Shared Session Types for Safe, Practical Concurrency[1]

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Carnegie Mellon University

Typelevel Summit Philadelphia 2019

1 Supported by a Mozilla Research Grant and NSF Grant No. CCF-1718267

Concurrency is ubiquitous

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The world surrounding us is inherently concurrent

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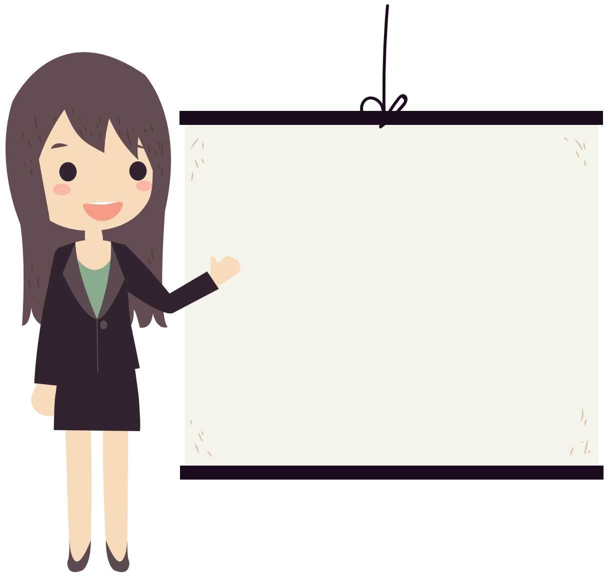

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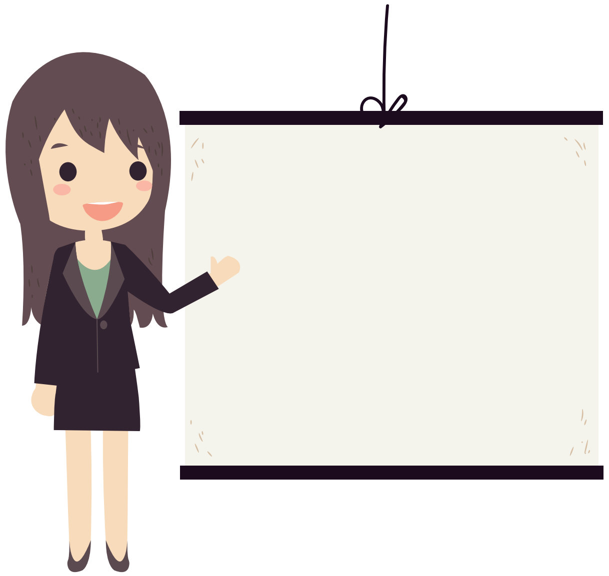

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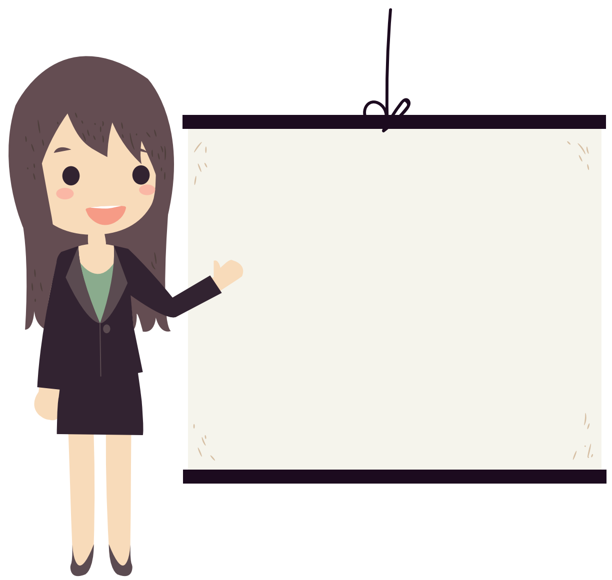

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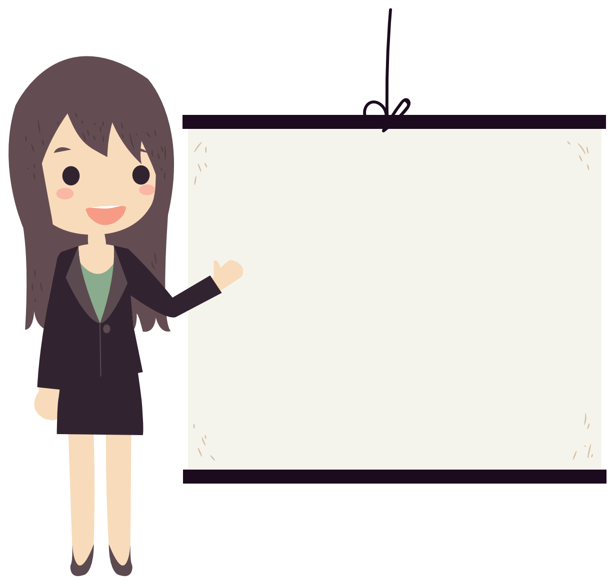

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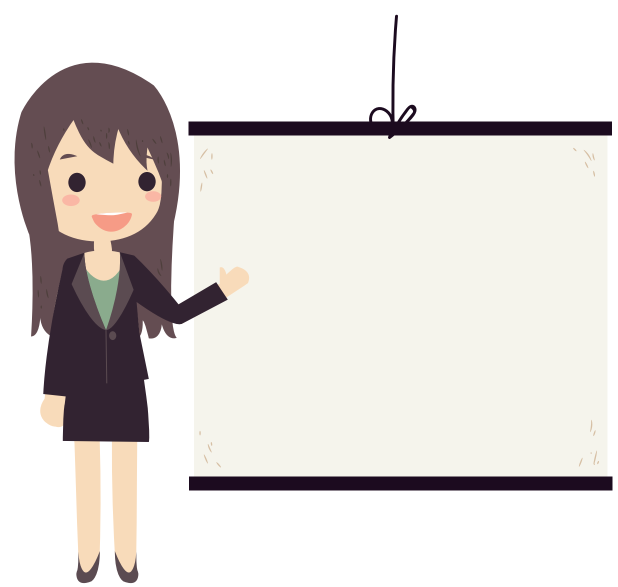

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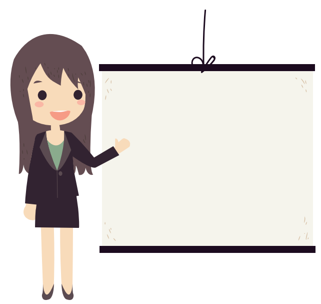

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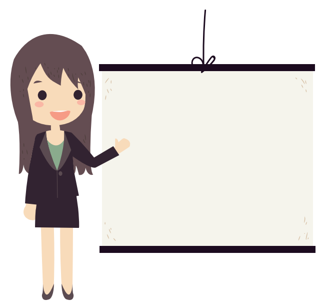



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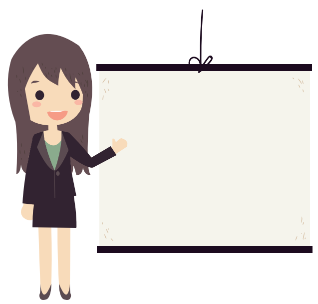

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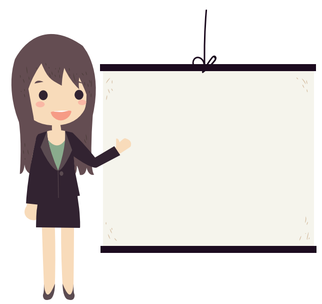



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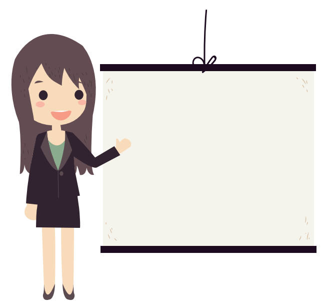



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→ programming languages must support concurrency

→ concurrent programming is notoriously difficult and error-prone

Two models for concurrent programming

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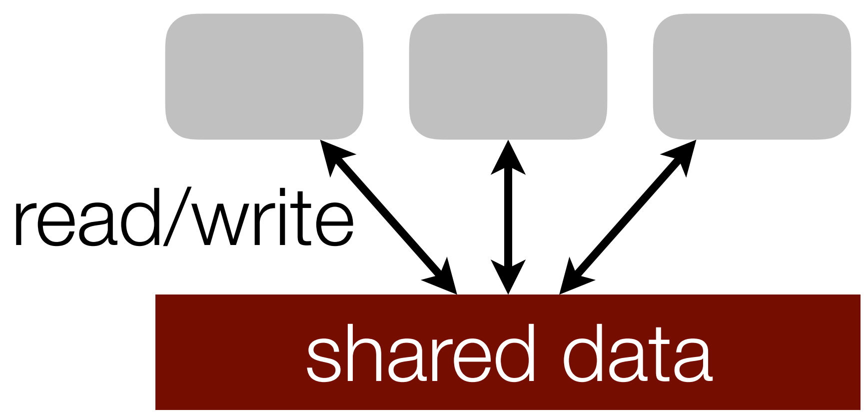
Shared memory



Legend: concurrently executing component

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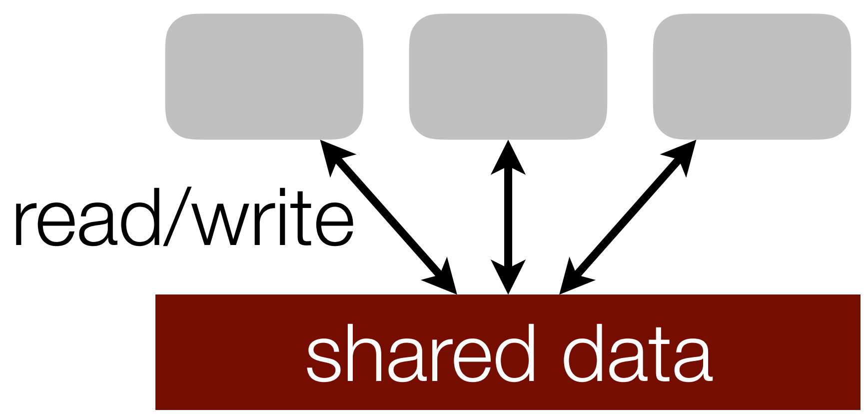
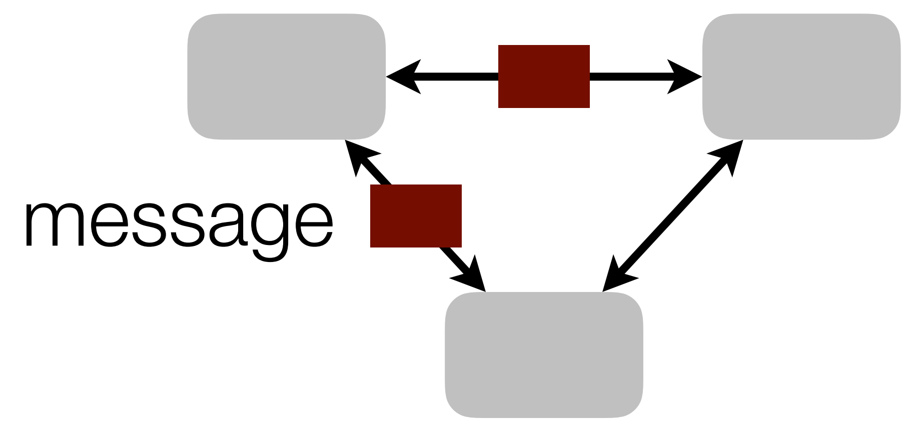


Message-passing



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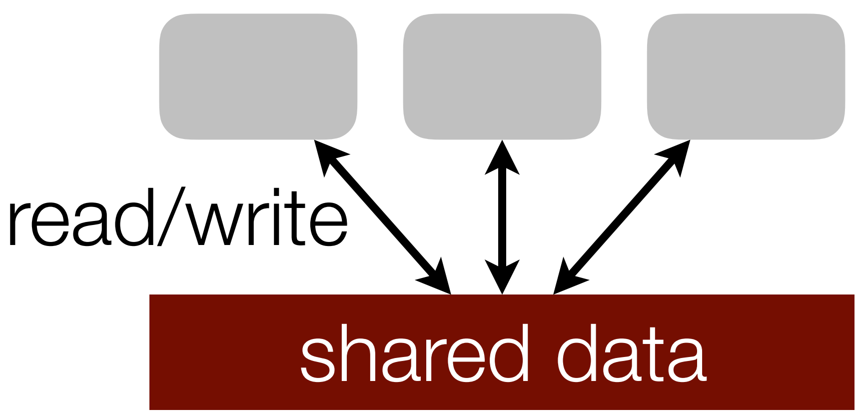

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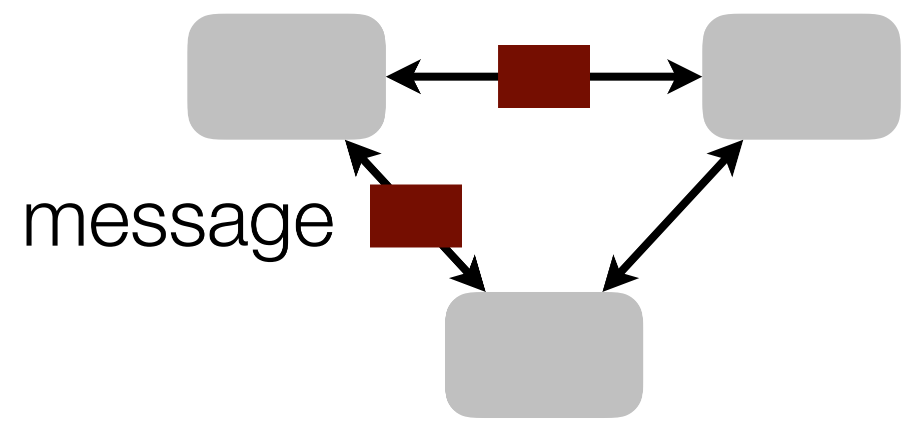

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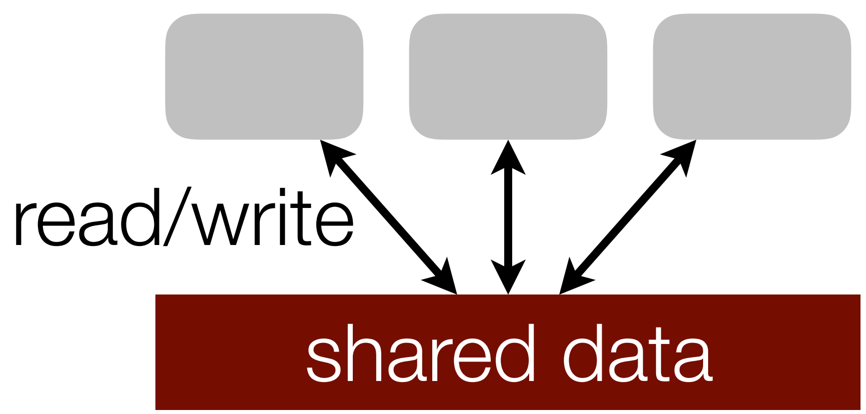

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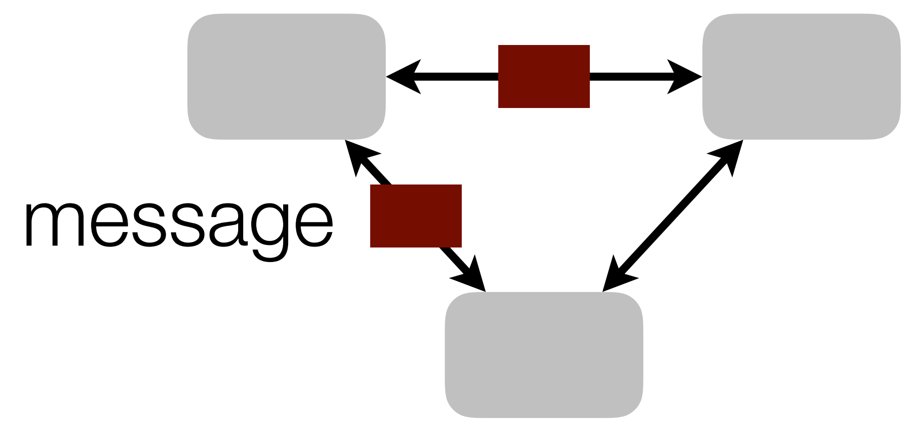

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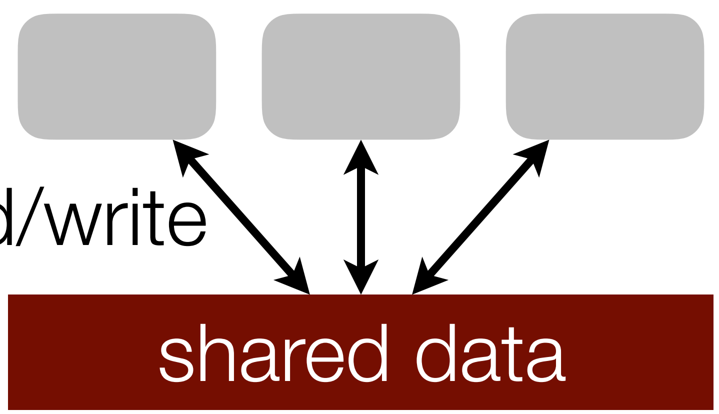

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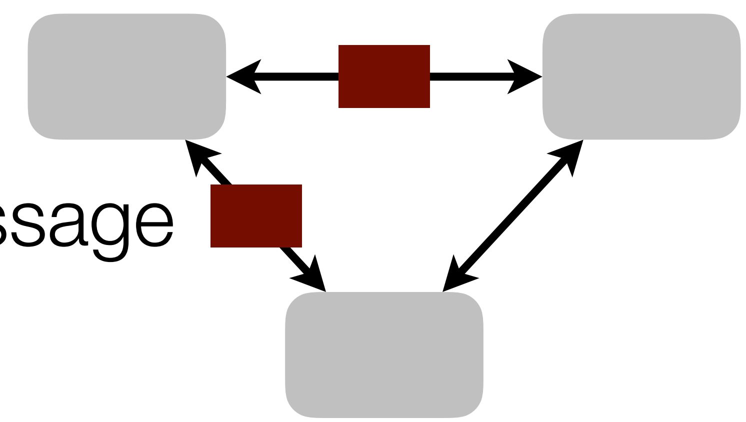

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→ message-passing offers higher-level of abstraction

Legend: [grey box] concurrently executing component

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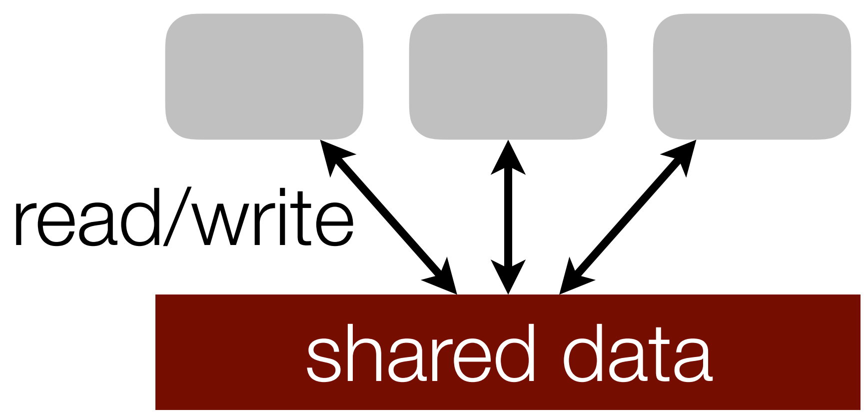

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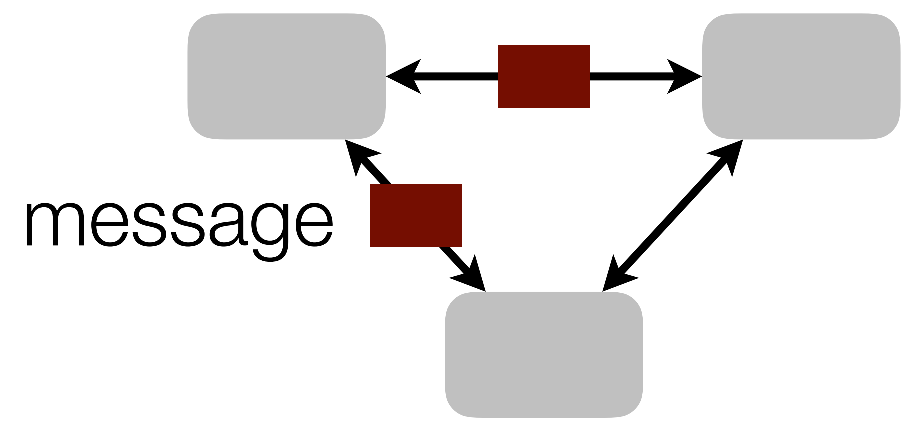

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message-passing offers higher-level of abstraction

message-passing adopted by practical languages such as Erlang, Go, and Rust.

