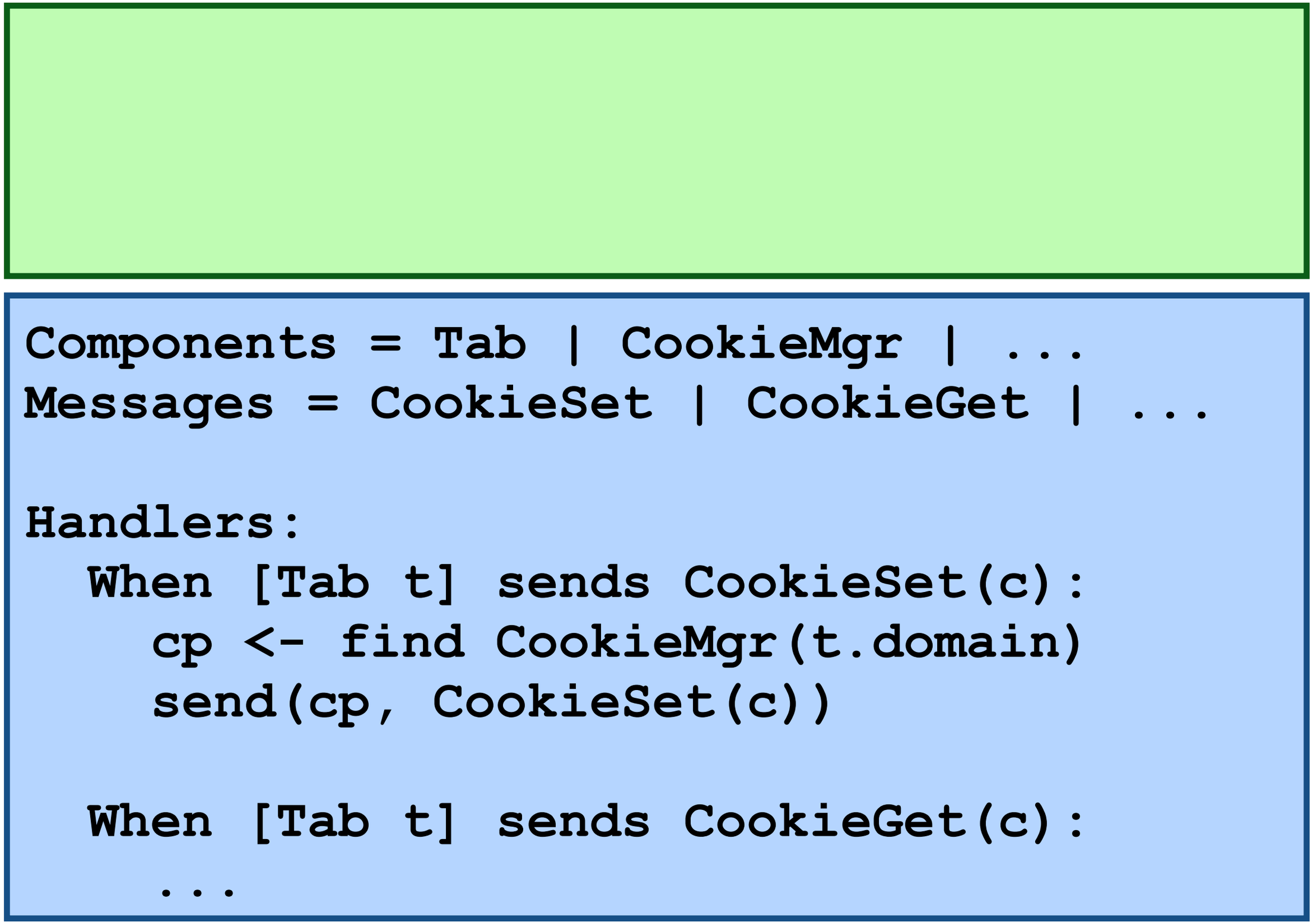

Example: Web browser kernel



Example: Web browser kernel

```
forall d c,
```

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

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

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

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):
    cp <- find CookieMgr(t.domain)
    send(cp, CookieSet(c))

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```

Example: Web browser kernel

```
forall d c,

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

Only if

```
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Handlers:
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    cp <- find CookieMgr(t.domain)
    send(cp, CookieSet(c))

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

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):
      cp <- find CookieMgr(t.domain)
      send(cp, CookieSet(c))

   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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```
Co                                          ...
M

H
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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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Example: Web browser kernel

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```
for
    [
E
    [

Com
Mes

Han
    W

    W
```

REFLEX Benefits:

. . .

Example: Web browser kernel

```
for
    [
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REFLEX Benefits:

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No lemmas

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Example: Web browser kernel

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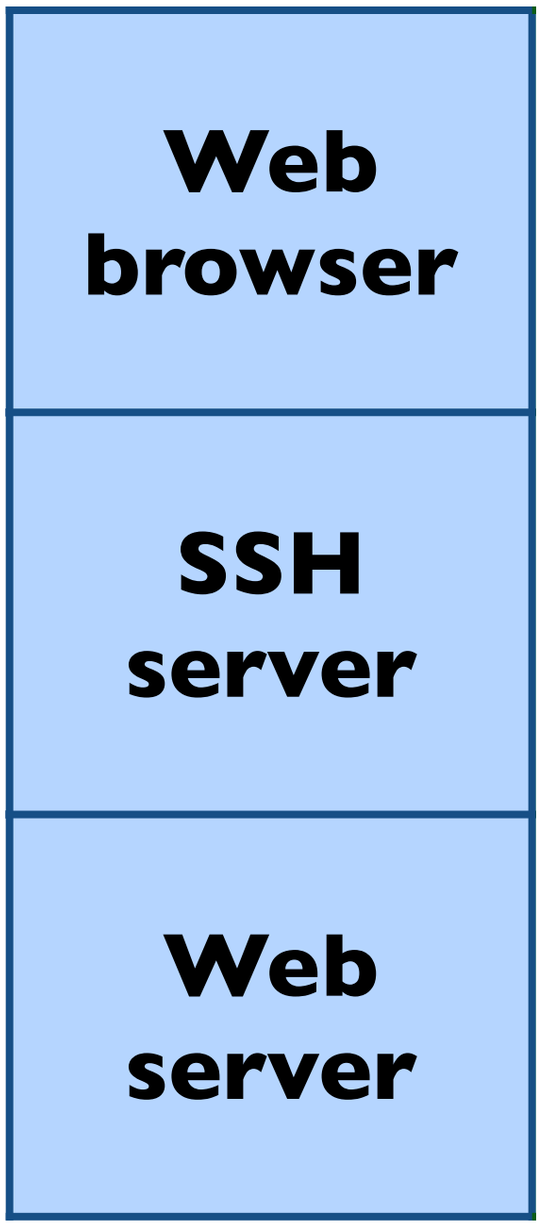
Evaluation

Evaluation



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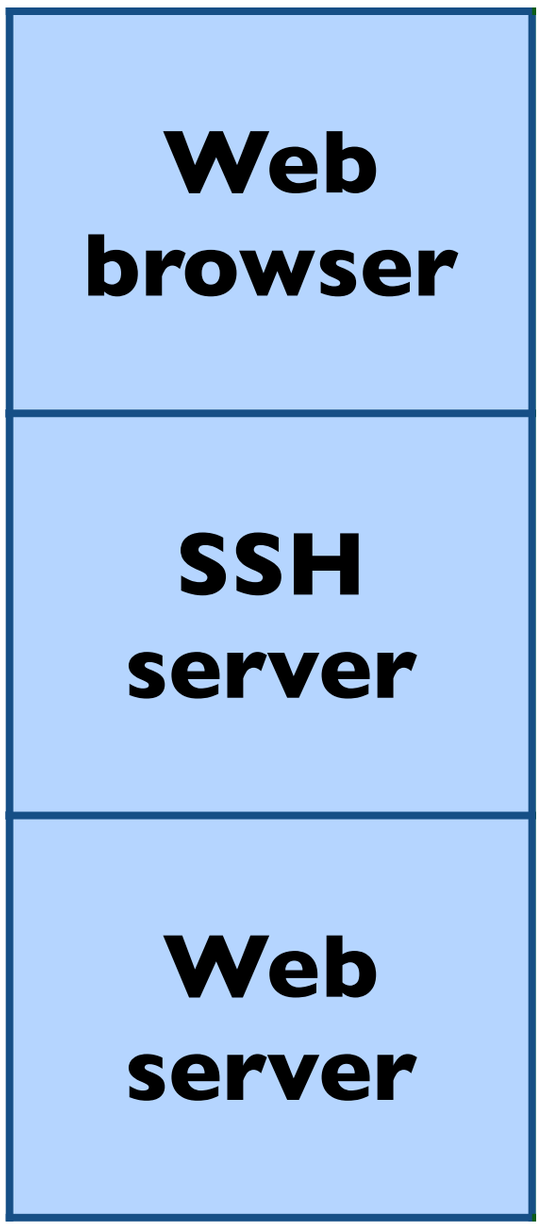

Auto verified 33 properties (80% in < 2 minutes)

Evaluation

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, …**

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Able to automate proofs of non-interference

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Development Effort: Systems

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Benchmark	*Language*	*Lines of Code/Spec*	
Browser	REFLEX	81	37
	C++, Python	970,240	-
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Webkit

OpenSSH

Expressiveness Limitations

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Strict subset of temporal logic + non-interference