Legend: concurrently executing component

My research

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- message-passing model
- session types to express protocols of message exchange and reason sequentially about communicating parties

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Contributions:

- shared session types
  - accommodate real-world programming scenarios
  - guarantee protocol adherence, data-race-freedom, and deadlock-freedom

Session types, what are they? Why do we need them in practice?

Message-passing concurrency in Servo

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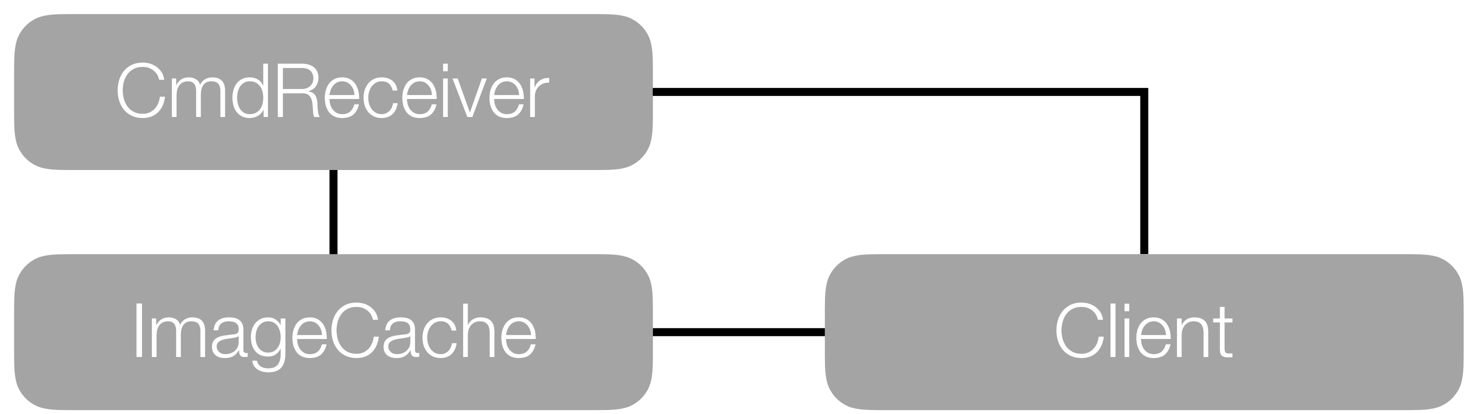

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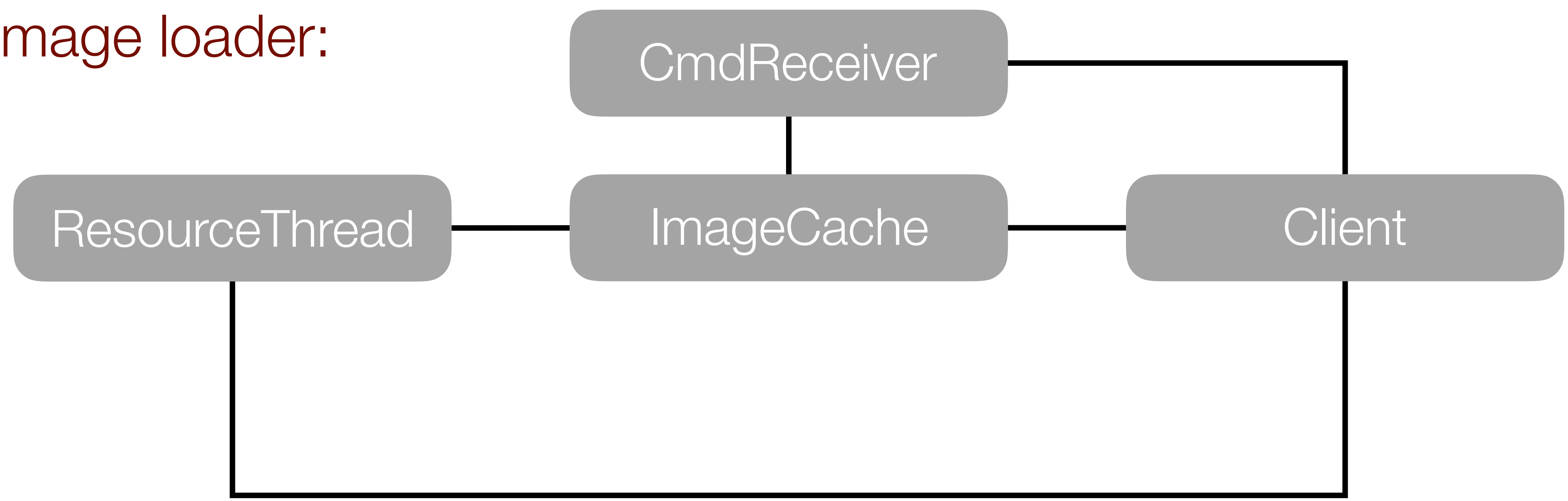

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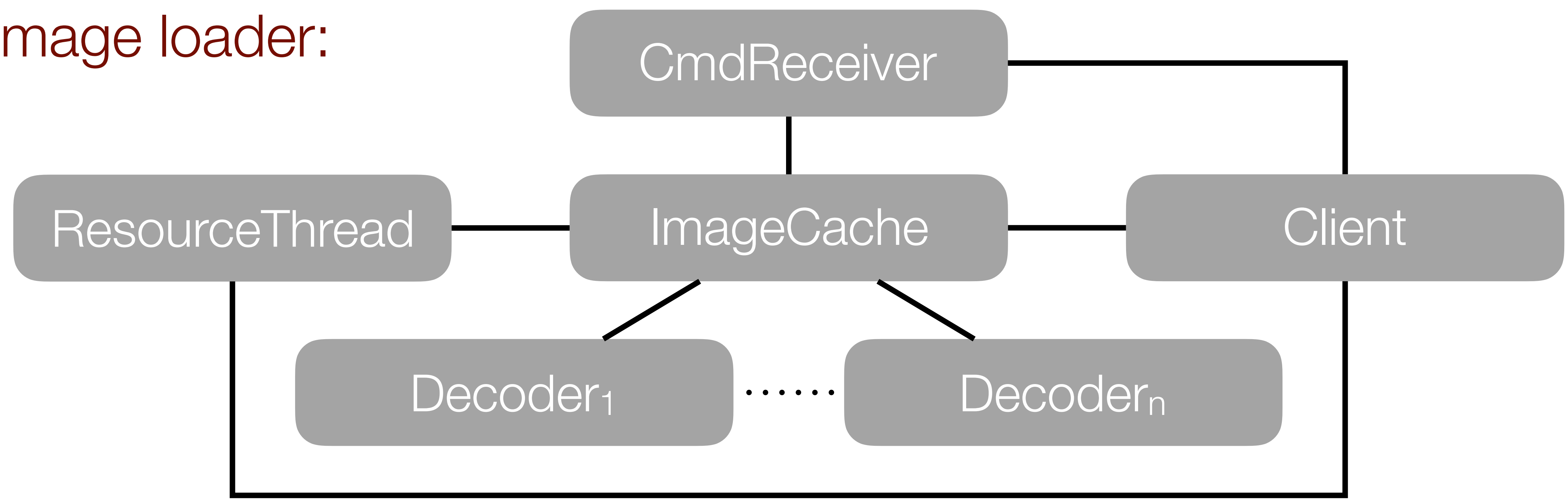

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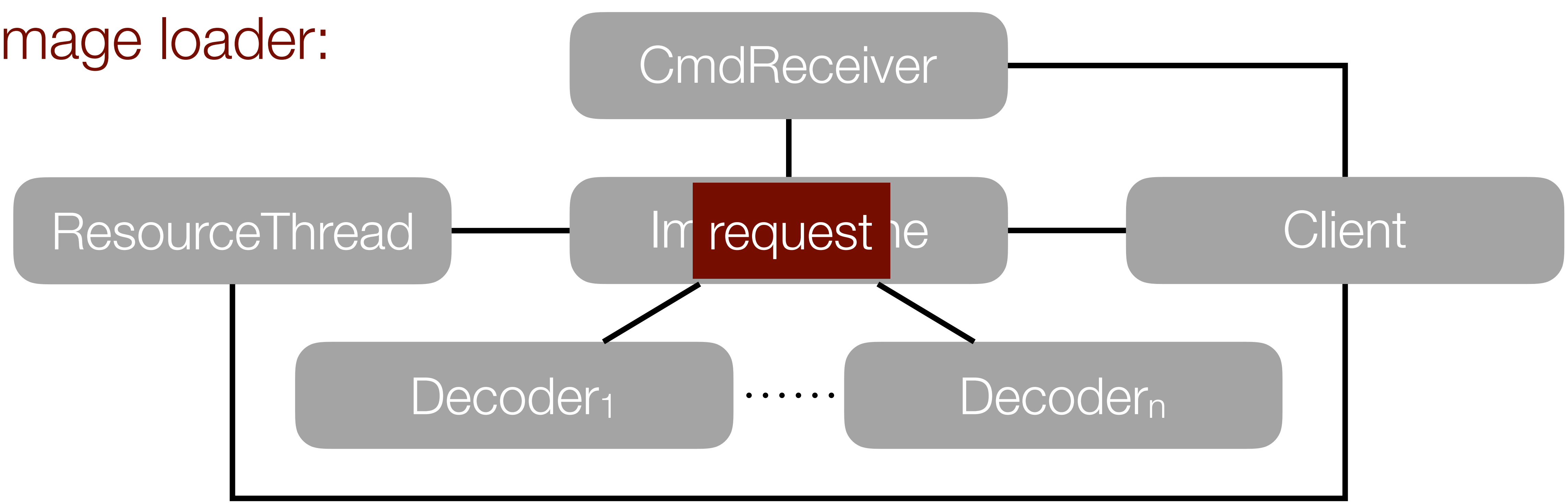

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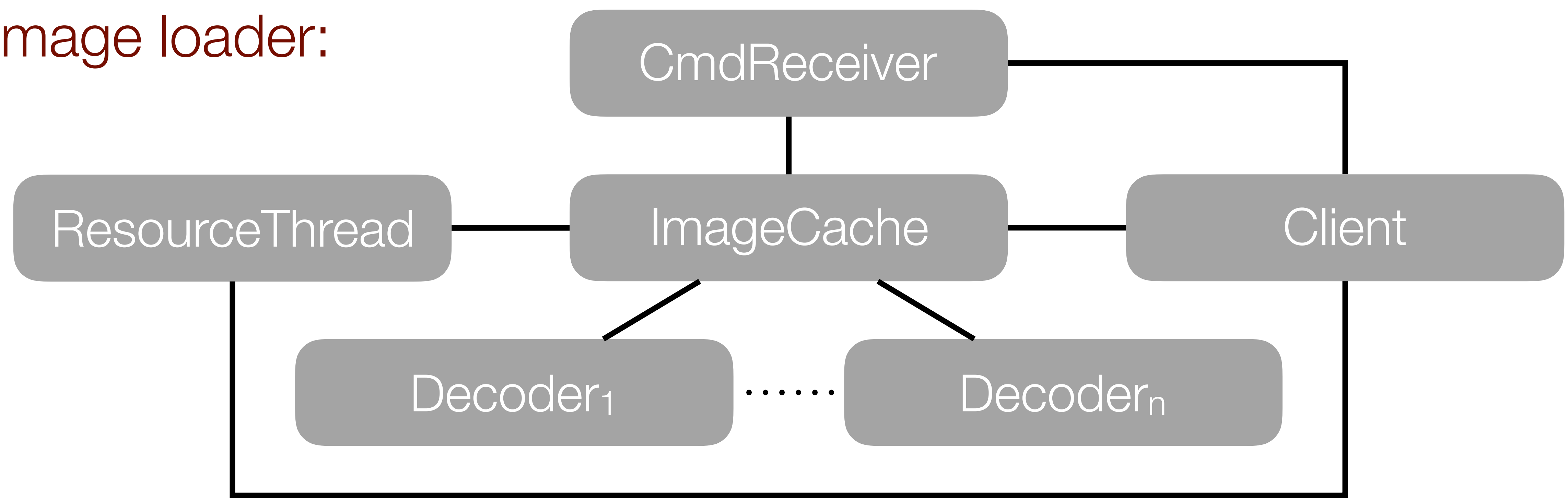

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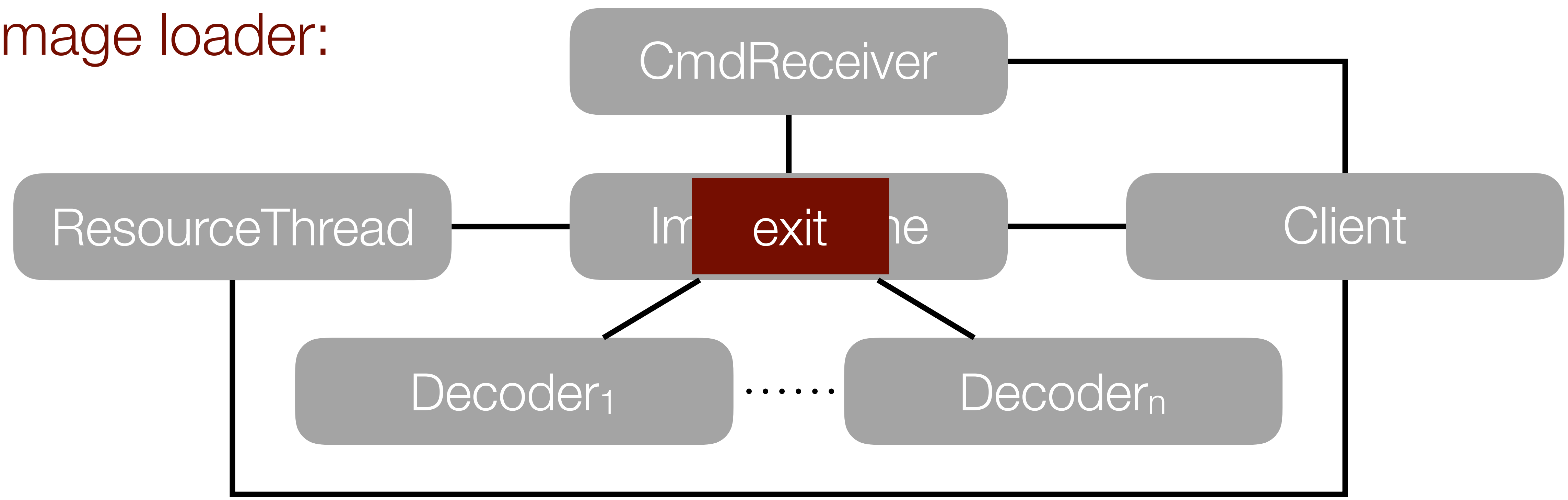

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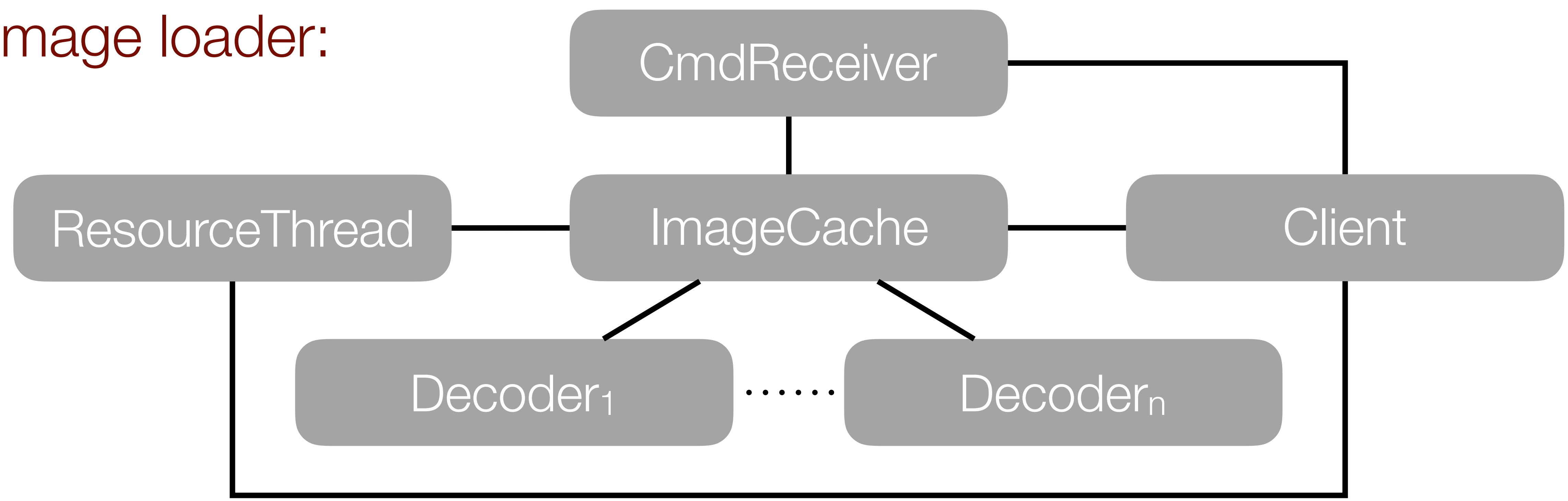

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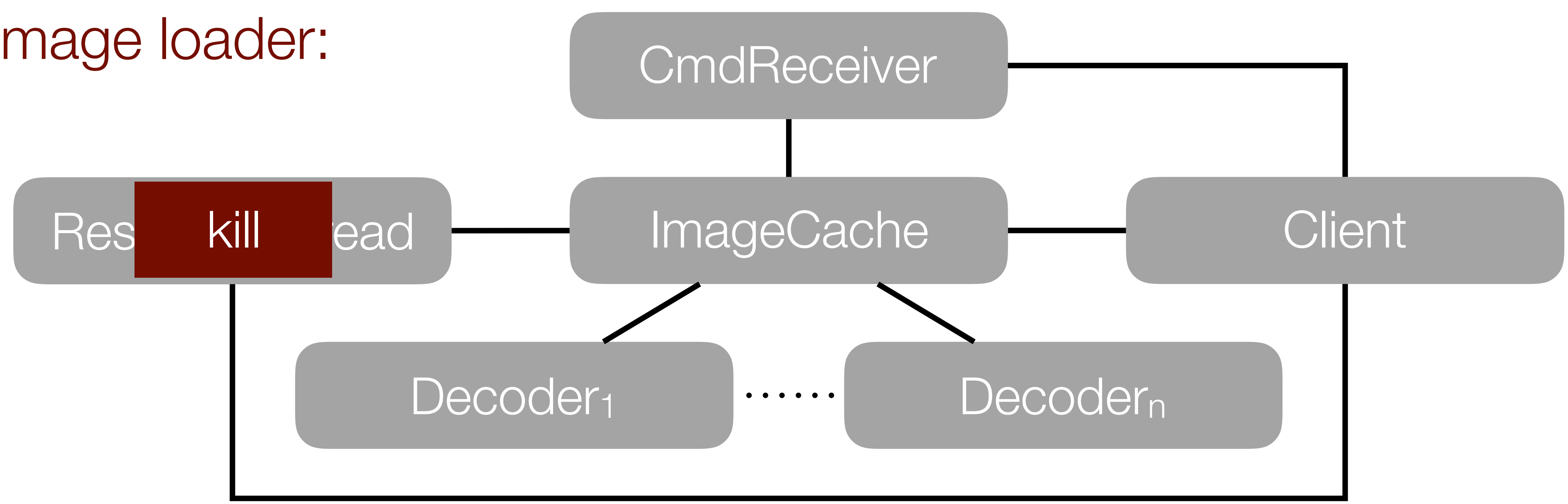