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Loop free handlers

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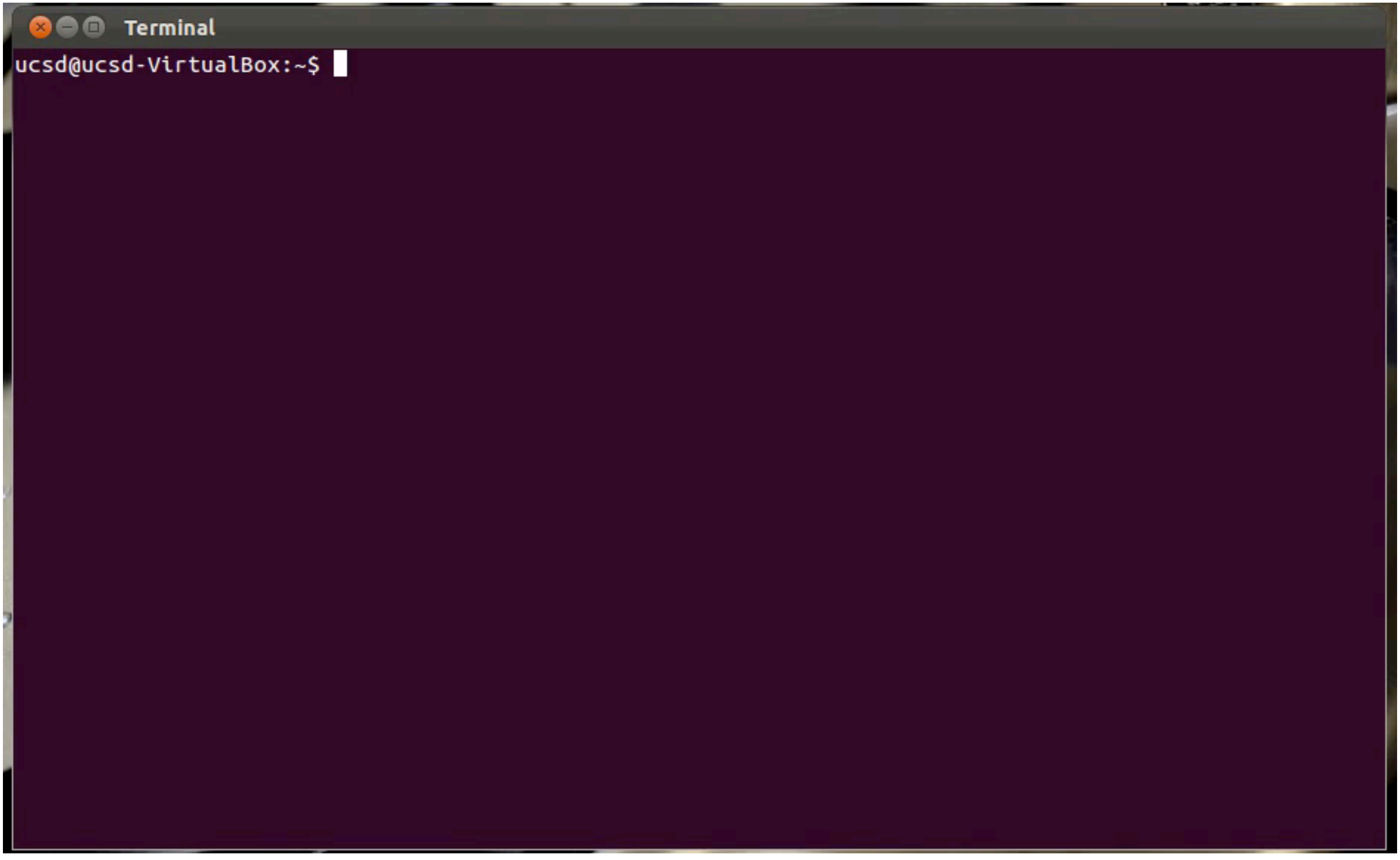
No user-defined unbounded data structures

SSH Server Kernel in REFLEX



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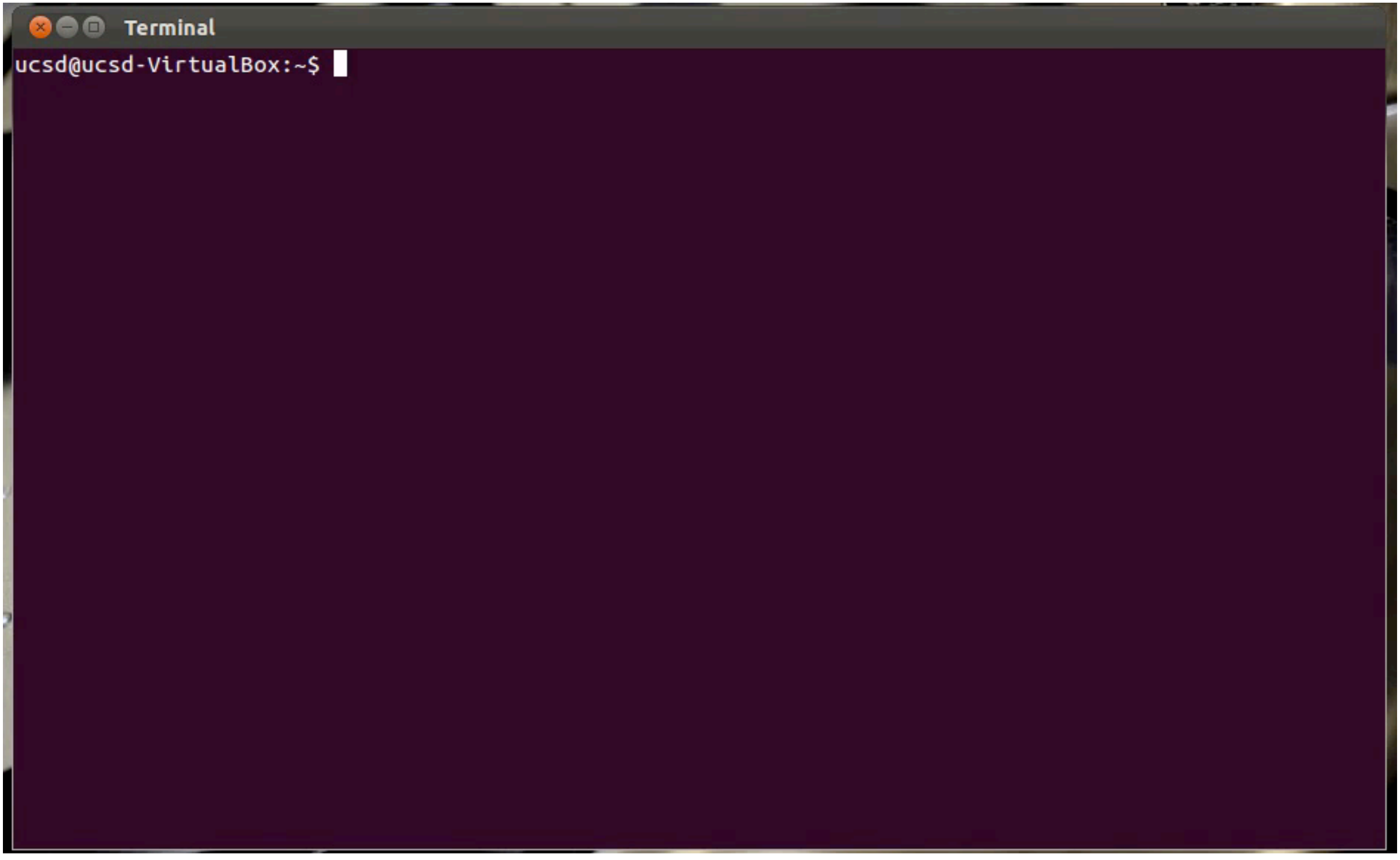

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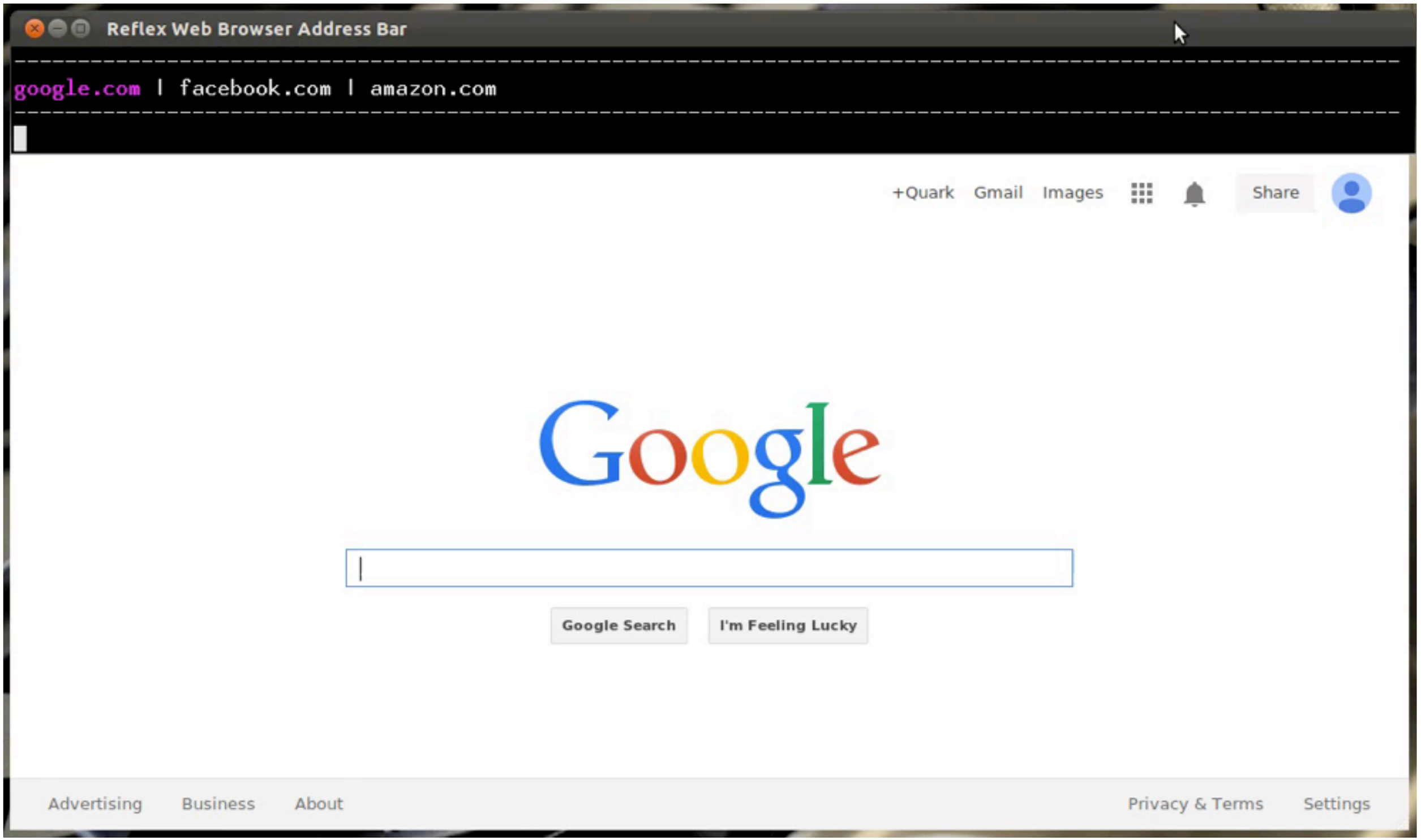

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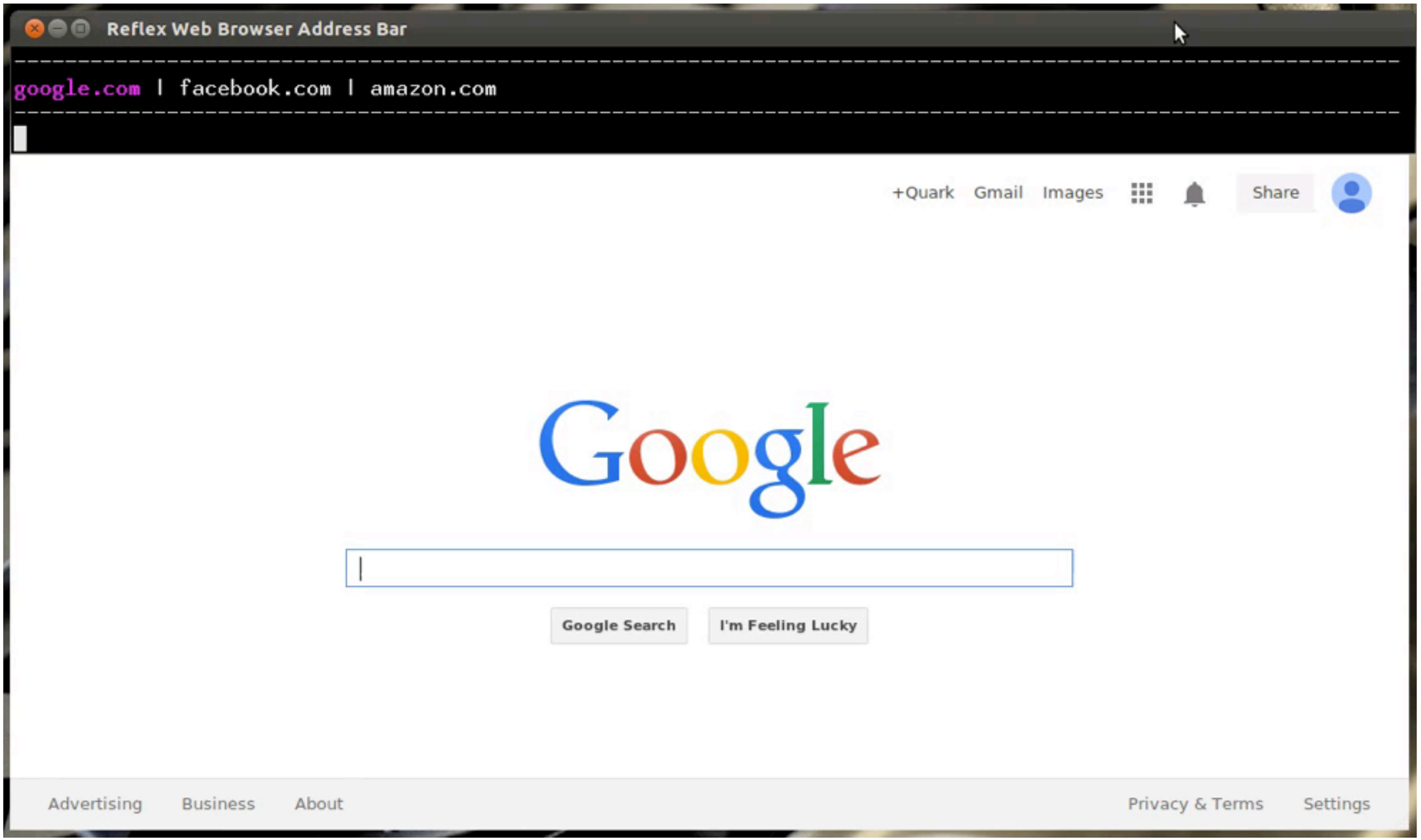

Ongoing: UAV controllers

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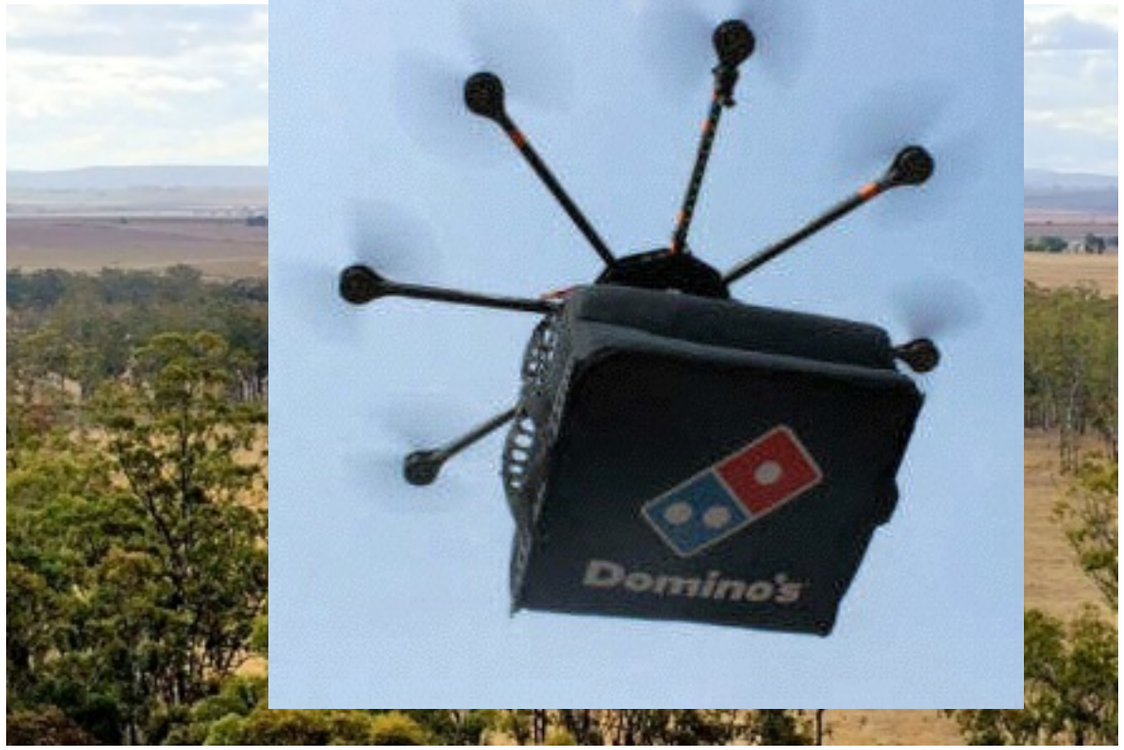

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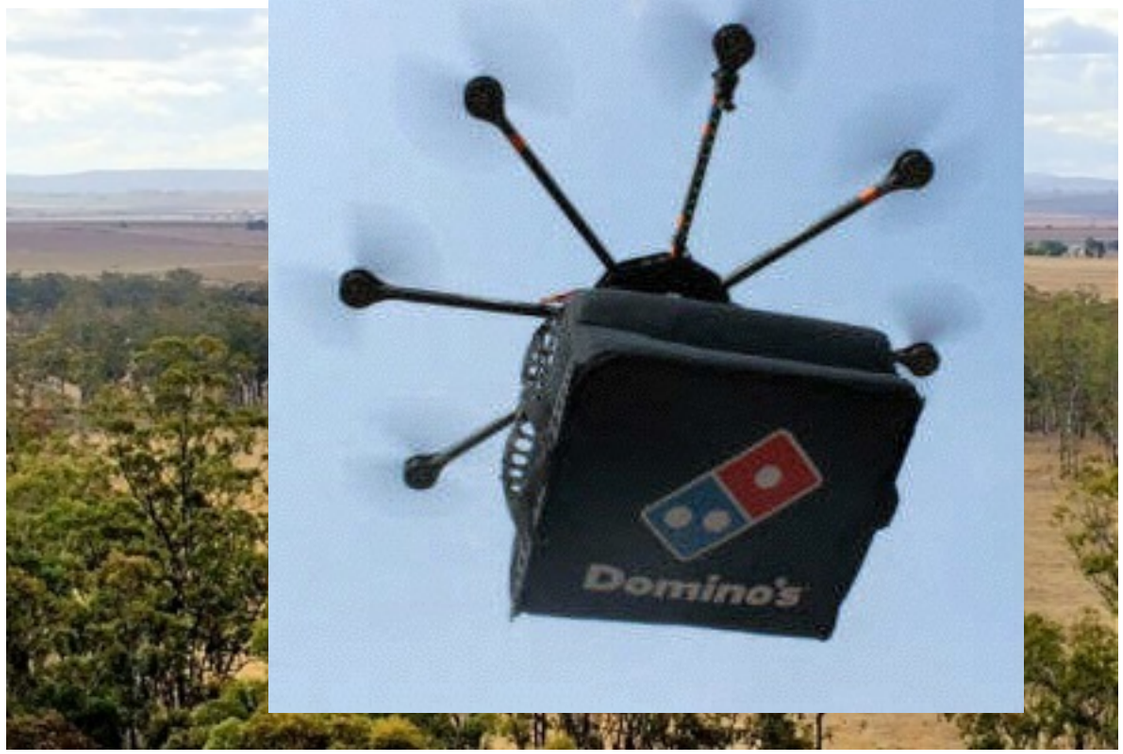