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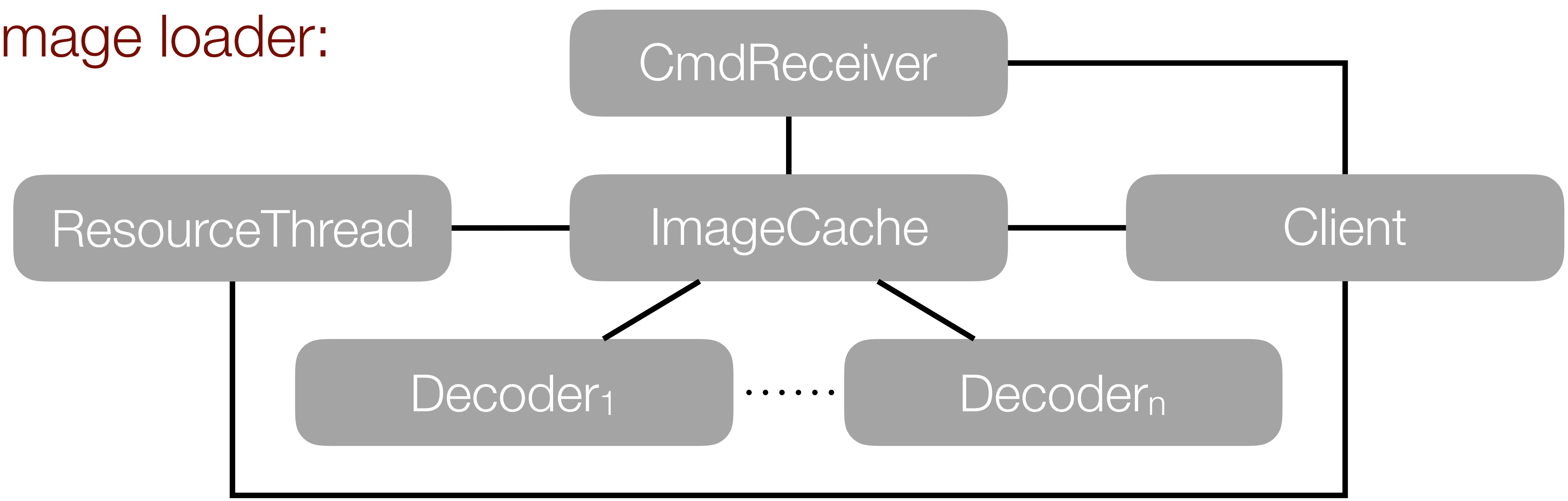

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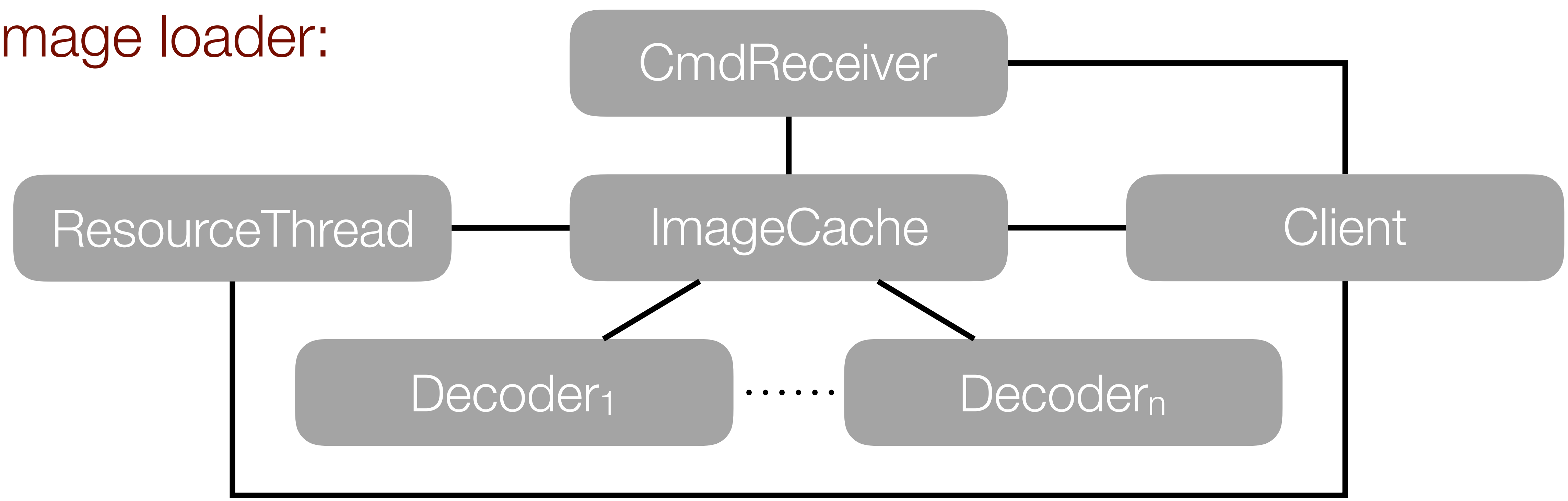

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- Example: enumeration for ImageCache

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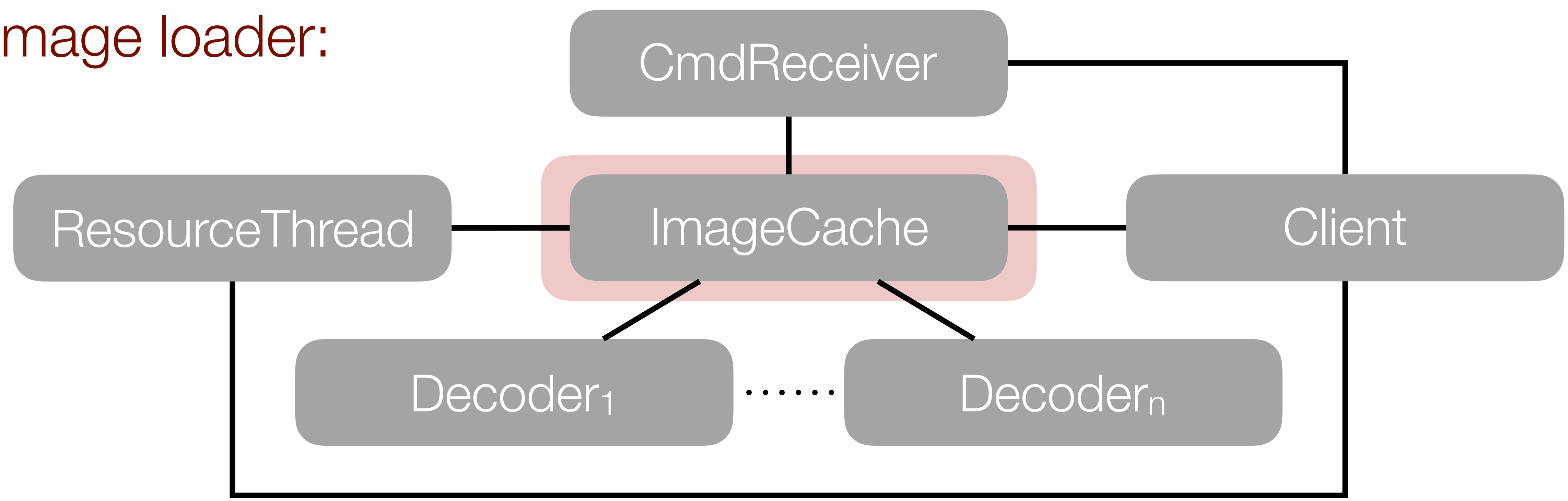

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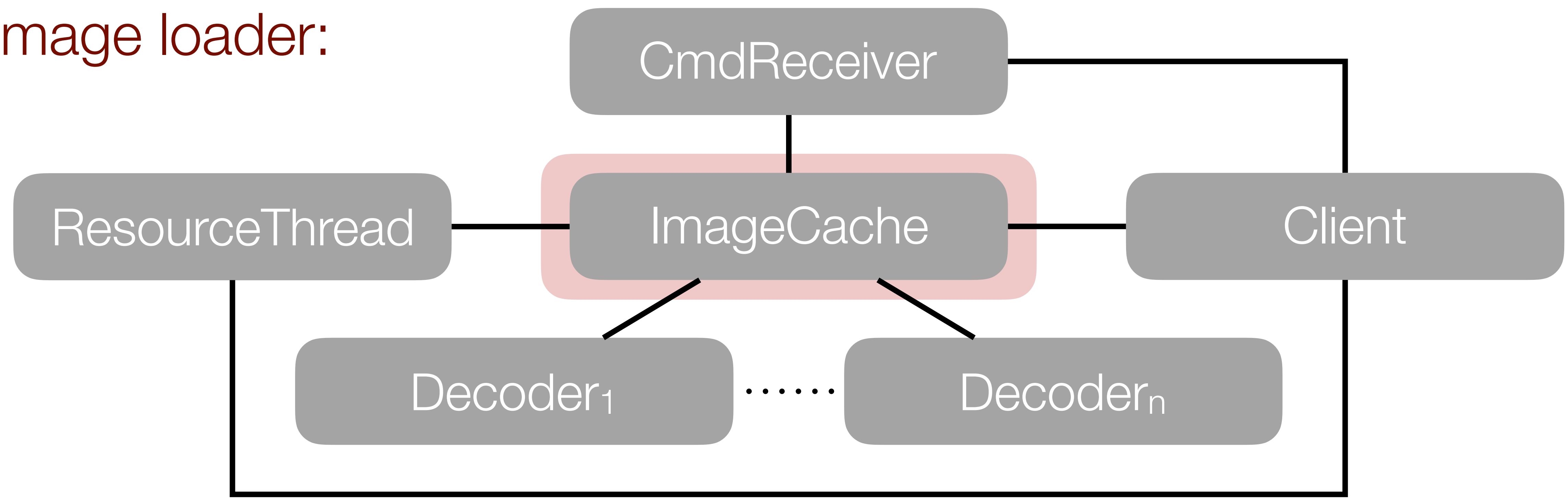

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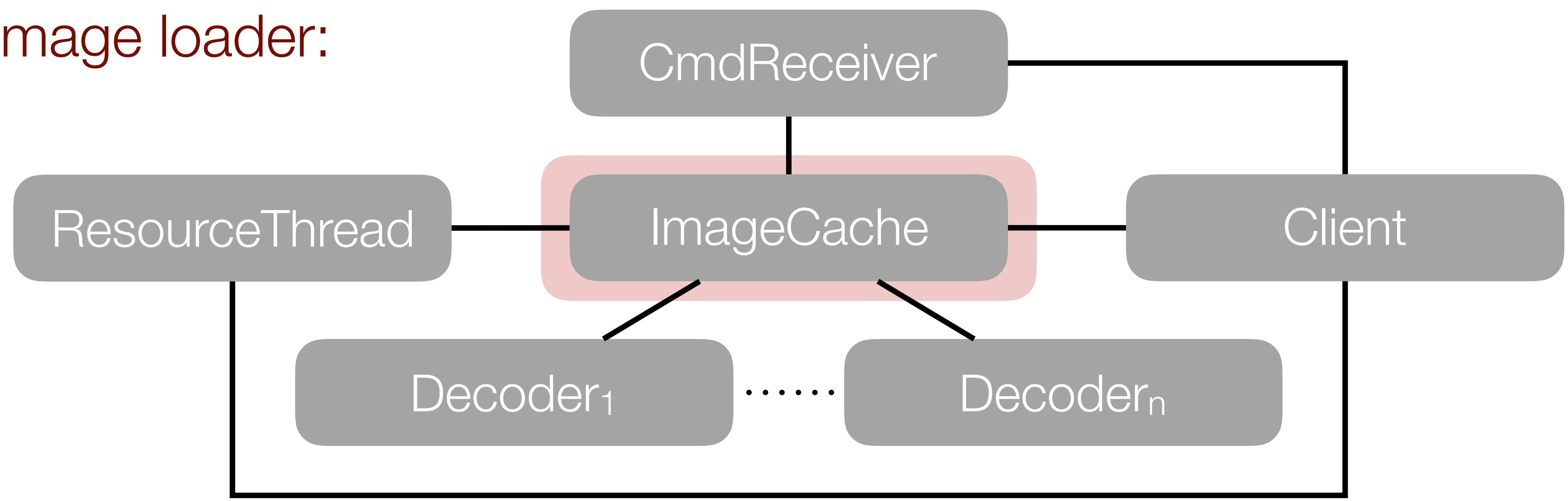

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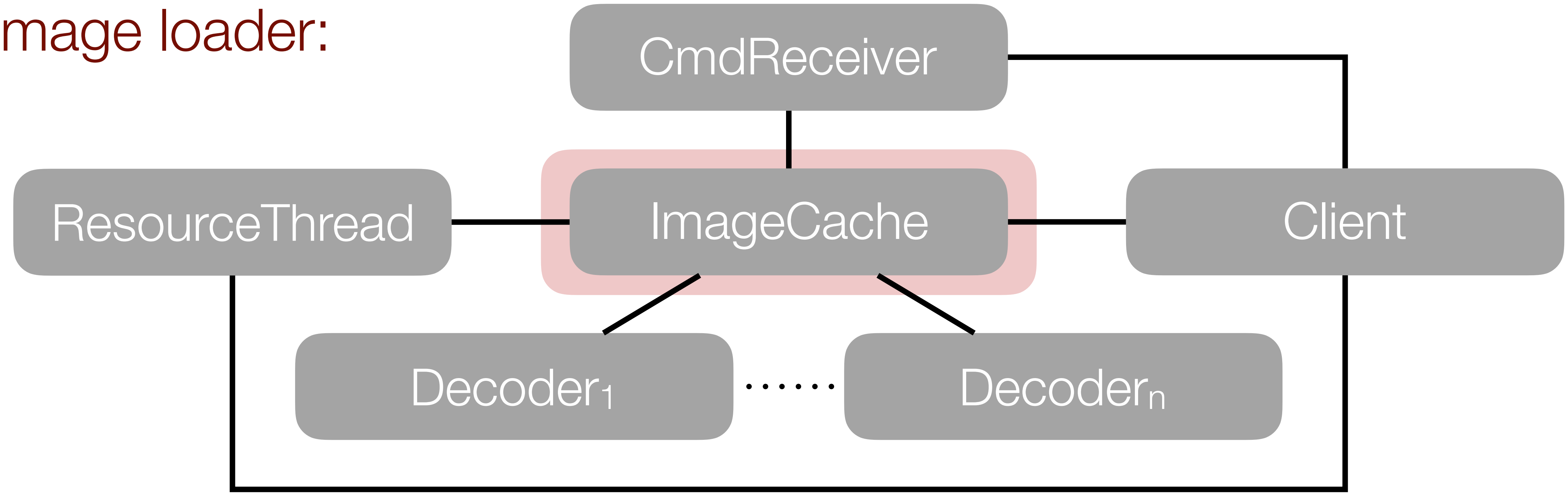

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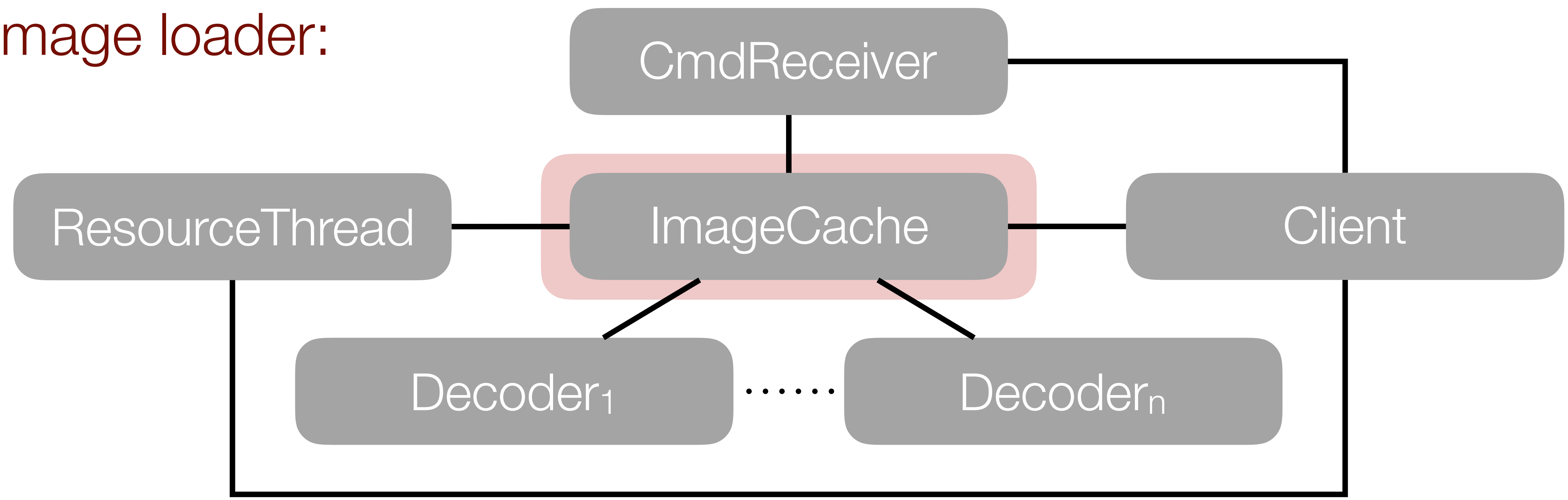

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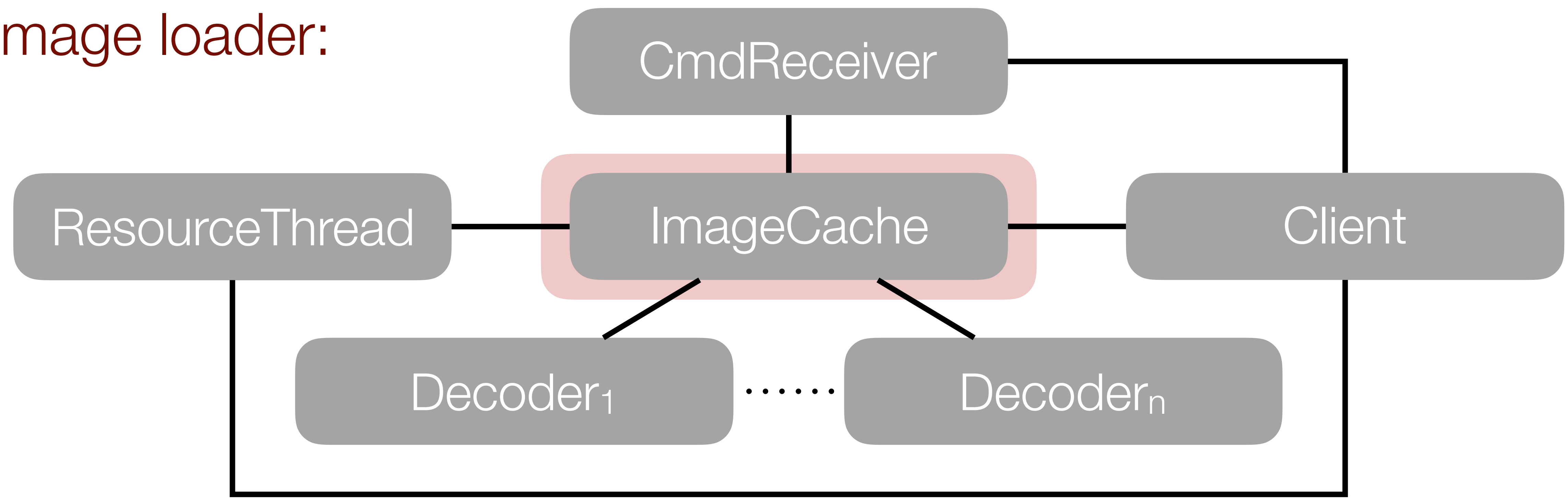

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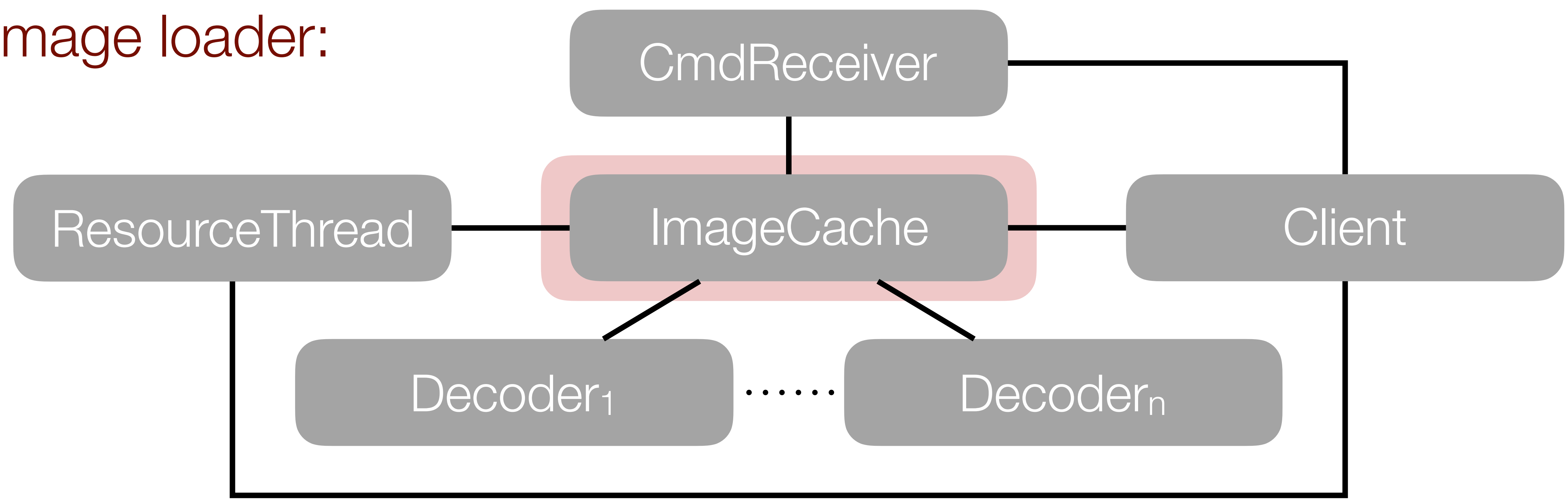