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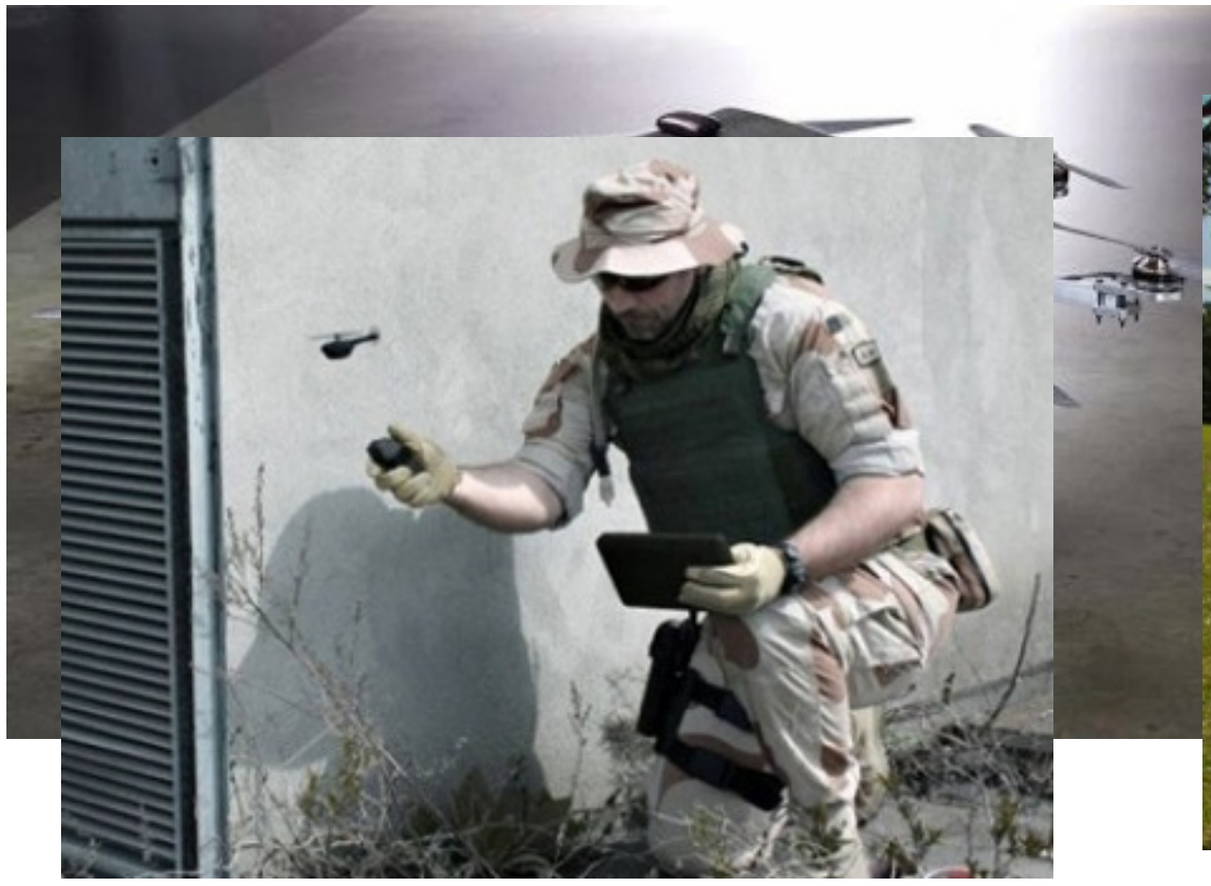

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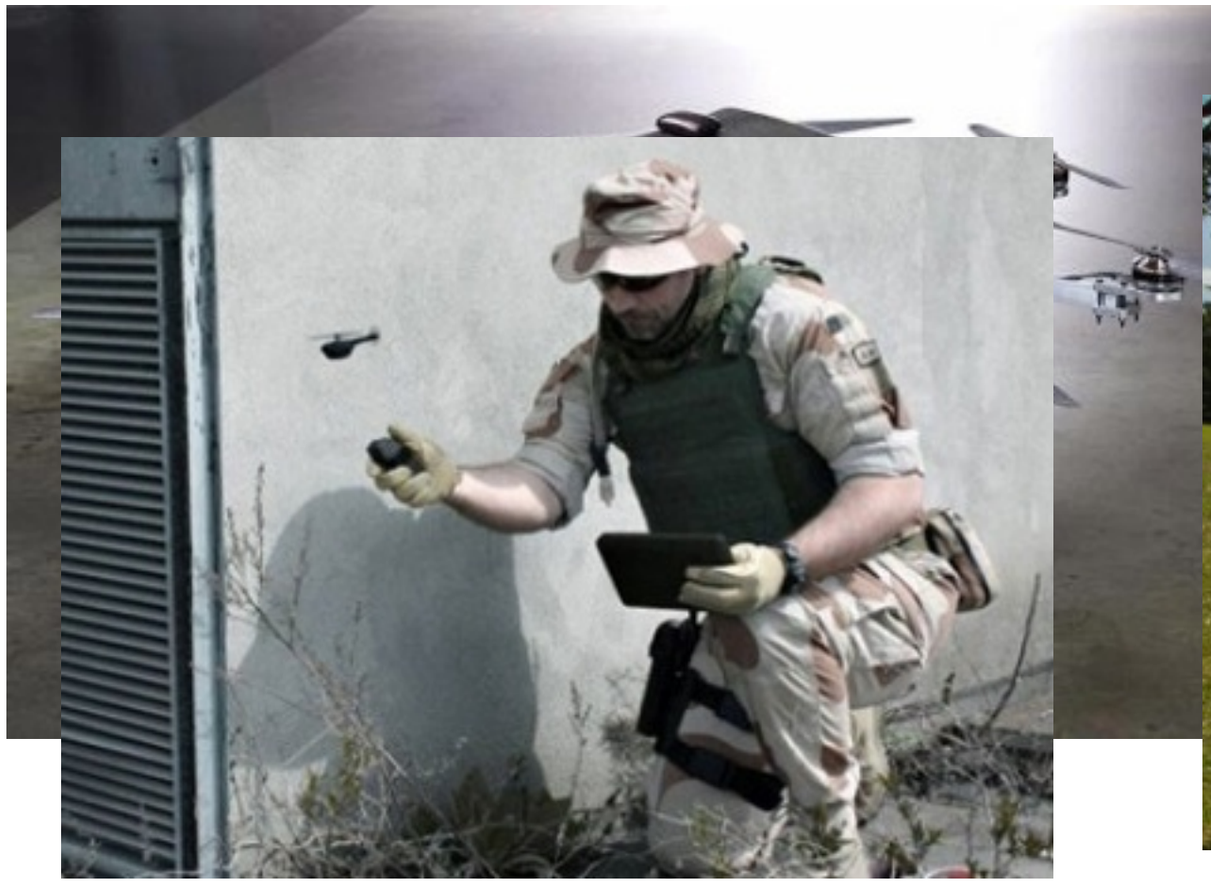

Used by military, companies, and individuals

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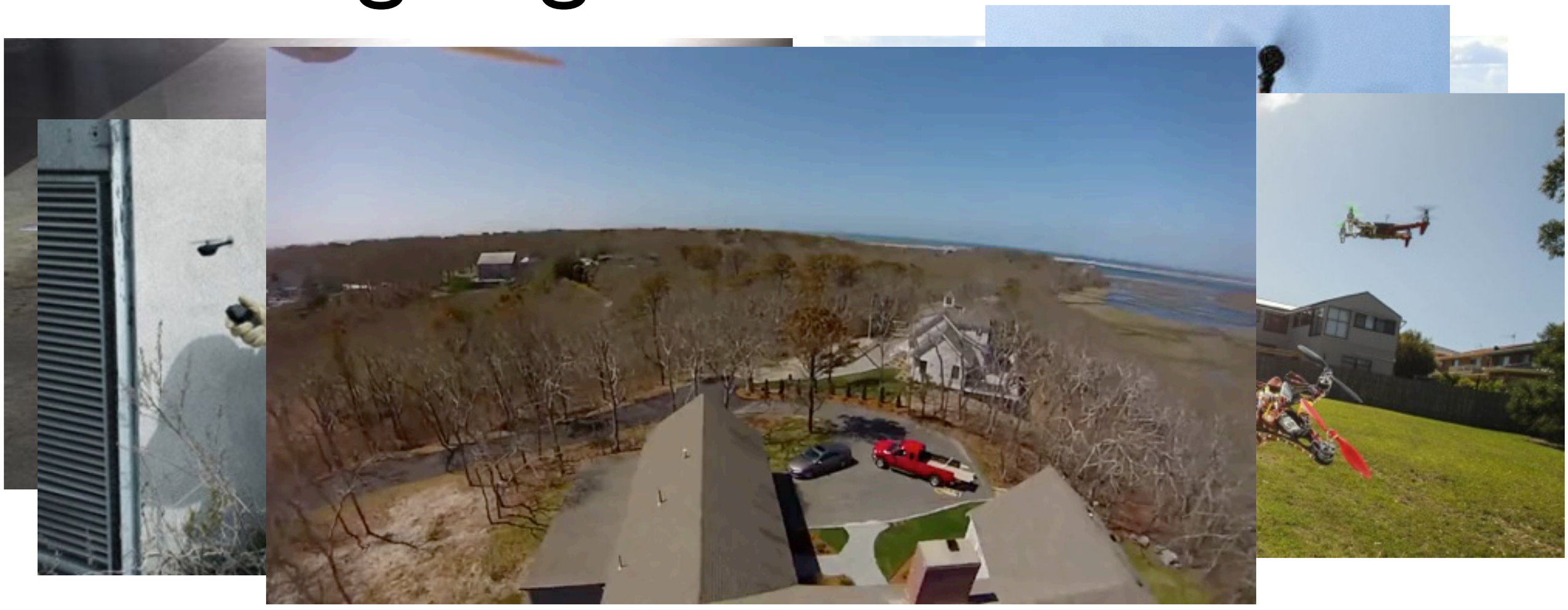


Used by military, companies, and individuals

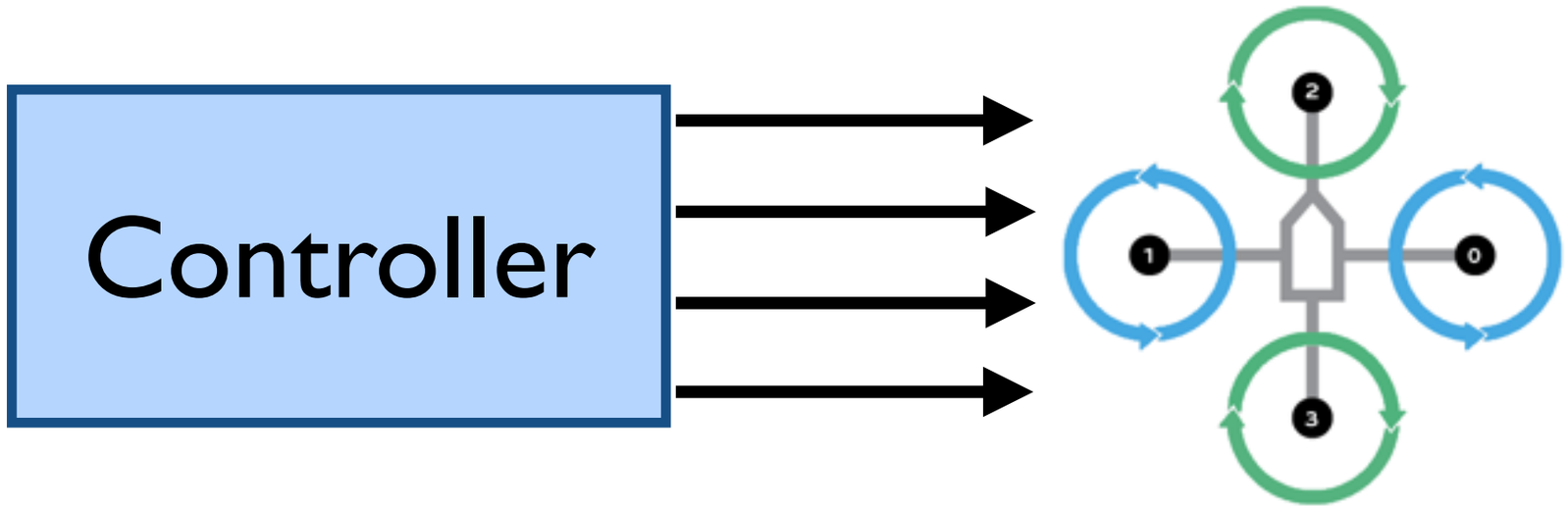
Safety critical

Ongoing: UAV controllers

Ongoing: UAV controllers

Controller

Ongoing: UAV controllers



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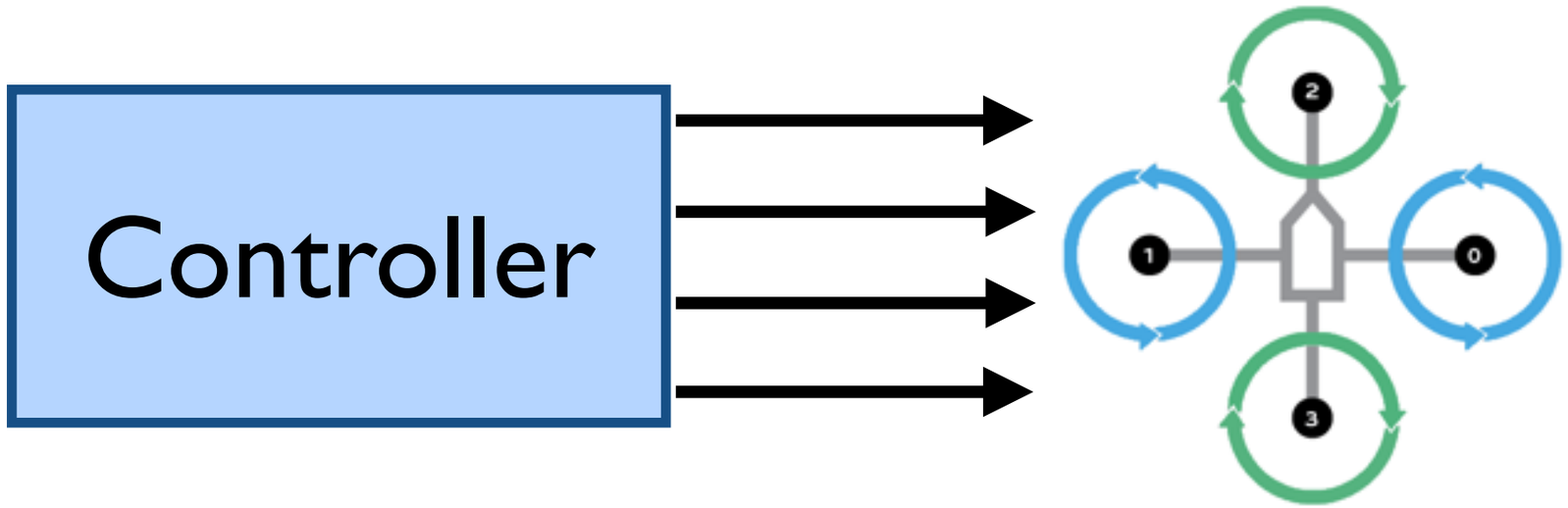
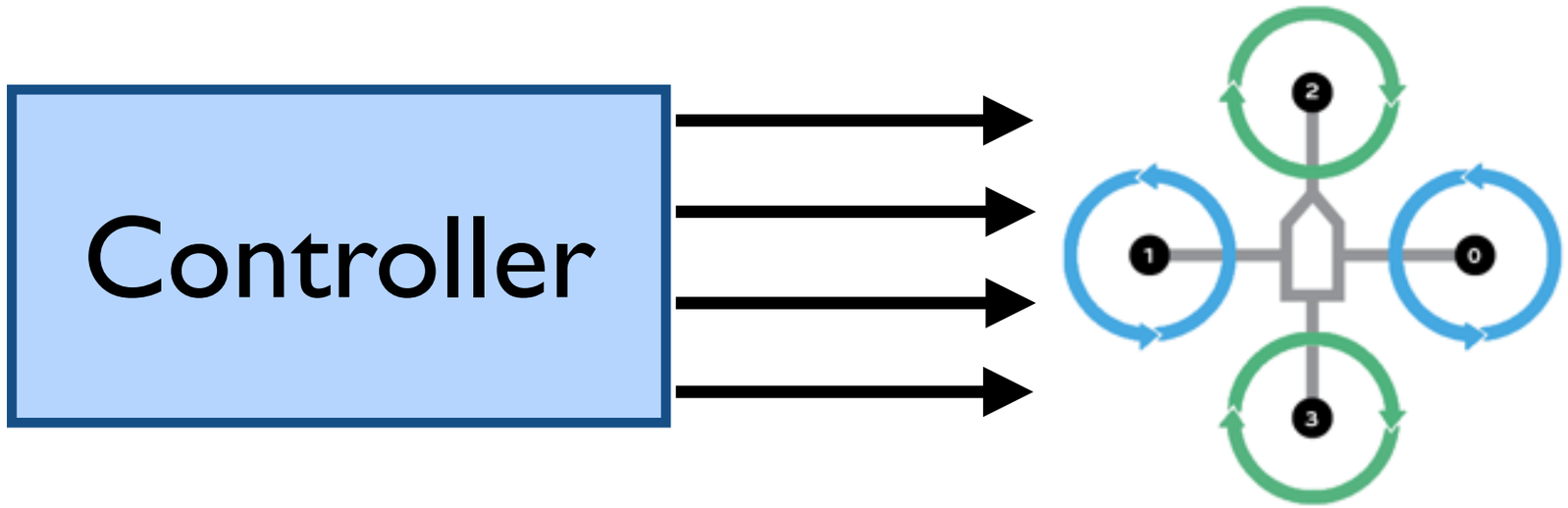