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implicit protocol

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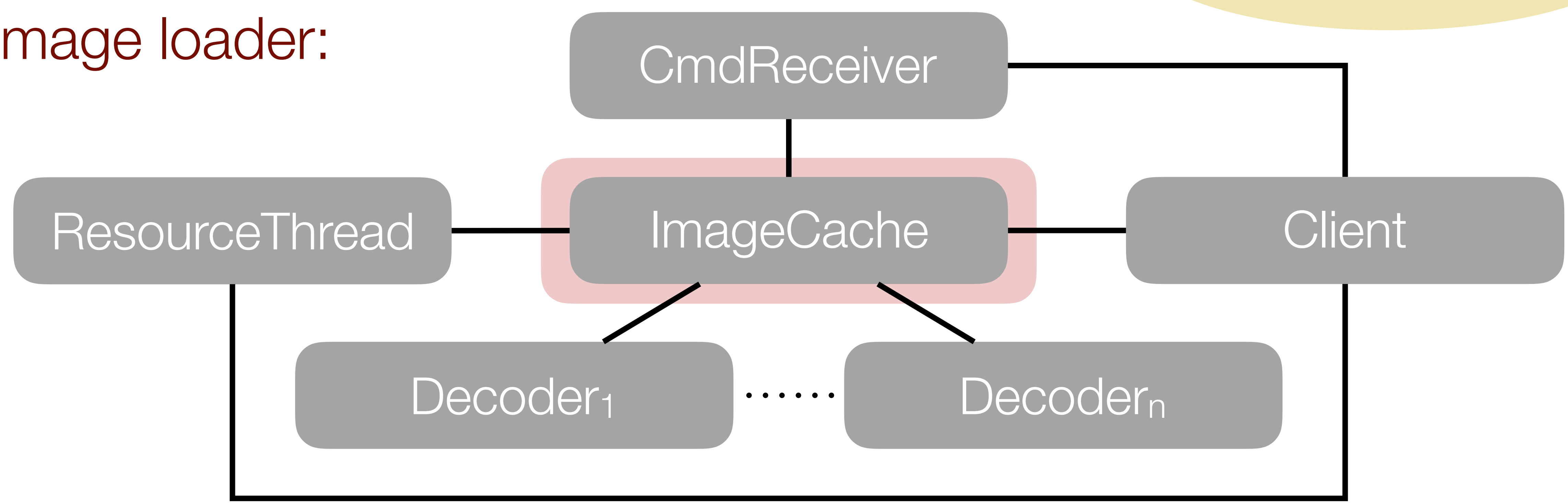

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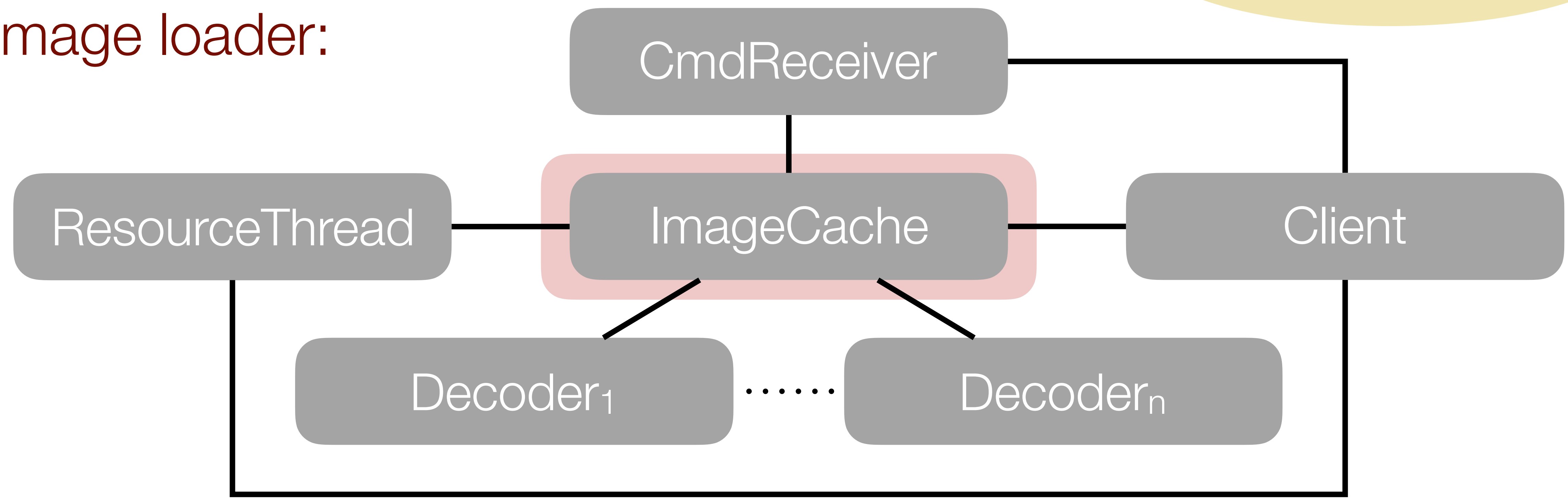

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- let’s use session types!

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 & & \oplus\{\overline{l_i : A_i}\} & \text{internal choice} \\
 & & A \multimap B & \text{channel input} \\
 & & A \otimes B & \text{channel output} \\
 & & \mathbf{1} & \text{termination}
\end{array}
$$

Session types

Session types define protocols of message exchange.

“protocol = sequence of actions”

A, B	$\triangleq$	$\&\{\overline{l_i : A_i}\}$	external choice
		$\oplus\{\overline{l_i : A_i}\}$	internal choice
		$A \multimap B$	channel input
		$A \otimes B$	channel output
		$\mathbf{1}$	termination

client
sends channel reference of
type A

Session types

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$$
\begin{array}{lcll}
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 & & A \otimes B & \text{channel output} \\
 & & \mathbf{1} & \text{termination}
\end{array}
$$

provider
sends channel reference of
type A

Session types

Session types define protocols of message exchange.

"protocol = sequence of actions"

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\begin{array}{lcll}
A, B & \triangleq & \&\{\overline{l_i : A_i}\} & \text{external choice} \\
 & & \oplus\{\overline{l_i : A_i}\} & \text{internal choice} \\
 & & A \multimap B & \text{channel input} \\
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		$\mathbf{1}$	termination

provider terminates

Session types

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		$\oplus\{\overline{l_i : A_i}\}$	internal choice
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 & & \oplus\{\overline{l_i : A_i}\} & \text{internal choice} \\
 & & A \multimap B & \text{channel input} \\
 & & A \otimes B & \text{channel output} \\
 & & \mathbf{1} & \text{termination} \\
 & & T \to A & \text{value input} \\
 & & T \times A & \text{value output} \\
T & \triangleq & \mathsf{int} \mid \mathsf{string} \mid \ldots &
\end{array}
$$

Session types

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support communication of values

$$
\begin{array}{llll}
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\end{array}
$$

Session type for image loader

$$
\begin{array}{lll l}
A, B & \triangleq & \&\{\overline{l_i : A_i}\} & \text{external choice} \\
 & & \oplus\{\overline{l_i : A_i}\} & \text{internal choice} \\
 & & A \multimap B & \text{channel input} \\
 & & A \otimes B & \text{channel output} \\
 & & \mathbf{1} & \text{termination} \\
 & & T \to A & \text{value input} \\
 & & T \times A & \text{value output} \\
T & \triangleq & \mathsf{int} \mid \mathsf{string} \mid \ldots &
\end{array}
$$

Session type for image loader

A, B	$\triangleq$	$\&\{\overline{l_i : A_i}\}$	external choice
		$\oplus\{\overline{l_i : A_i}\}$	internal choice
		$A \multimap B$	channel input
		$A \otimes B$	channel output
		$\mathbf{1}$	termination
		$T \rightarrow A$	value input
		$T \times A$	value output
T	$\triangleq$	$\mathsf{int} \mid \mathsf{string} \mid \ldots$	

$\mathsf{ImgCacheCmd} =$

Session type for image loader

$$
\begin{array}{lcll}
A, B & \triangleq & \&\{\overline{l_i : A_i}\} & \text{external choice} \\
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 & & A \multimap B & \text{channel input} \\
 & & A \otimes B & \text{channel output} \\
 & & \mathbf{1} & \text{termination} \\
 & & T \rightarrow A & \text{value input} \\
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\end{array}
$$

$\mathsf{ImgCacheCmd} = \& \, \{$

$\}$

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T & \triangleq & \mathsf{int} \mid \mathsf{string} \mid \ldots &
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$$

$$
\begin{array}{ll}
\mathsf{ImgCacheCmd} = \& & \{\mathsf{RequestImage} : \\
 & \quad \ldots \\
 & \quad \mathsf{Exit} : \\
 & \\
 & \}
\end{array}
$$

Session type for image loader

$$
\begin{array}{lcll}
A, B & \triangleq & \&\{\overline{l_i : A_i}\} & \text{external choice} \\
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\begin{aligned}
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& \ldots \\
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\} &
\end{aligned}
$$

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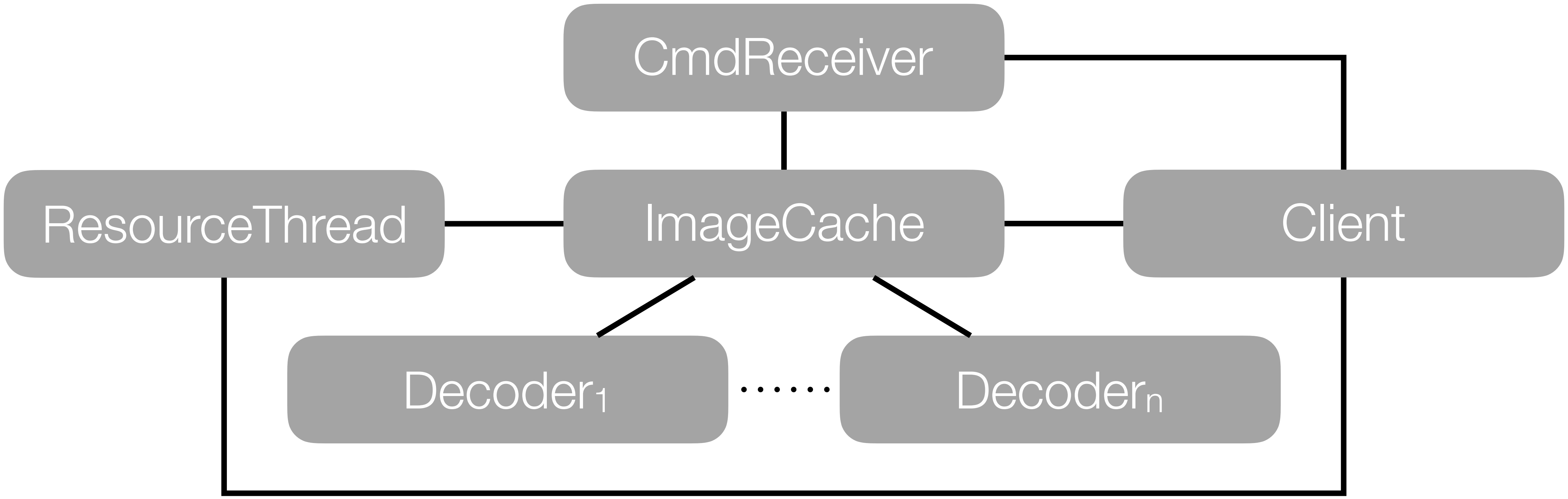
&\qquad\qquad \mathsf{Done} : \mathsf{ResourceThread} \otimes \mathbf{1}\}\\
\}&
\end{aligned}
$$



Session type for image loader

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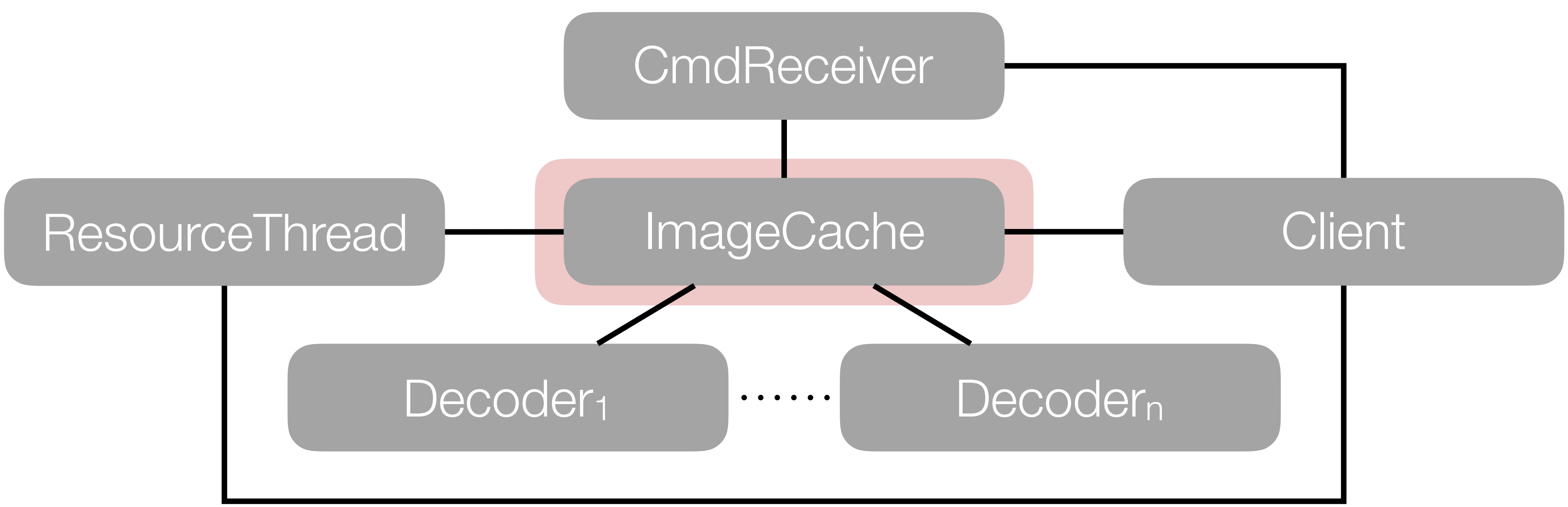
\begin{aligned}
\mathsf{ImgCacheCmd} = \&\{&\mathsf{RequestImage} : \mathsf{string} \to \mathsf{Requester} \multimap \mathsf{ImgCacheCmd},\\
&\ldots\\
&\mathsf{Exit} : \oplus\{\mathsf{Running} : \mathsf{ImgCacheCmd},\\
&\qquad\qquad \mathsf{Done} : \mathsf{ResourceThread} \otimes \mathbf{1}\}\\
\}&
\end{aligned}
$$

ImageCache:



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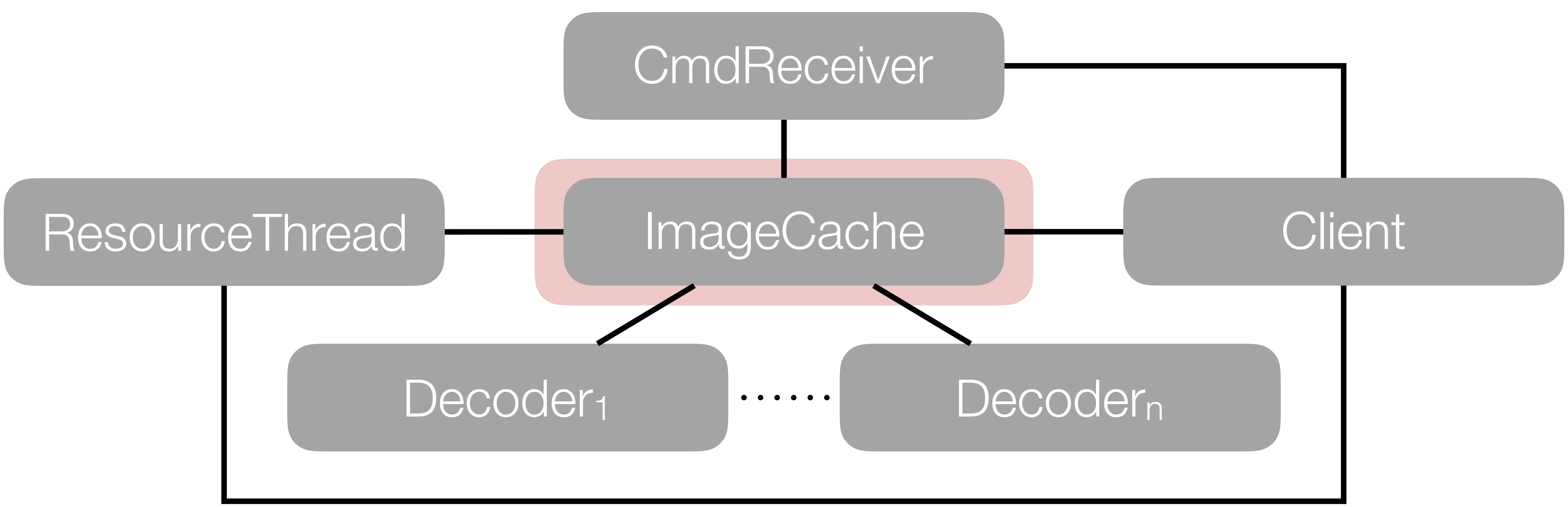
ImageCache: $\mathsf{ImgCacheCmd}$



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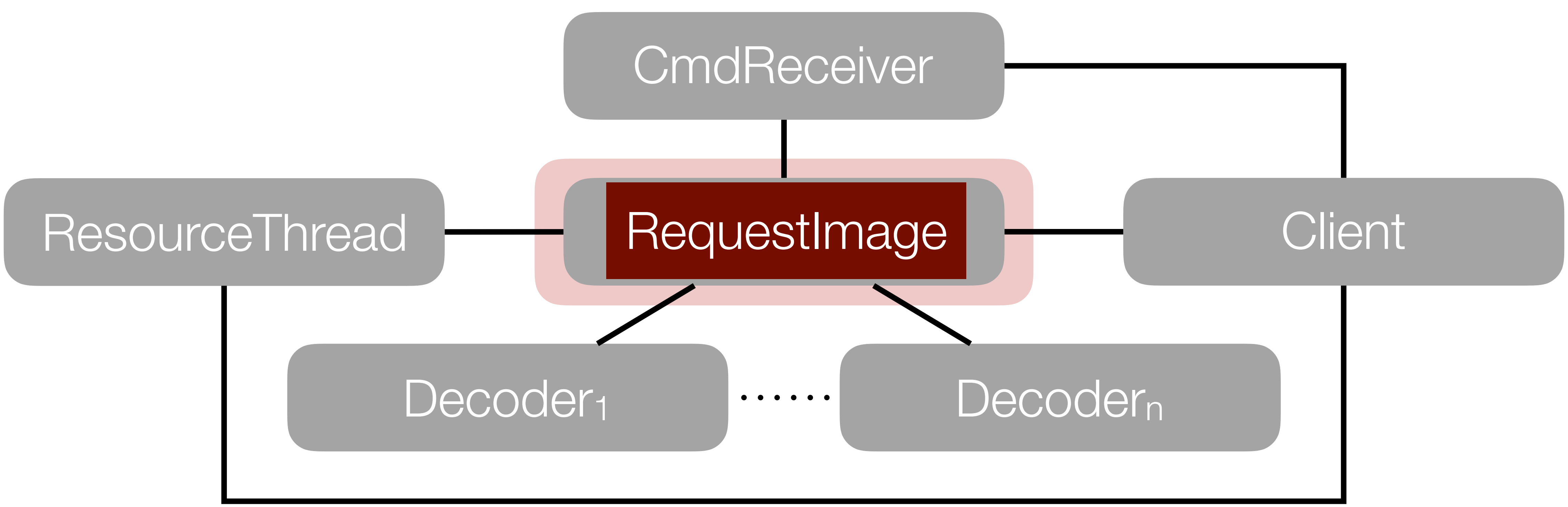