Height is always < 400 ft

Ongoing: UAV controllers



Height is always < 400 ft

UAV eventually reaches target location

Ongoing: UAV controllers

DSL for dynamics and properties

DSL for controllers

Spec

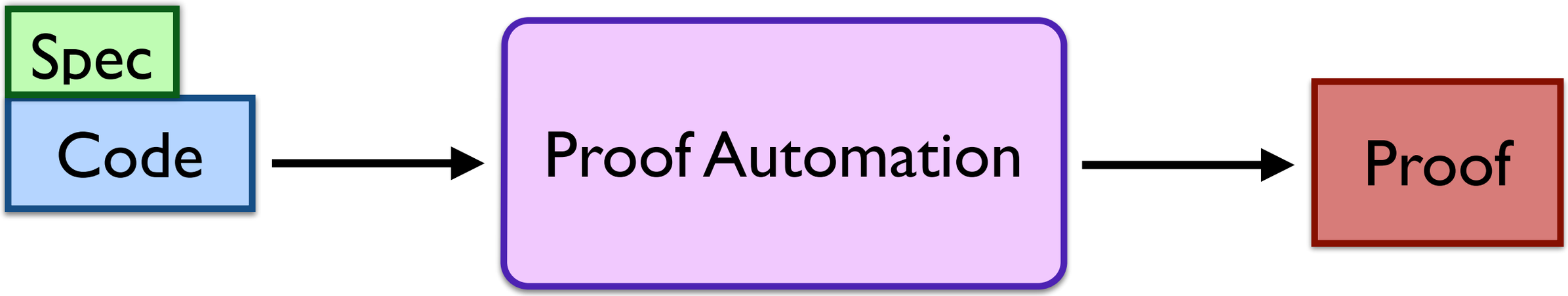
Code

Proof Automation

Ongoing: UAV controllers

DSL for dynamics and properties

DSL for controllers



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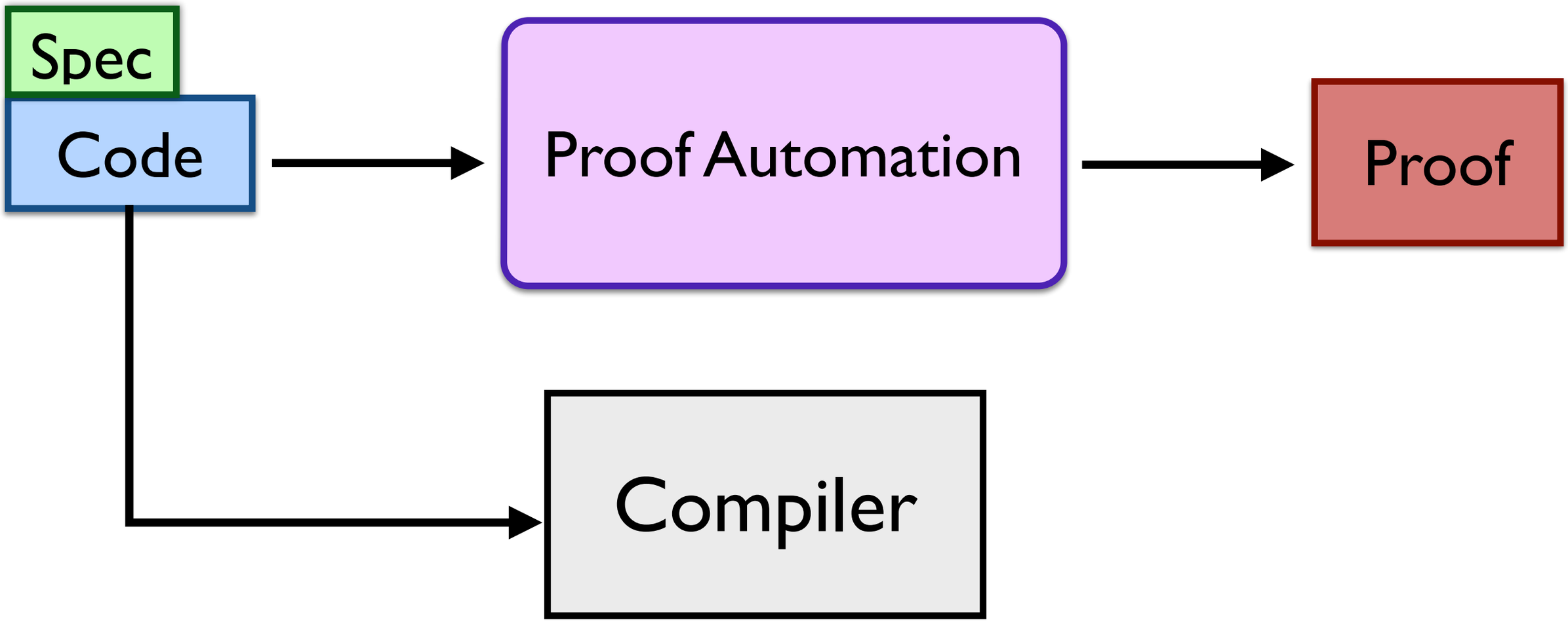

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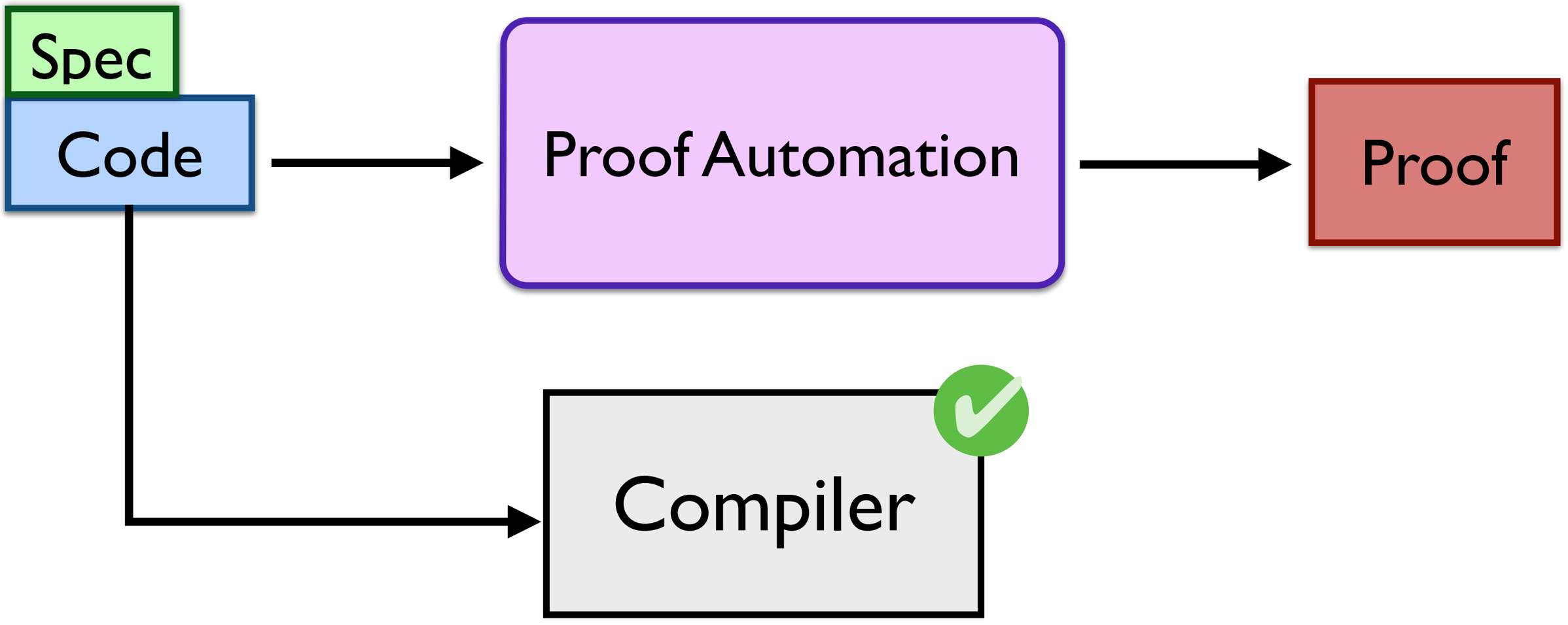

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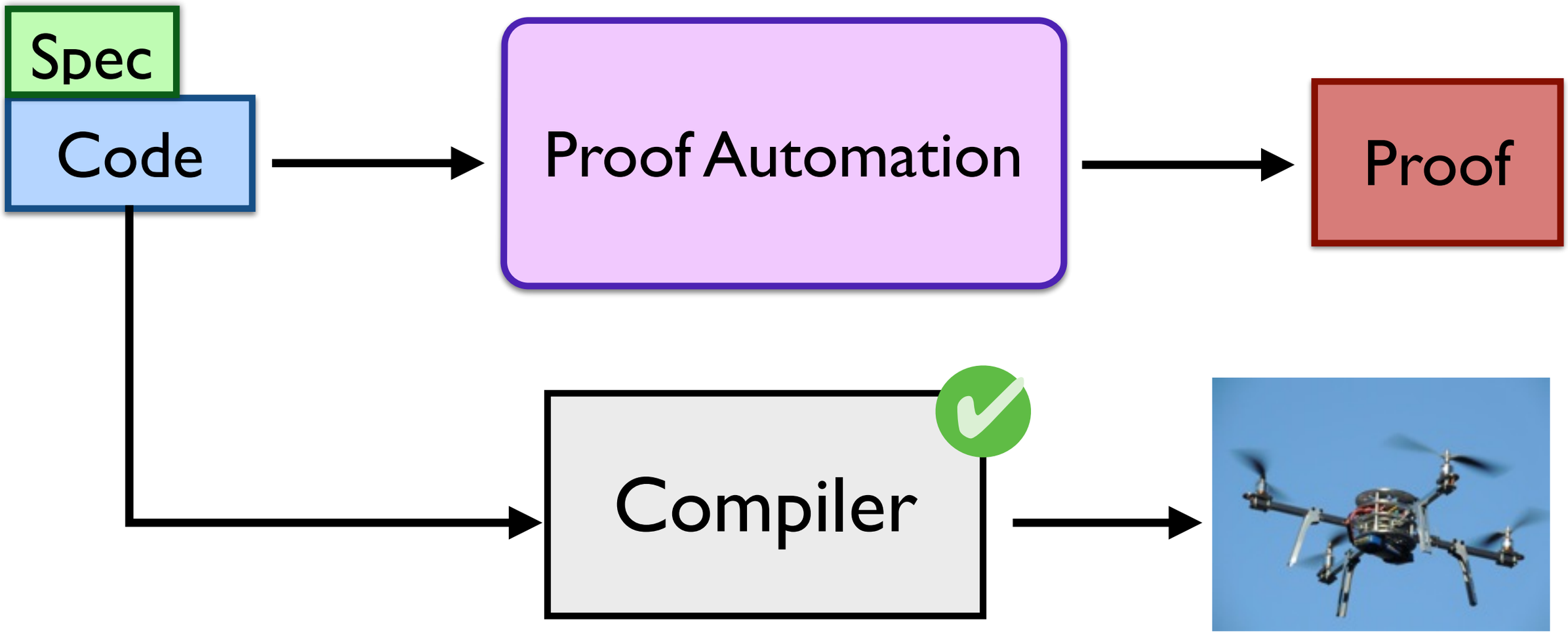