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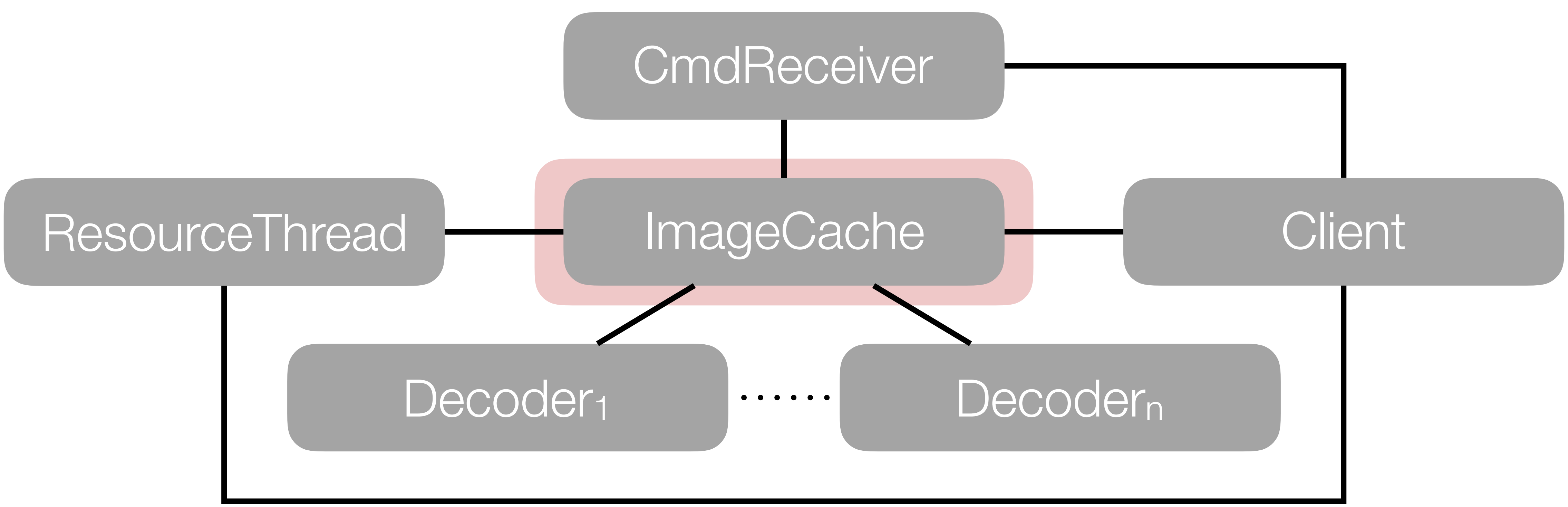

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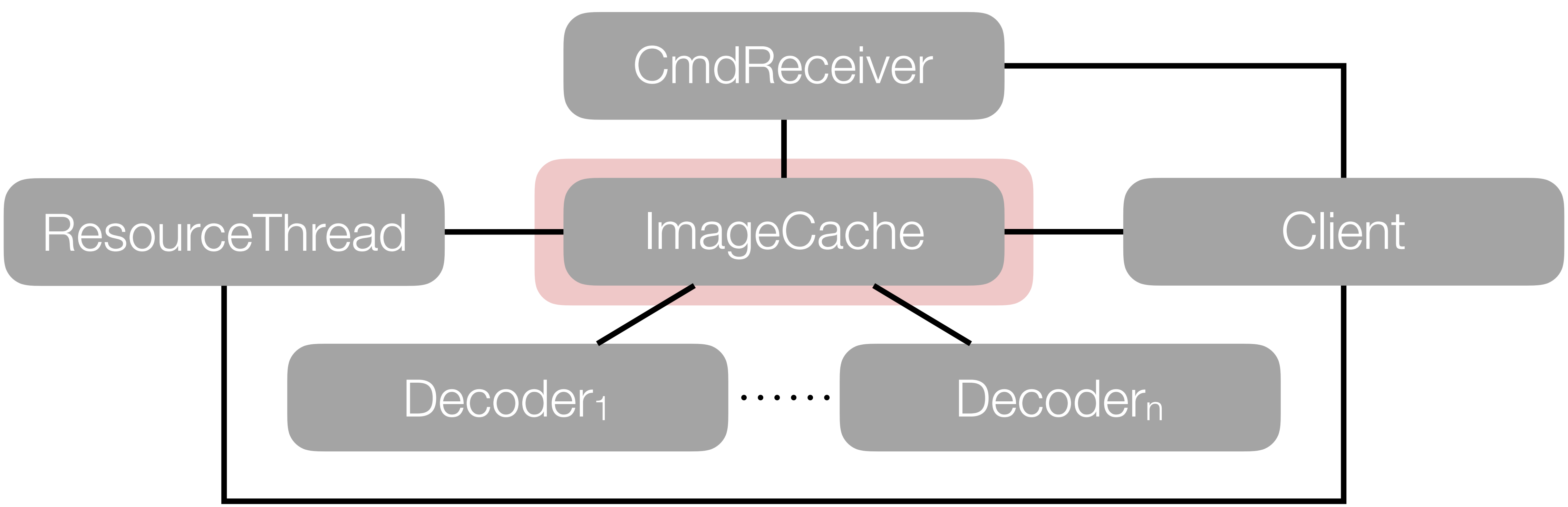
ImageCache: $\mathsf{string} \to \mathsf{Requester} \multimap \mathsf{ImgCacheCmd}$



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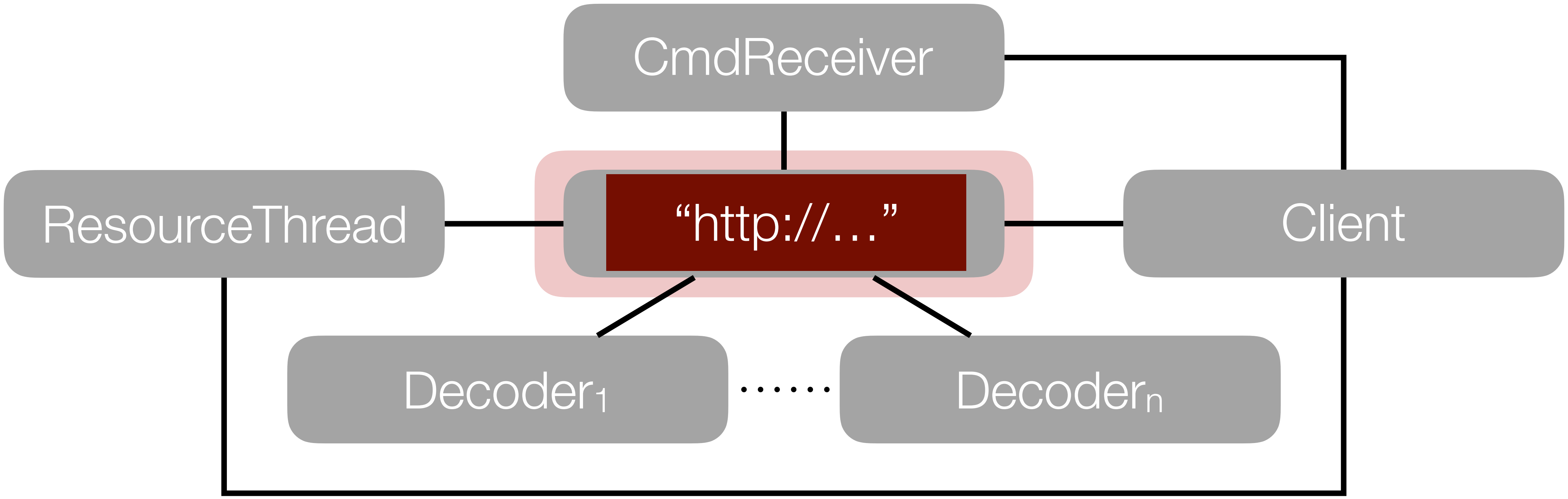

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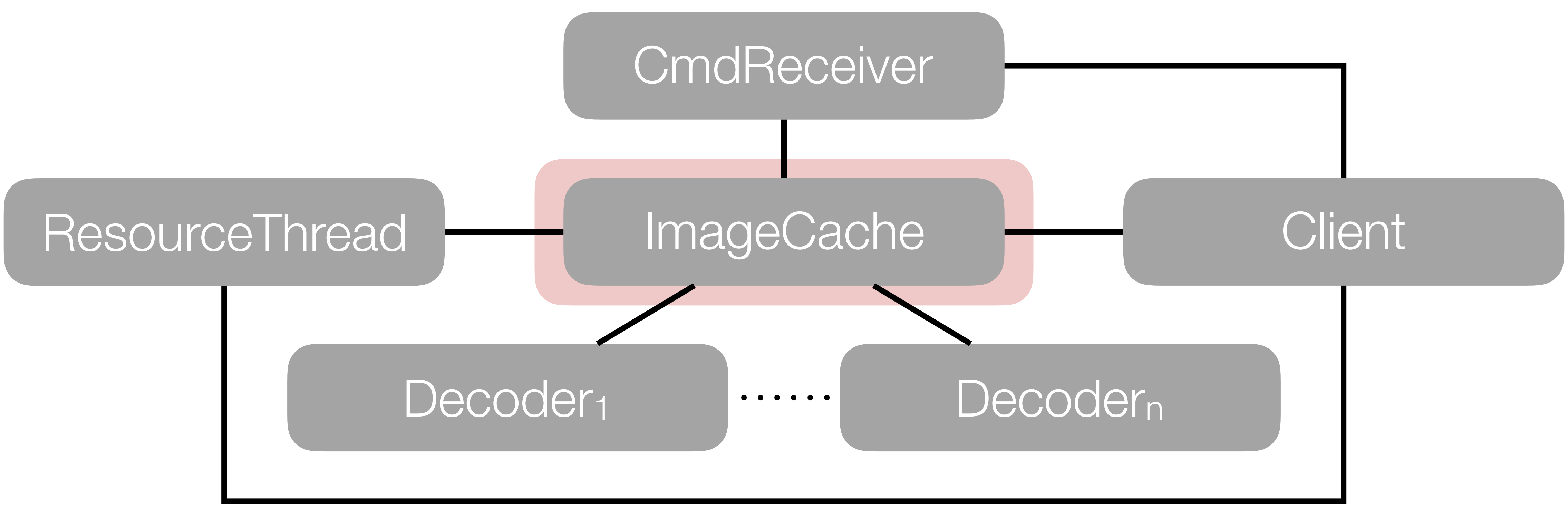

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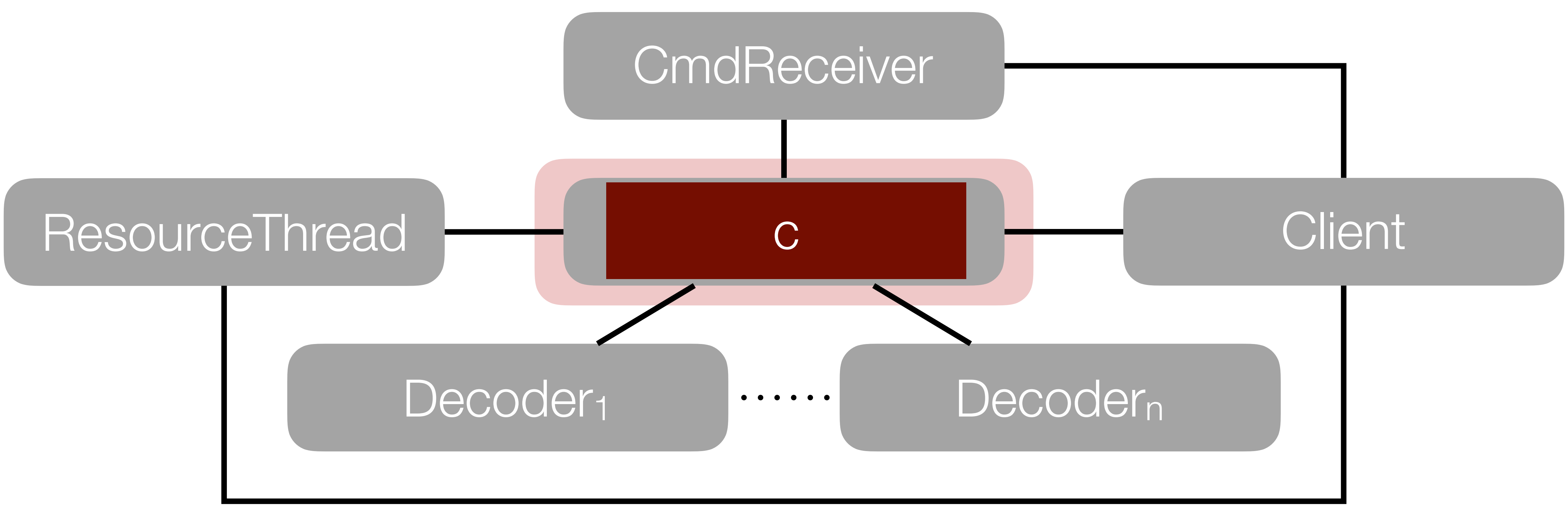

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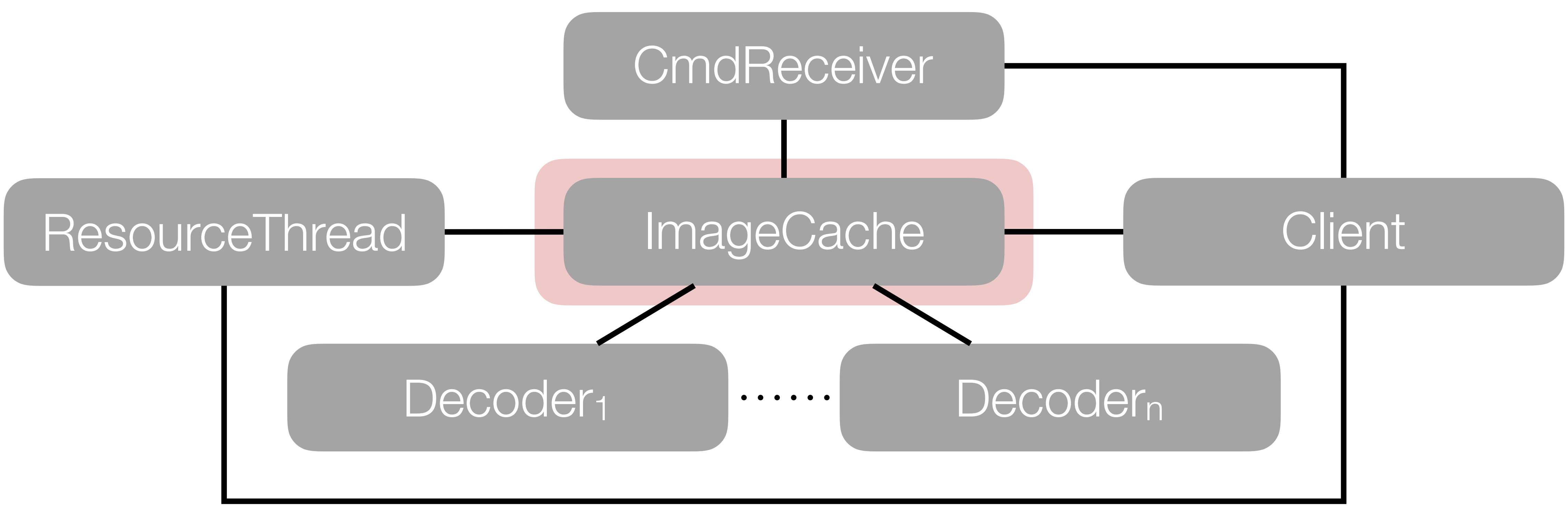

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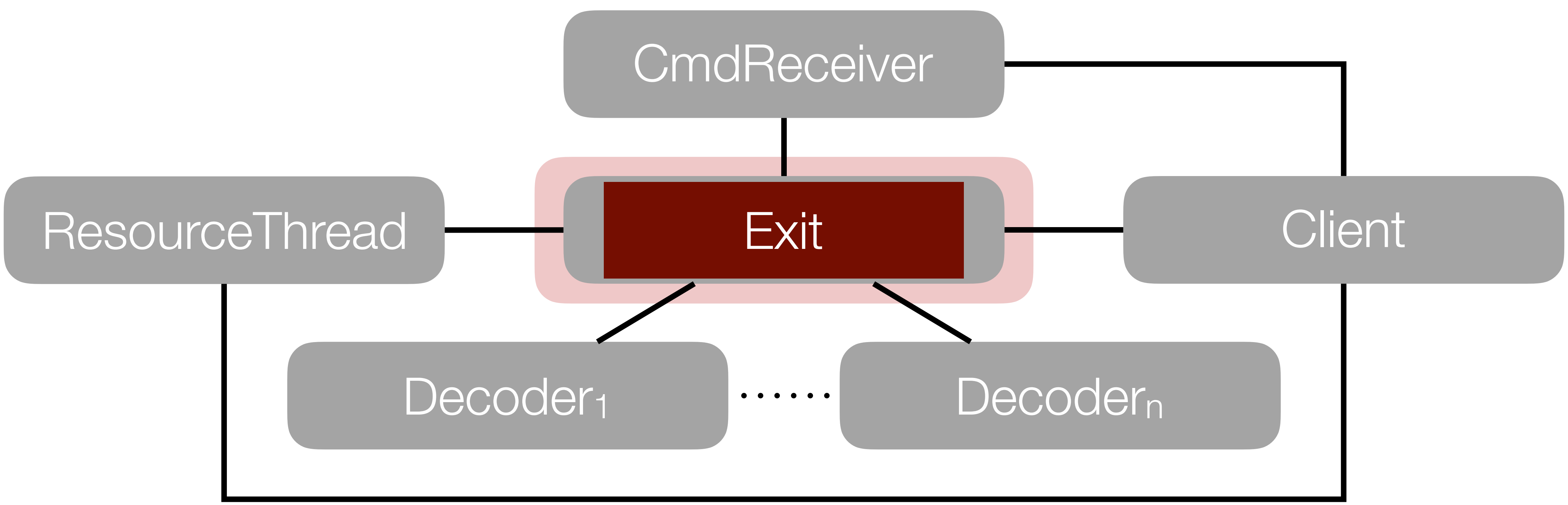

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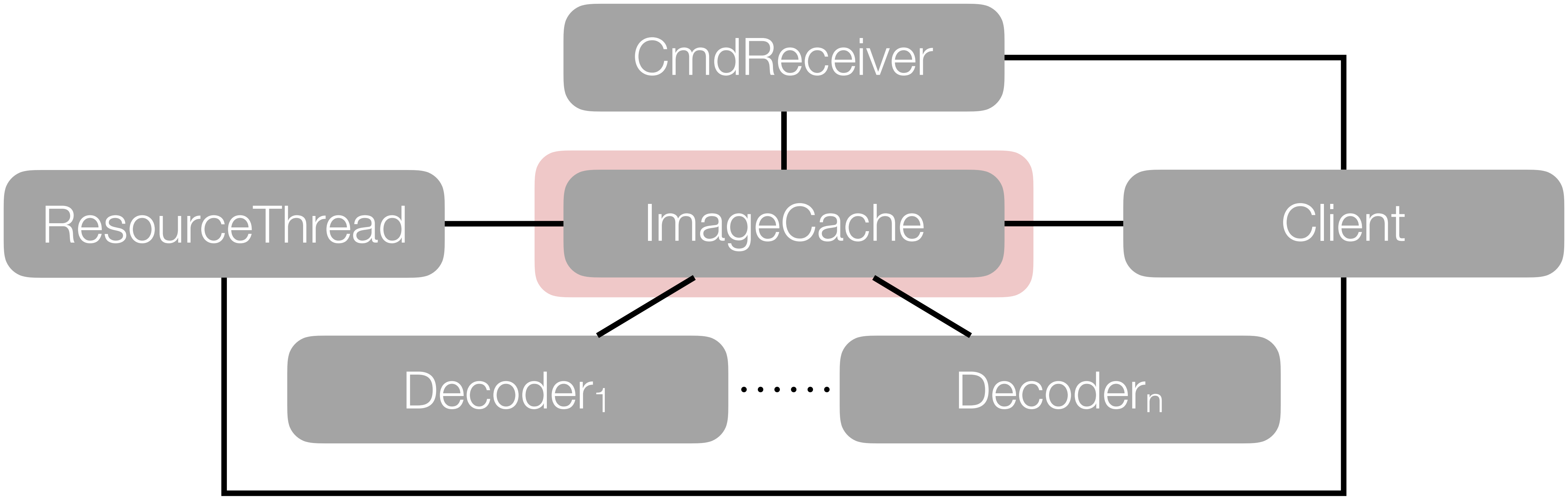

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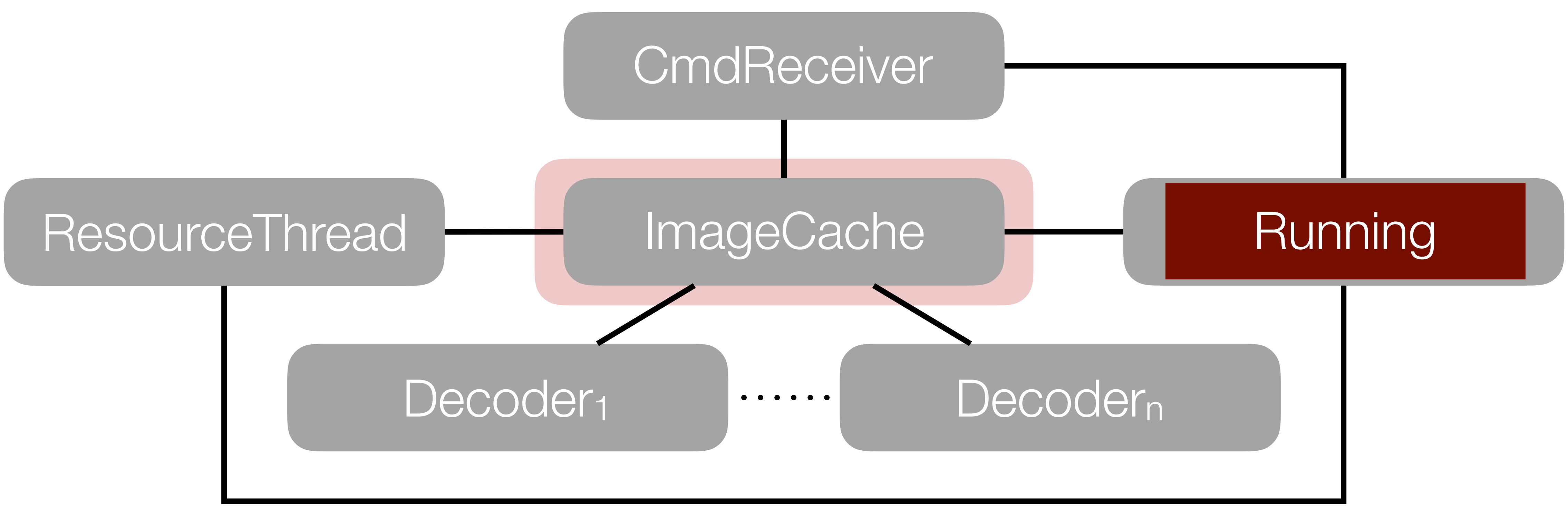

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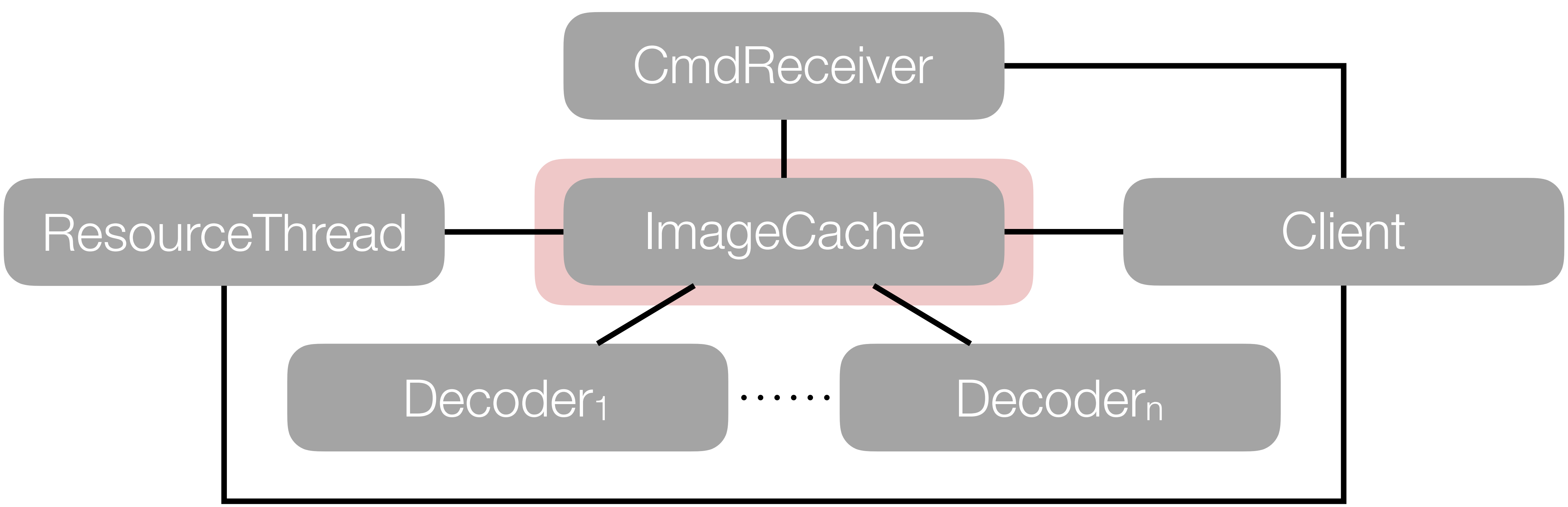
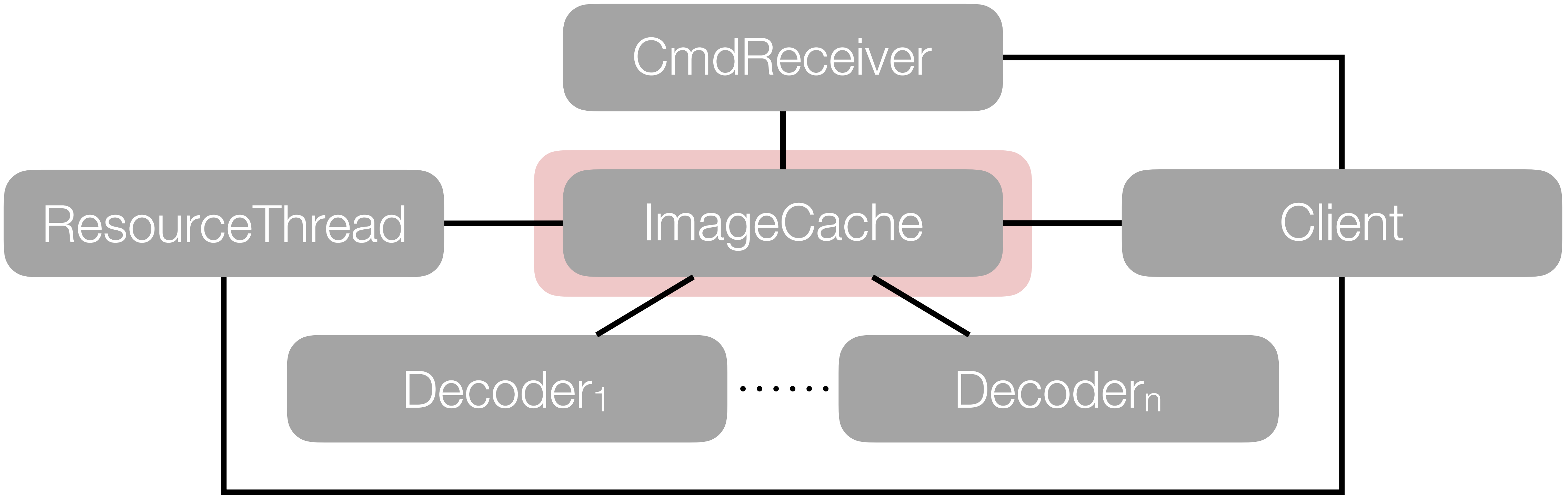


Session type for image loader

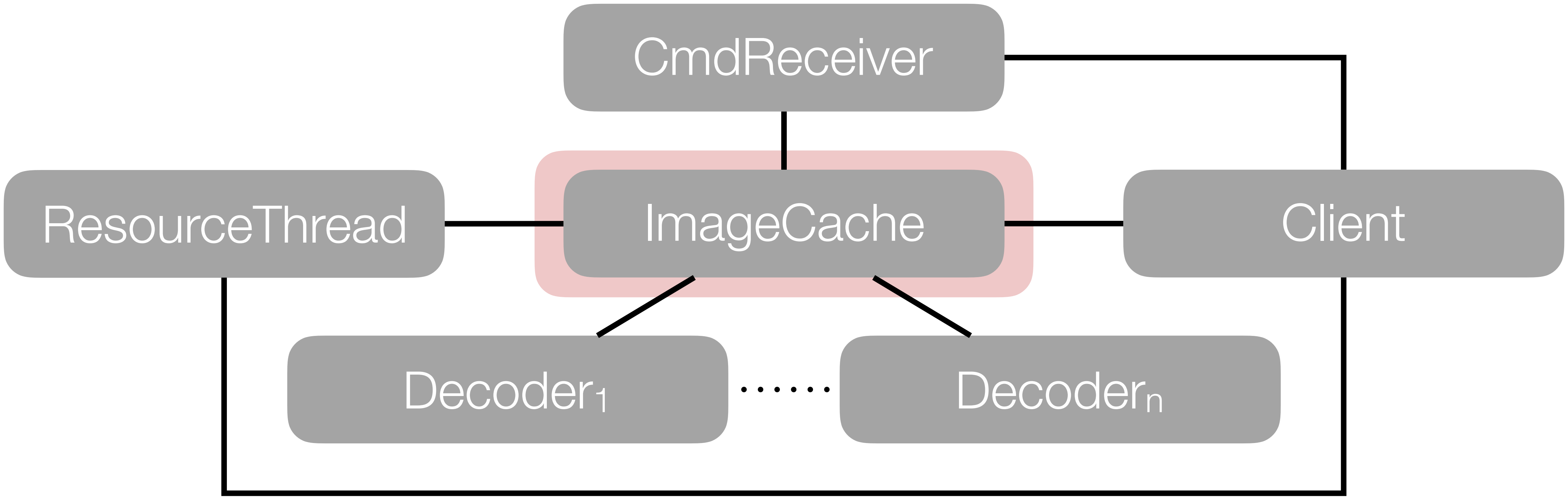
ImageCache: ImgCacheCmd



Session type for image loader

components change their session type along with message exchange

ImageCache: $\mathsf{ImgCacheCmd}$



Taking stock

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➡ **Session types are the types of message-passing concurrency.**

Session types in research and practice

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Research

- active research area since inception in 90s [Honda 1993]
- logical reconstruction based on linear logic, providing strong guarantees [Caires & Pfenning 2010, Wadler 2012]
- extension of logical session types to sharing [Balzer & Pfenning ICFP 2017, Balzer et al. CONCUR 2018, Balzer et al. ESOP 2019]

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Practice

- Lightweight integration of session types or session libraries (with varying static guarantees) into Scala, Java, Haskell, OCaml, Go, Rust, Python.
- Collaboration with Mozilla Research on integrating our work.

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Logic-based shared session types

Linear logic session types

Linear logic session types

Provide strong guarantees:

- Data-race-freedom
- Protocol adherence (a.k.a. session fidelity, preservation)
- Deadlock-freedom (a.k.a. progress)

Linear logic session types

exactly one client

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exactly one client

processes graph forms
a tree at run-time

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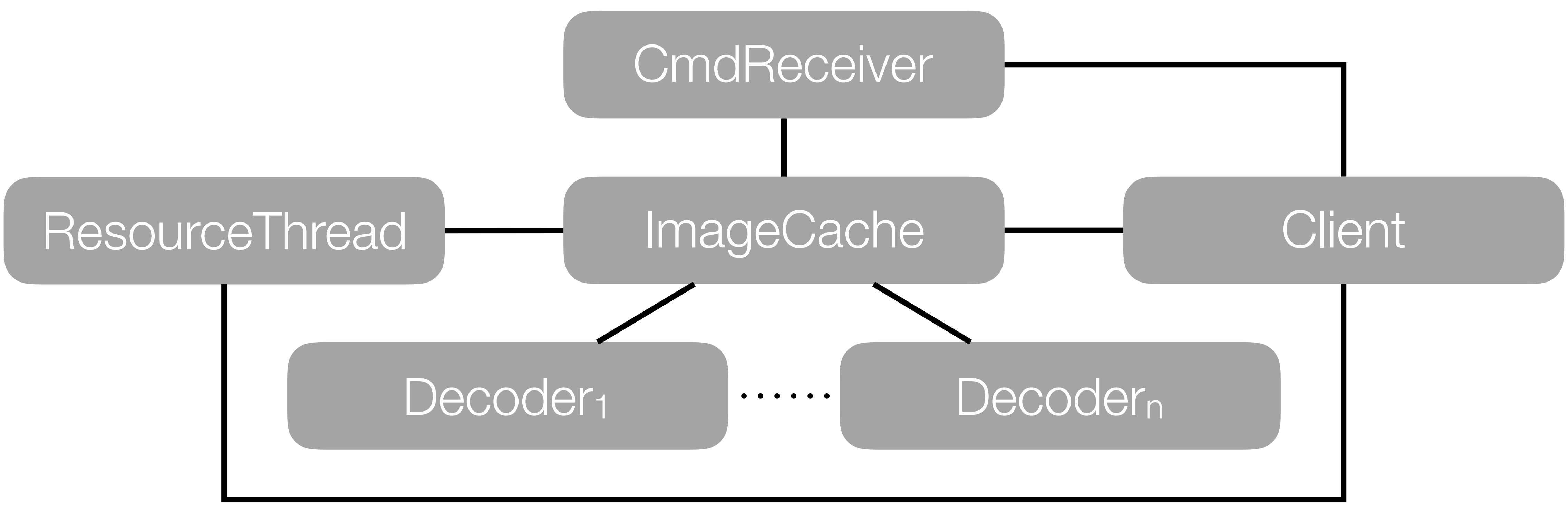

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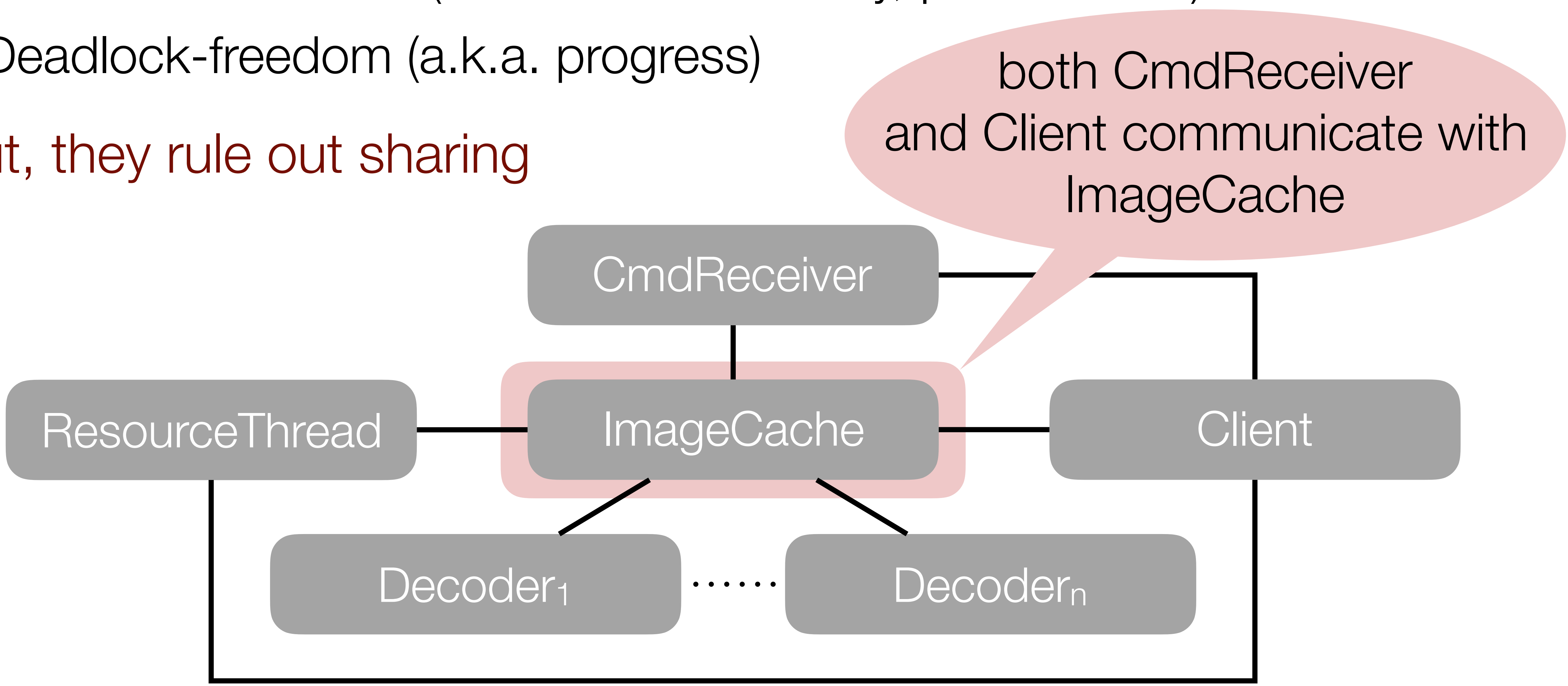

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→ Linear logic session types cannot accommodate certain practical programming scenarios.

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➡ Linear logic session types cannot accommodate certain practical programming scenarios.

➡ Let's introduce sharing while maintaining above guarantees.