Goal

End-to-end guarantee in Coq

Conclusion

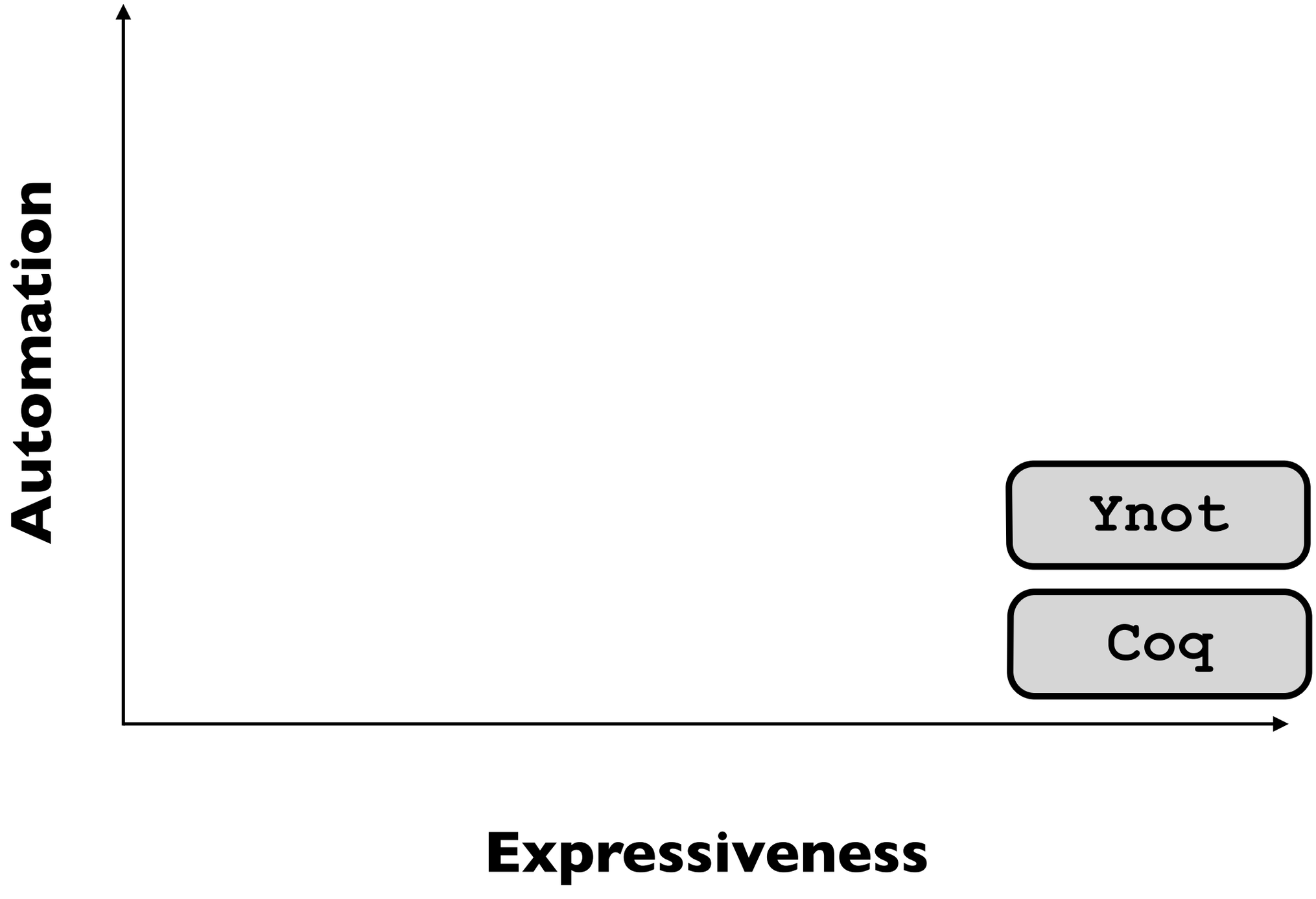
Proof assistant based verification

Conclusion

Proof assistant based verification

Conclusion

Proof assistant based verification



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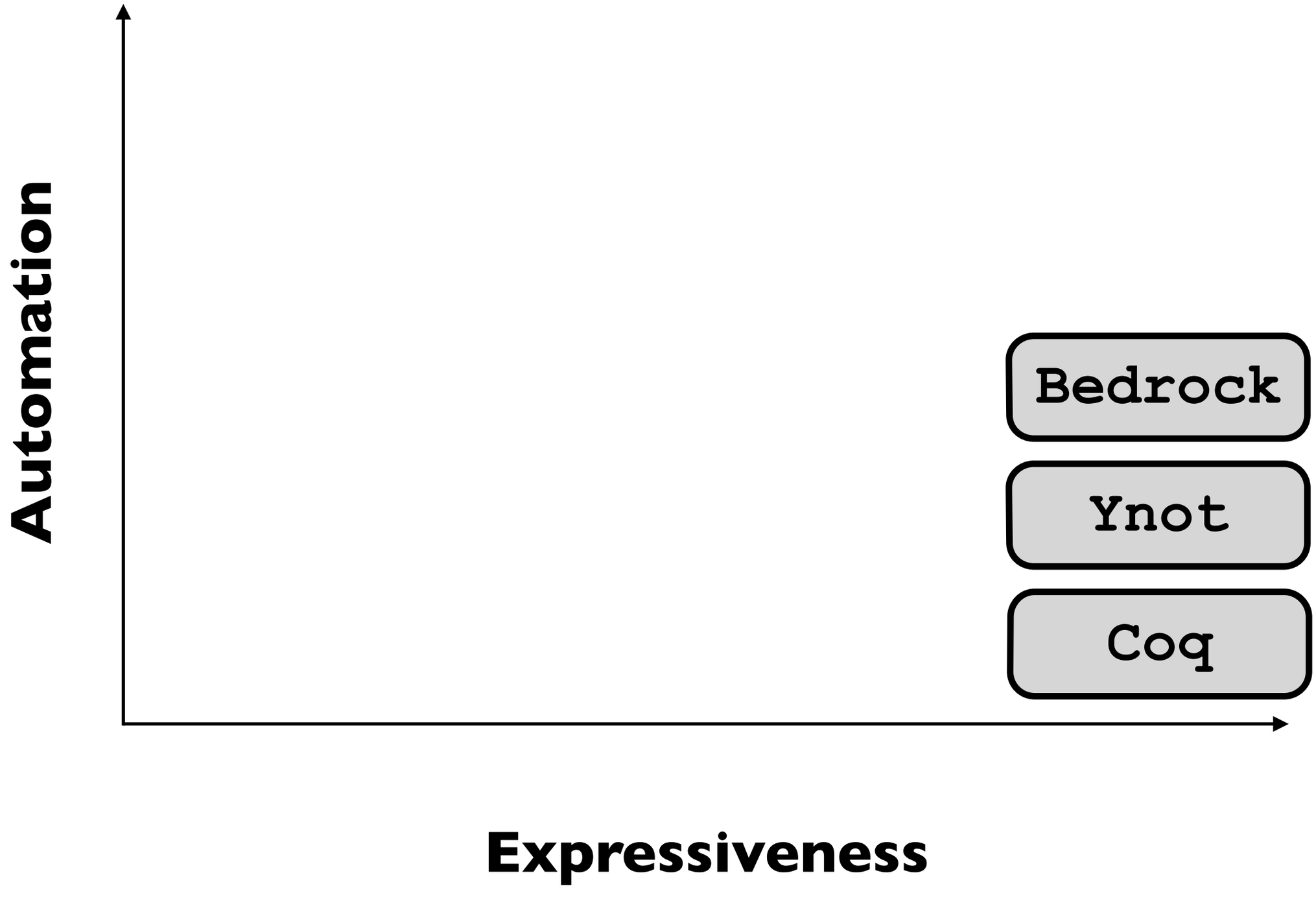