Challenges of sharing

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$$
\begin{aligned}
\mathsf{ImgCacheCmd} = \mathbin{\&} \{ & \mathsf{RequestImage} : \mathsf{string} \rightarrow \mathsf{Requester} \multimap \mathsf{ImgCacheCmd}, \\
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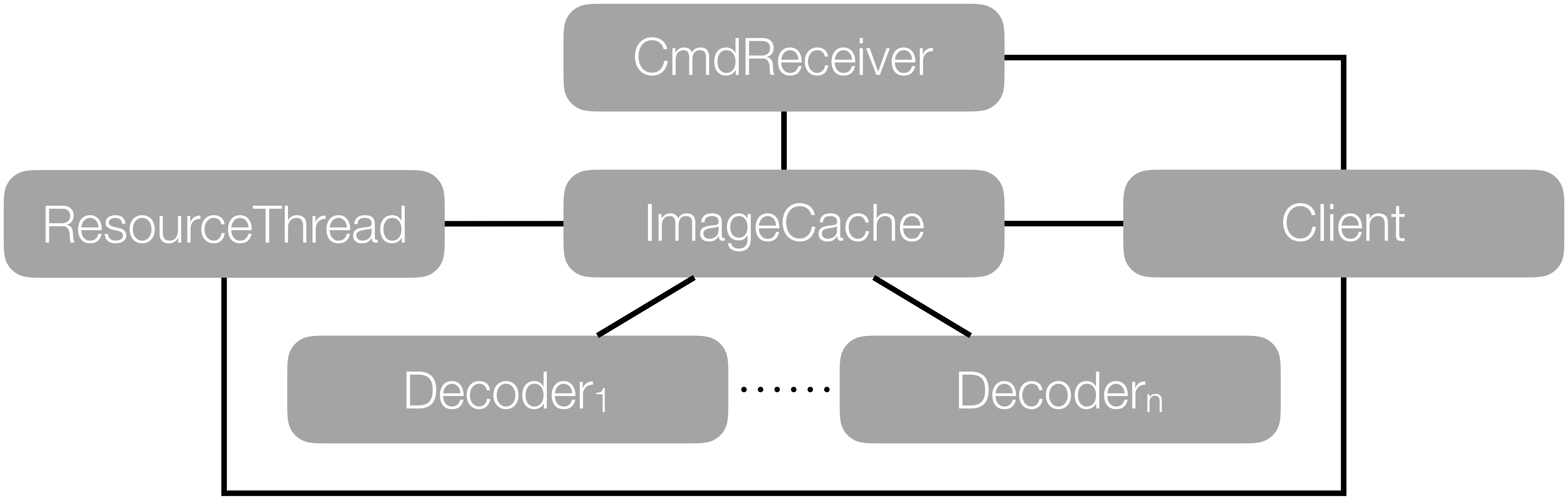

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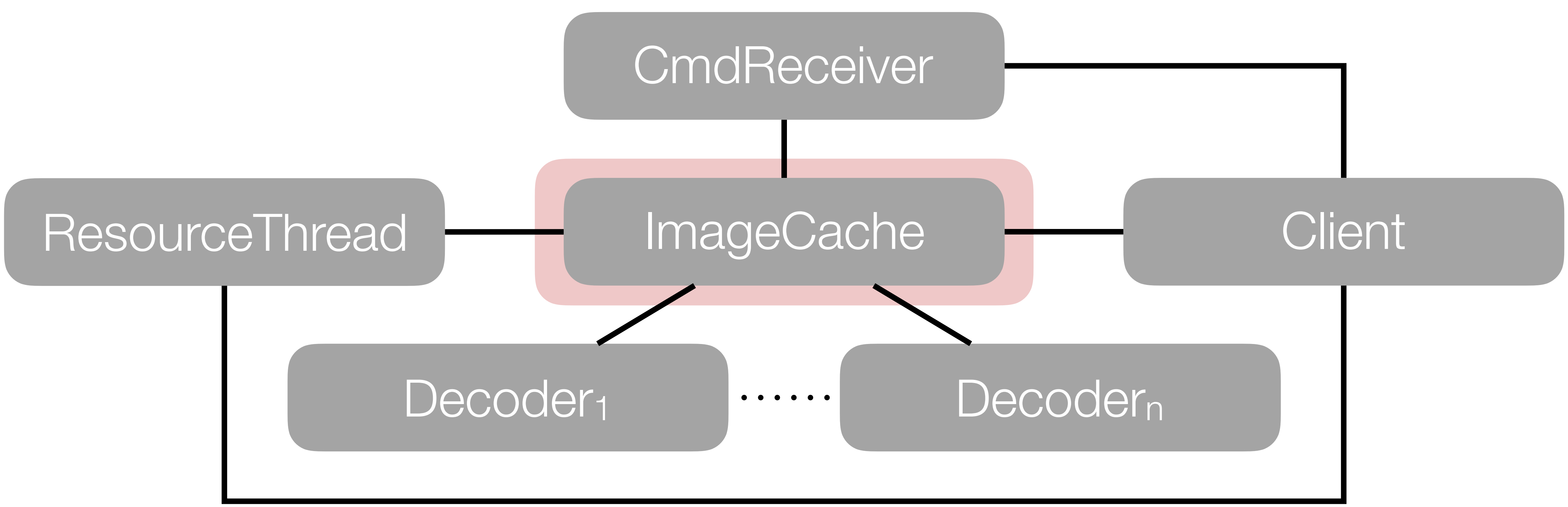
$$
\begin{aligned}
\mathsf{ImgCacheCmd} = \&\, \{ & \mathsf{RequestImage} : \mathsf{string} \rightarrow \mathsf{Requester} \multimap \mathsf{ImgCacheCmd}, \\
& \ldots \\
& \mathsf{Exit} : \oplus \{ \mathsf{Running} : \mathsf{ImgCacheCmd}, \\
& \qquad\qquad \mathsf{Done} : \mathsf{ResourceThread} \otimes \mathbf{1} \} \\
\}
\end{aligned}
$$

ImageCache: $\mathsf{ImgCacheCmd}$



Challenges of sharing

$$\begin{aligned}\mathsf{ImgCacheCmd} = \& \{&\mathsf{RequestImage} : \mathsf{string} \to \mathsf{Requester} \multimap \mathsf{ImgCacheCmd},\\ &\ldots\\ &\mathsf{Exit} : \oplus \{\mathsf{Running} : \mathsf{ImgCacheCmd},\\ &\qquad\qquad \mathsf{Done} : \mathsf{ResourceThread} \otimes \mathbf{1}\}\\ \}&\end{aligned}$$

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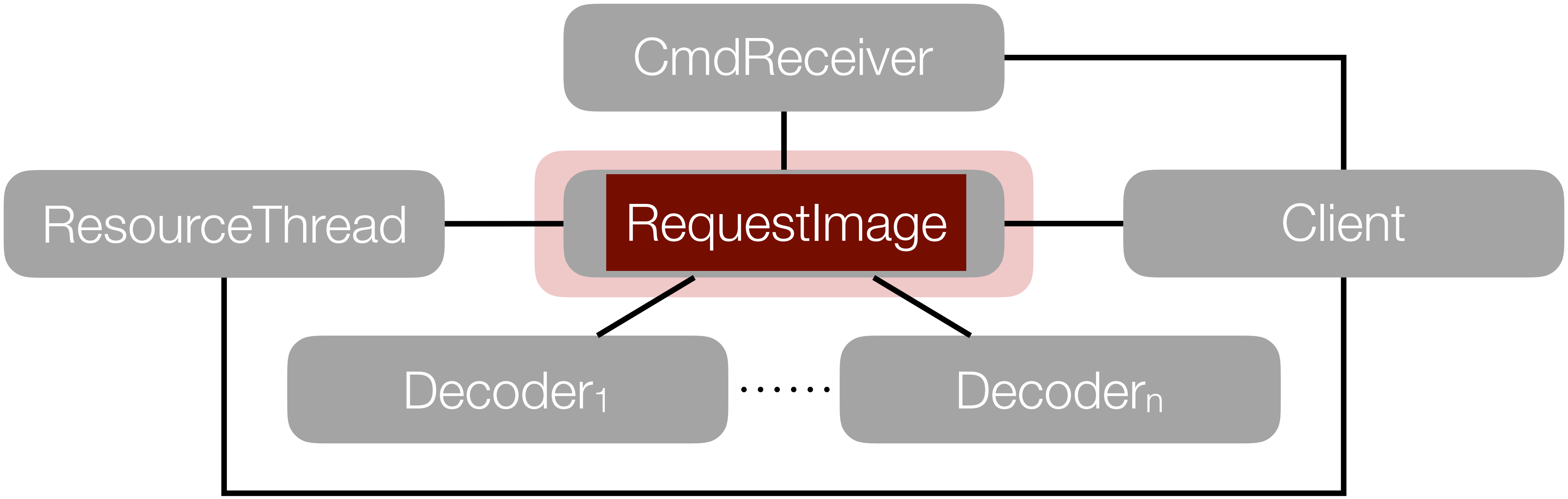

Challenges of sharing

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\begin{aligned}
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&\ldots\\
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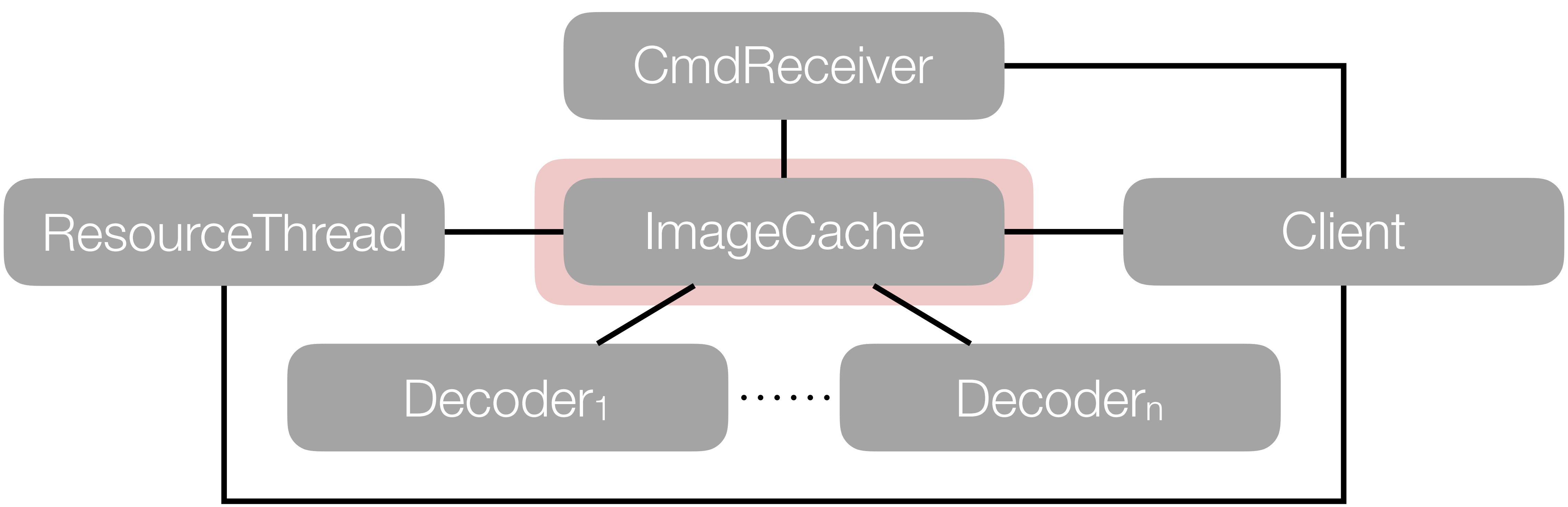

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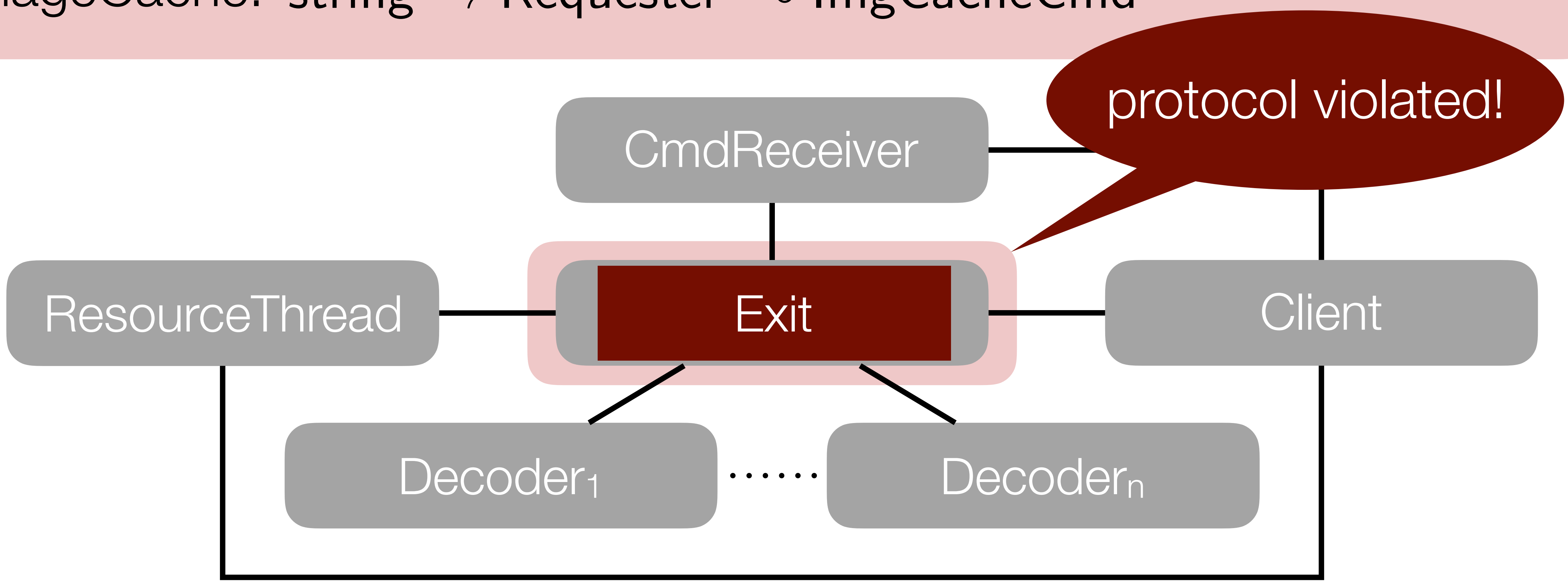

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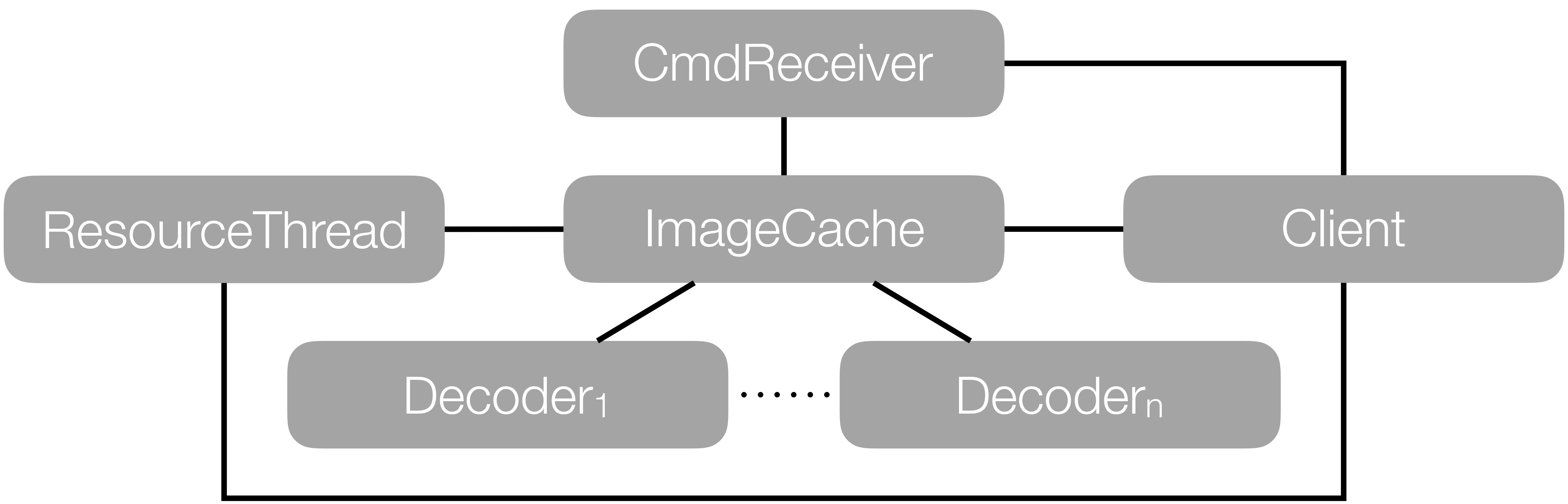
How to restore protocol adherence in the presence of sharing (a.k.a. aliasing)?



Idea: acquire-release

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Clients of shared channels must communicate along that channel in mutual exclusion from each other.

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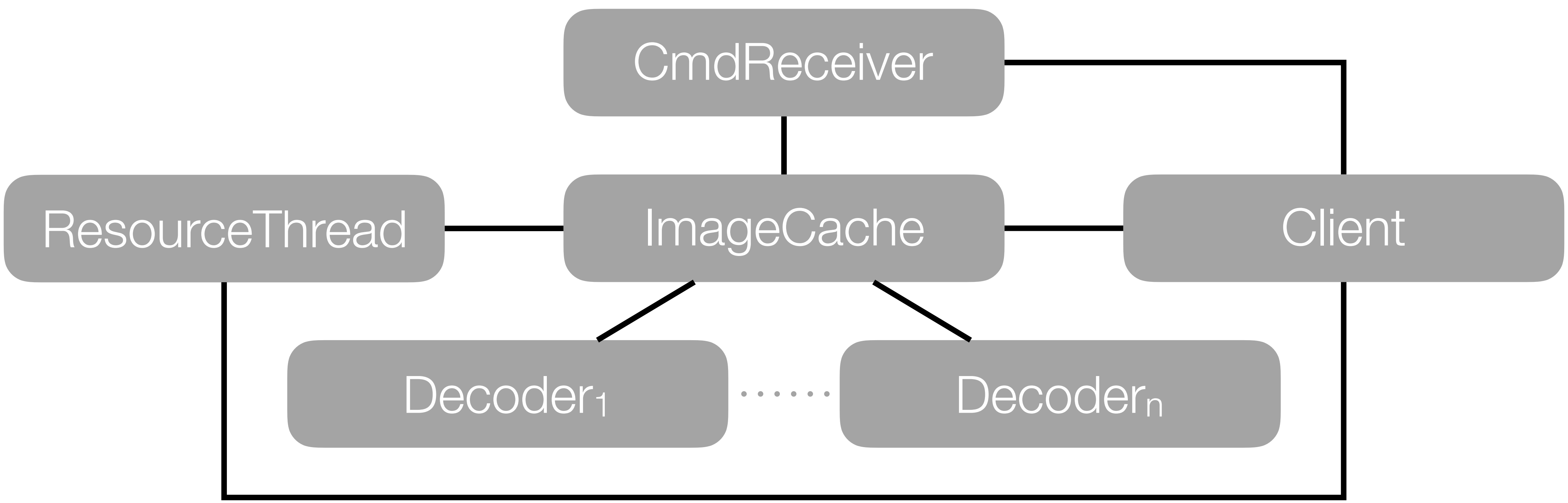

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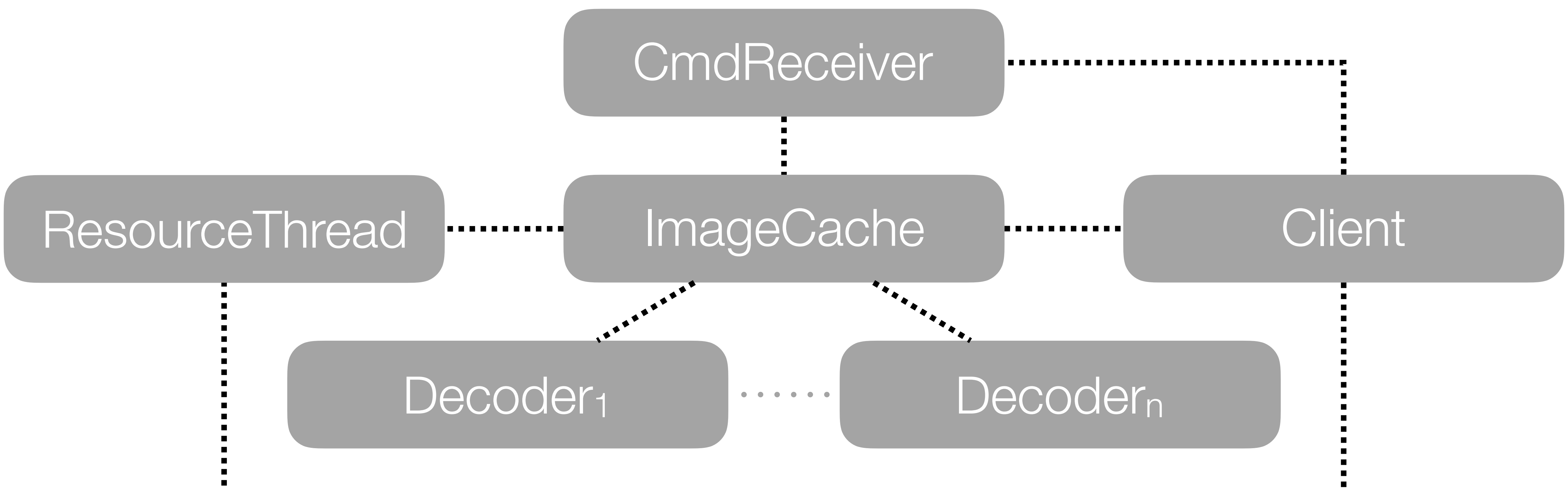