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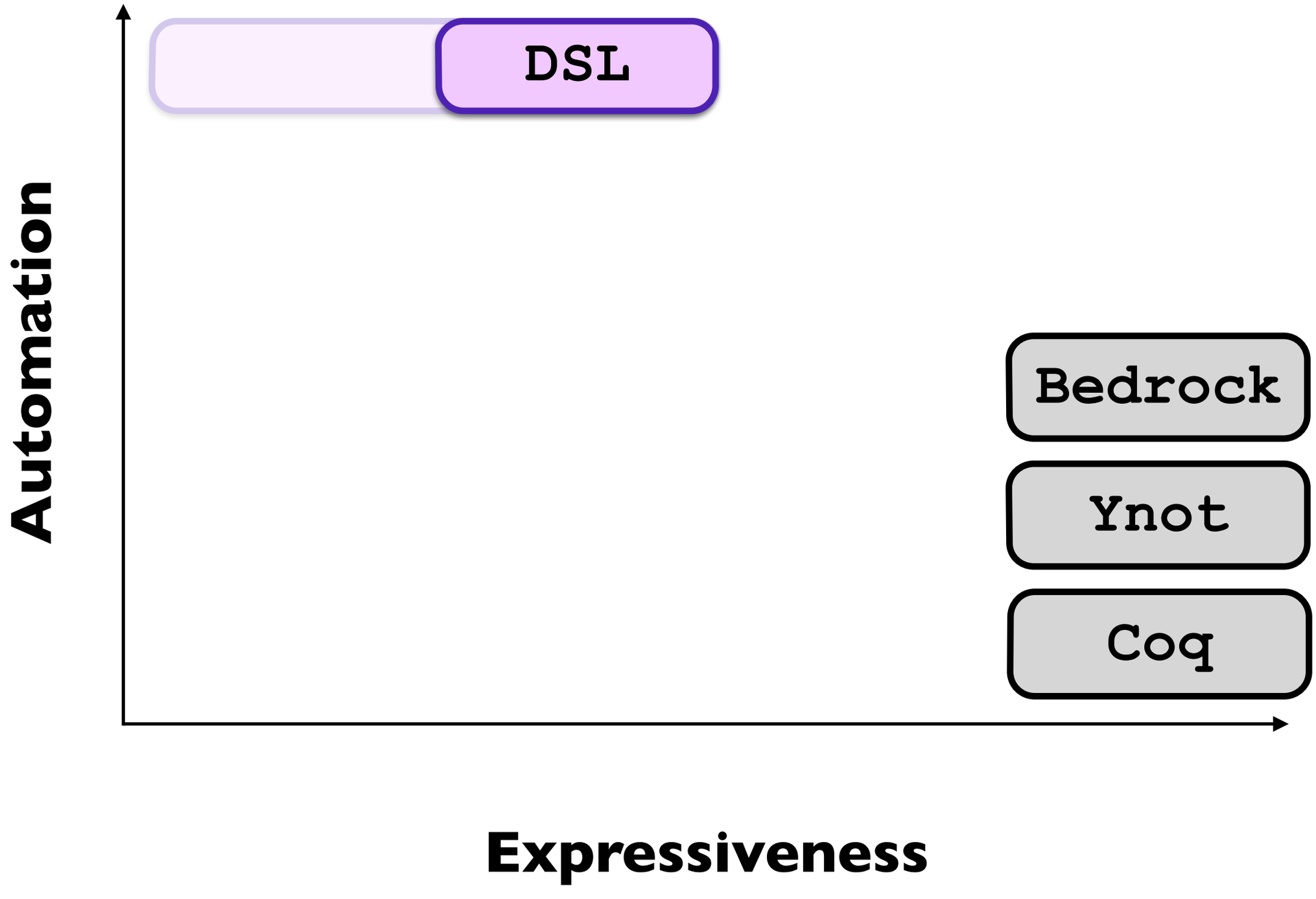
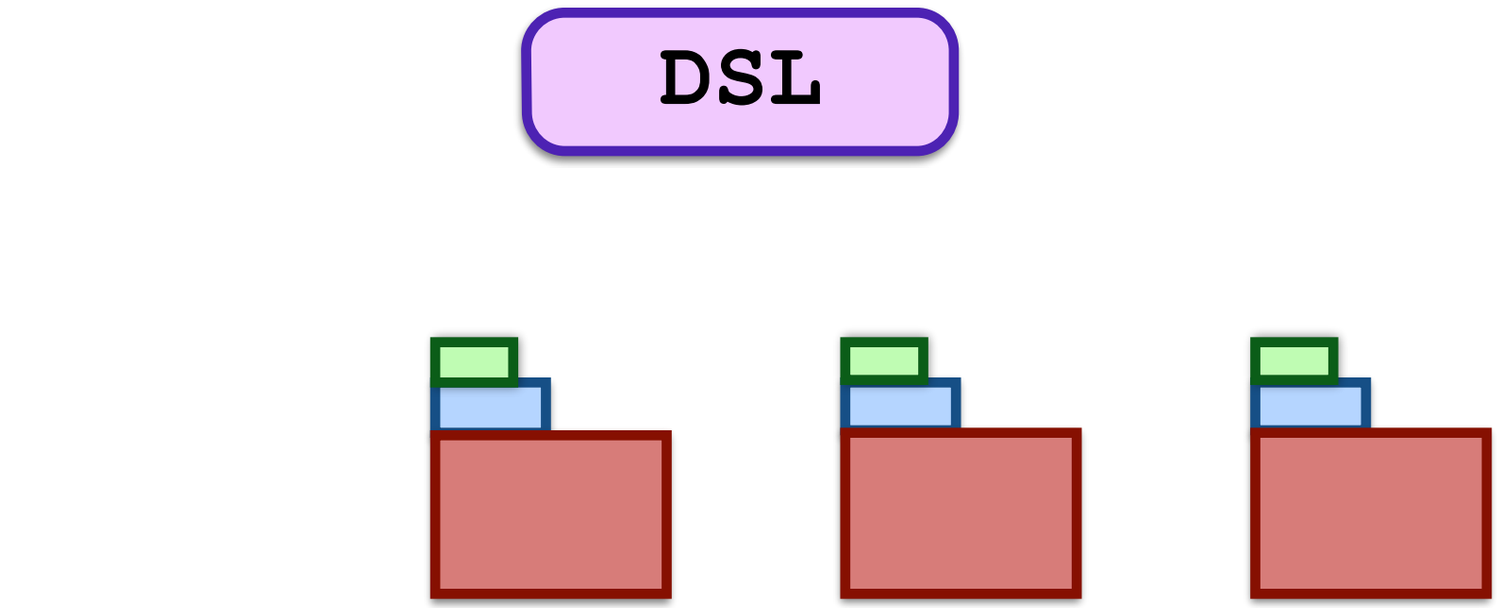


Conclusion

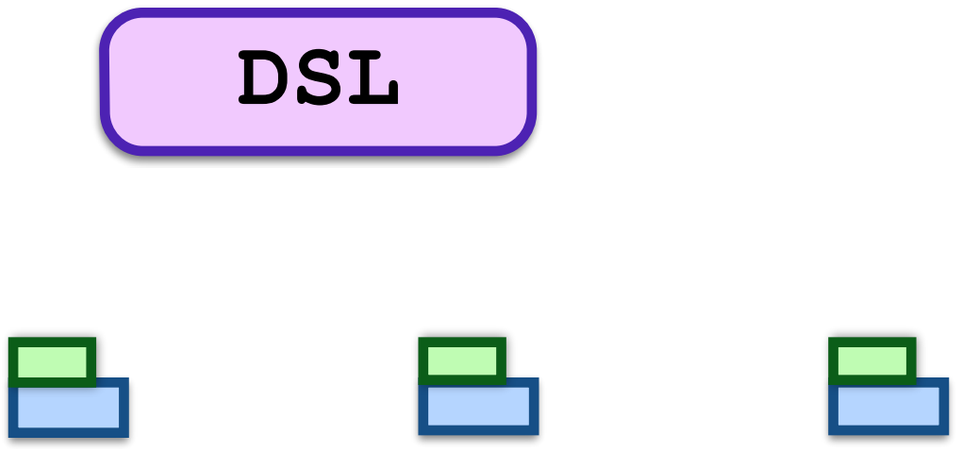
DSL

Conclusion



DSL expressive enough for entire domain

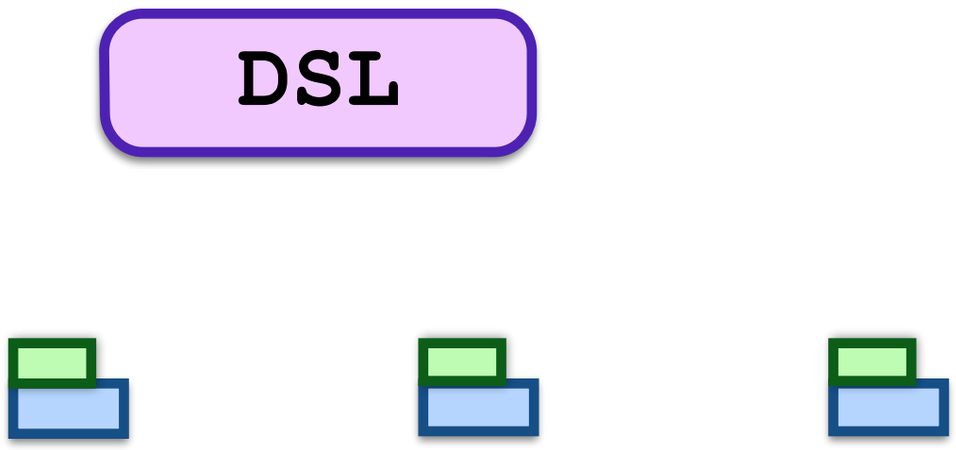
Conclusion



DSL expressive enough for entire domain

Automation eliminates manual proof burden

Conclusion



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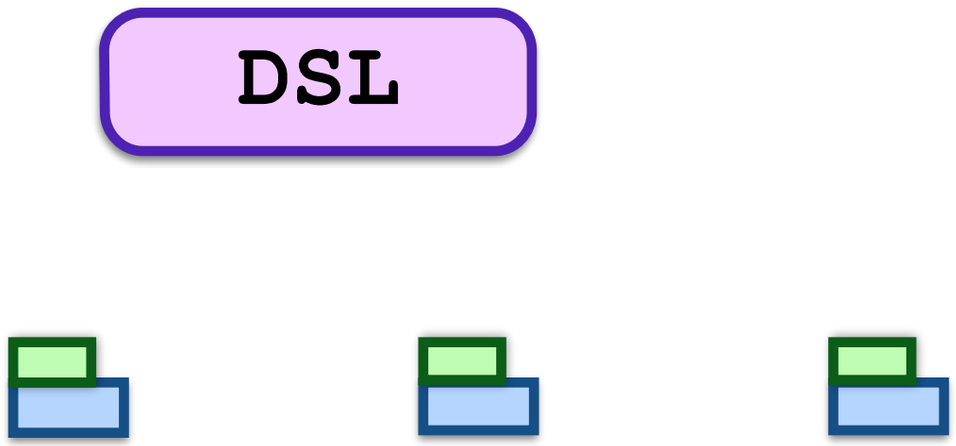
http://goto.ucsd.edu/reflex/

Thank You!



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