Legend: ······· shared channel

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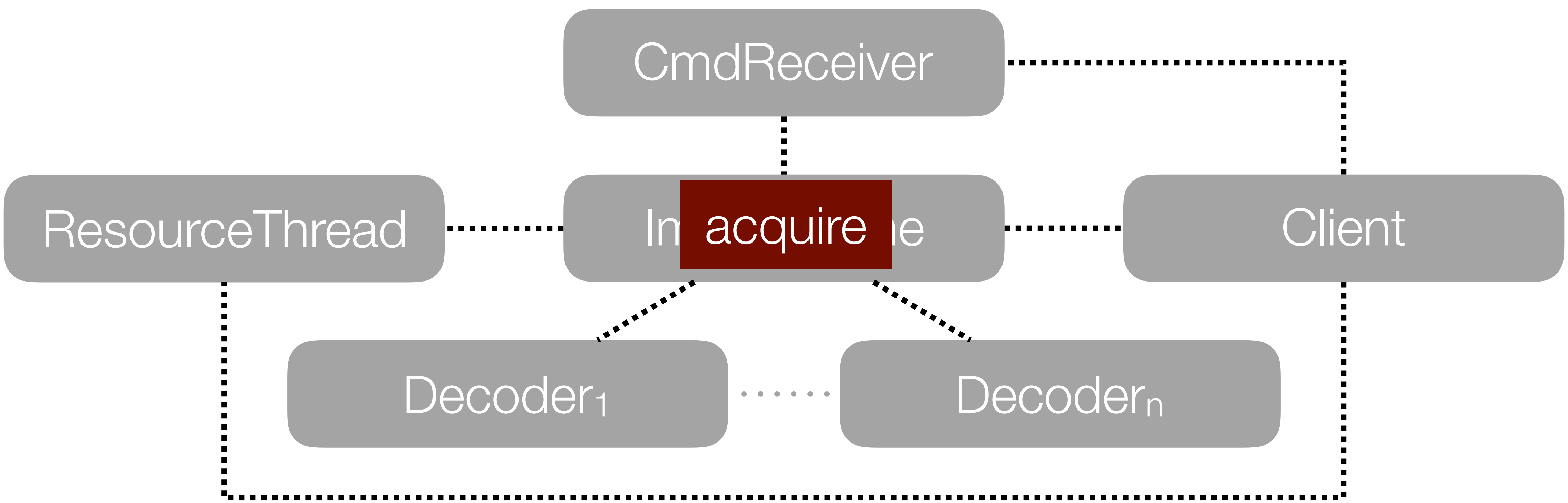

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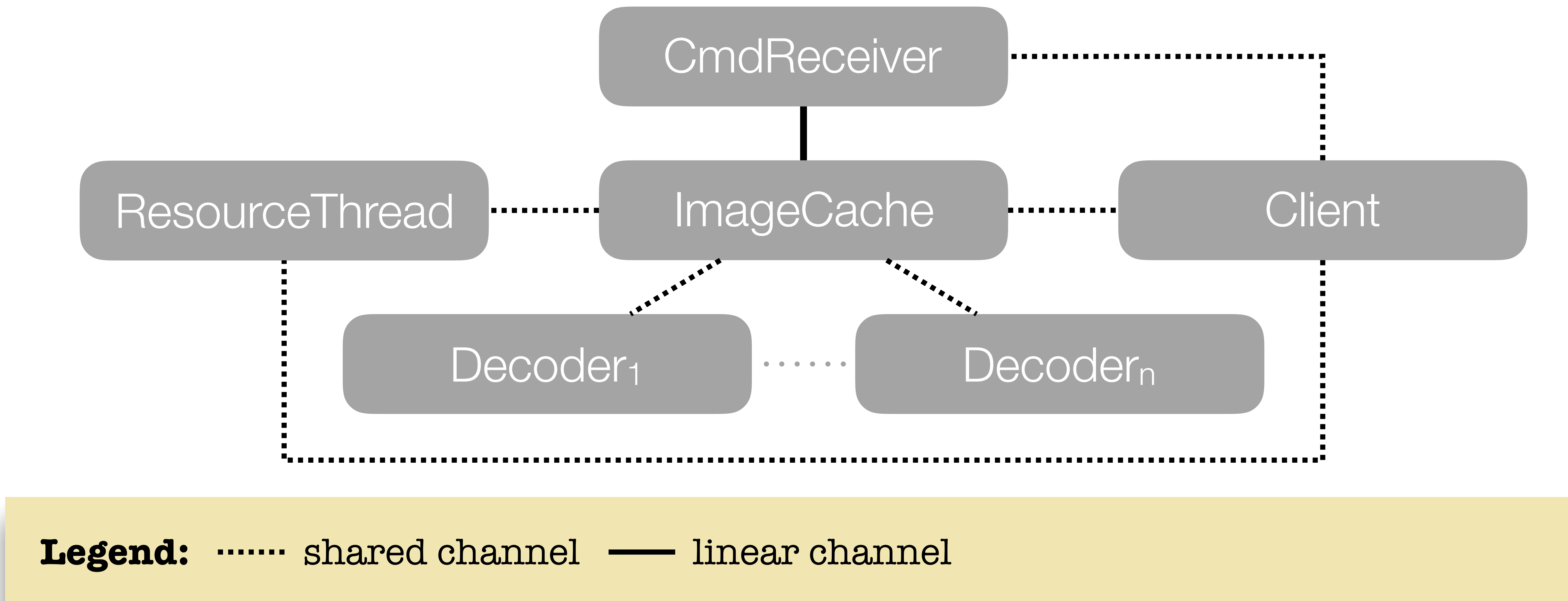

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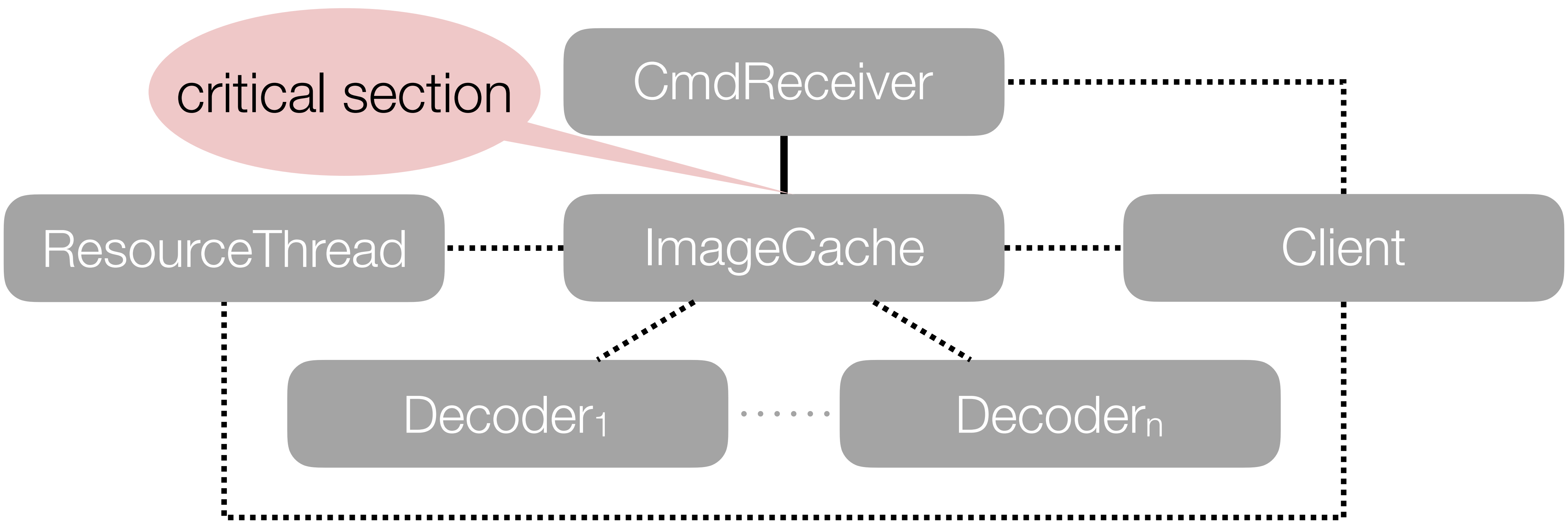

Legend: ······· shared channel —— linear channel

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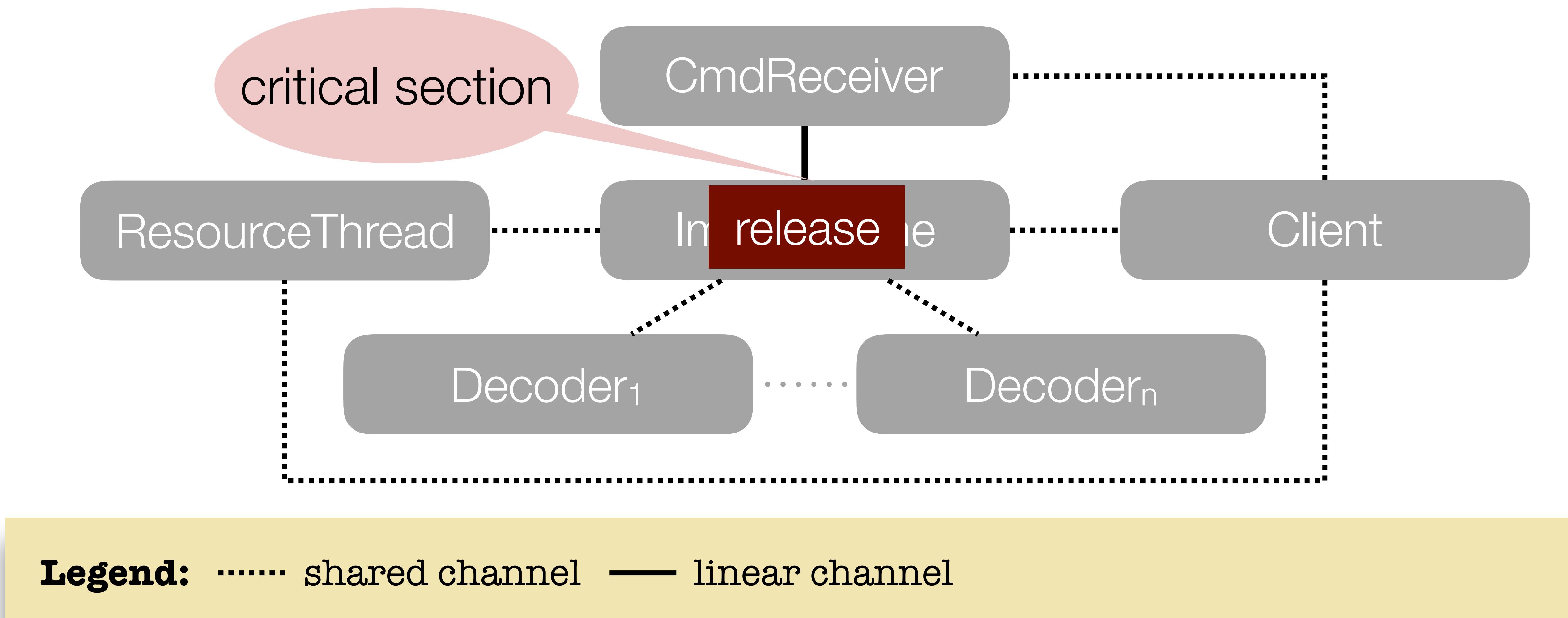

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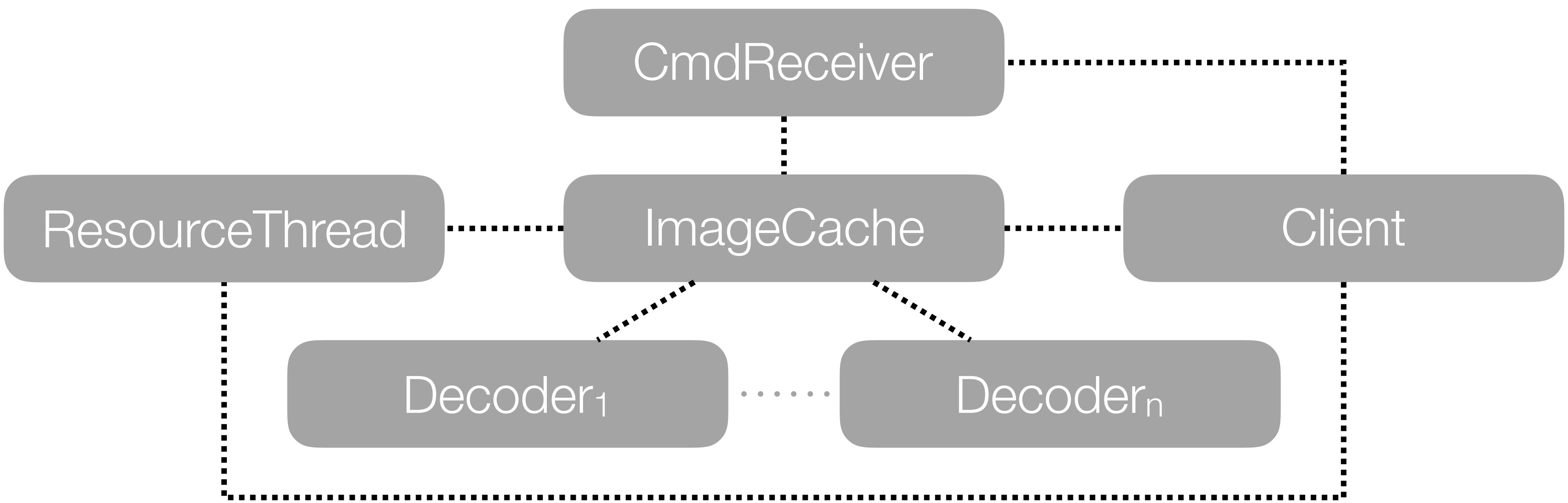

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Have we restored protocol adherence?

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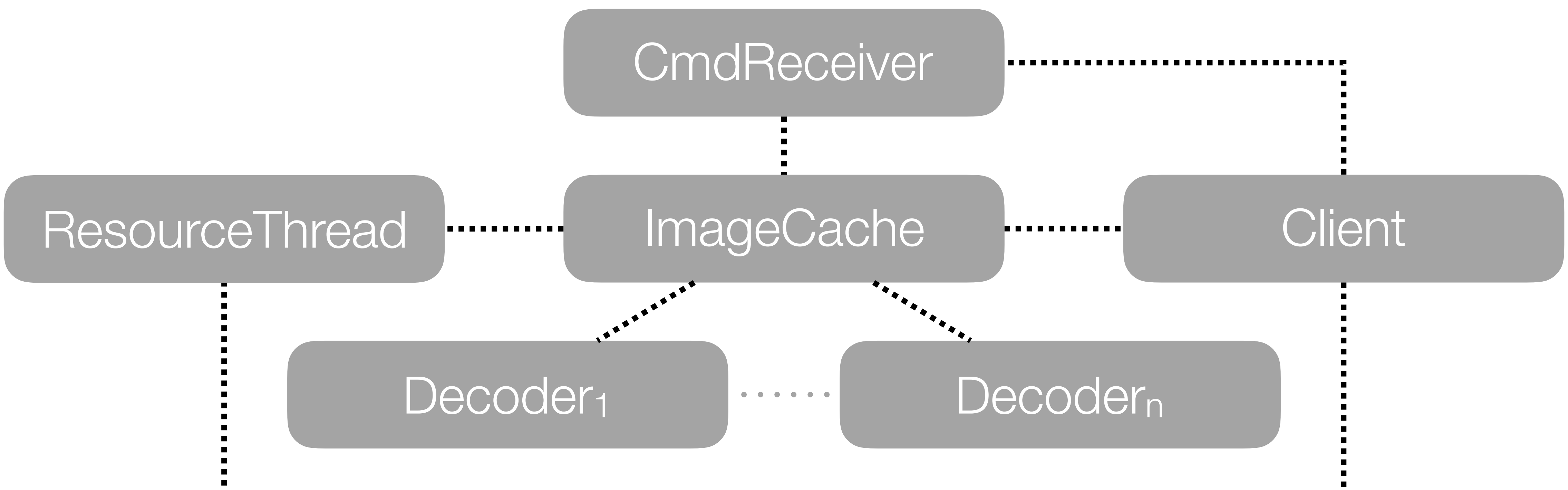
$$\begin{aligned}\mathsf{ImgCacheCmd} = \&\{&\mathsf{RequestImage} : \mathsf{string} \rightarrow \mathsf{Requester} \multimap \mathsf{ImgCacheCmd},\\ &\mathsf{Exit} : \oplus\,\{\mathsf{Running} : \mathsf{ImgCacheCmd},\\ &\qquad\qquad \mathsf{Done} : \mathsf{ResourceThread} \otimes \mathbf{1}\}\}\end{aligned}$$



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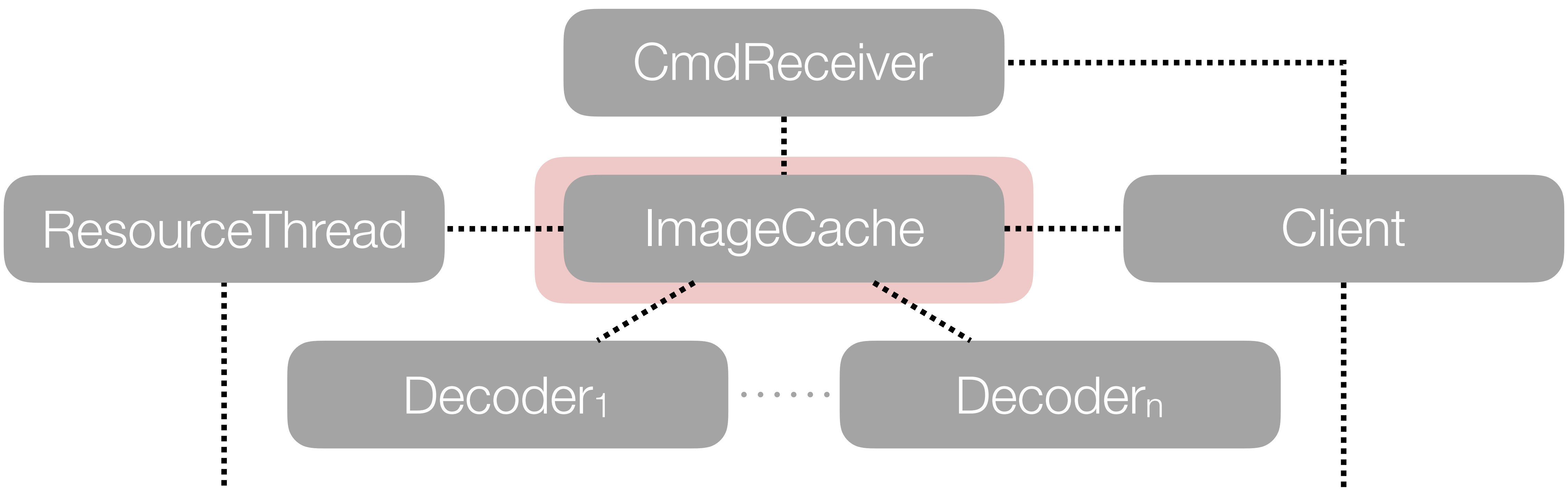
ImageCache: $\mathsf{ImgCacheCmd}$



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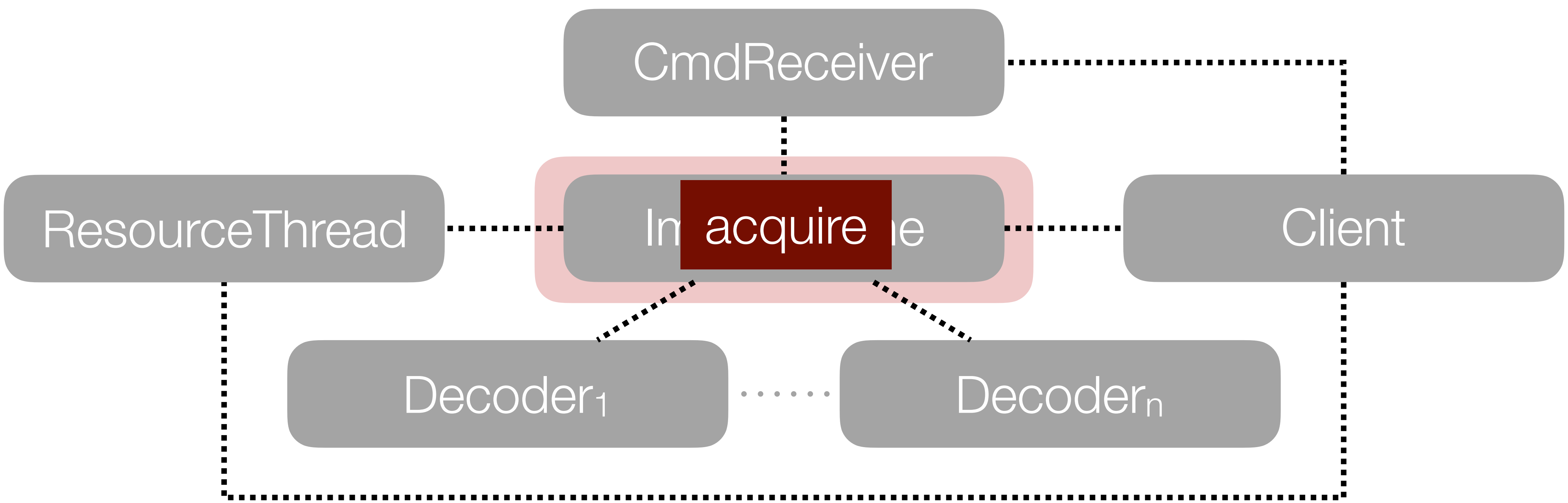

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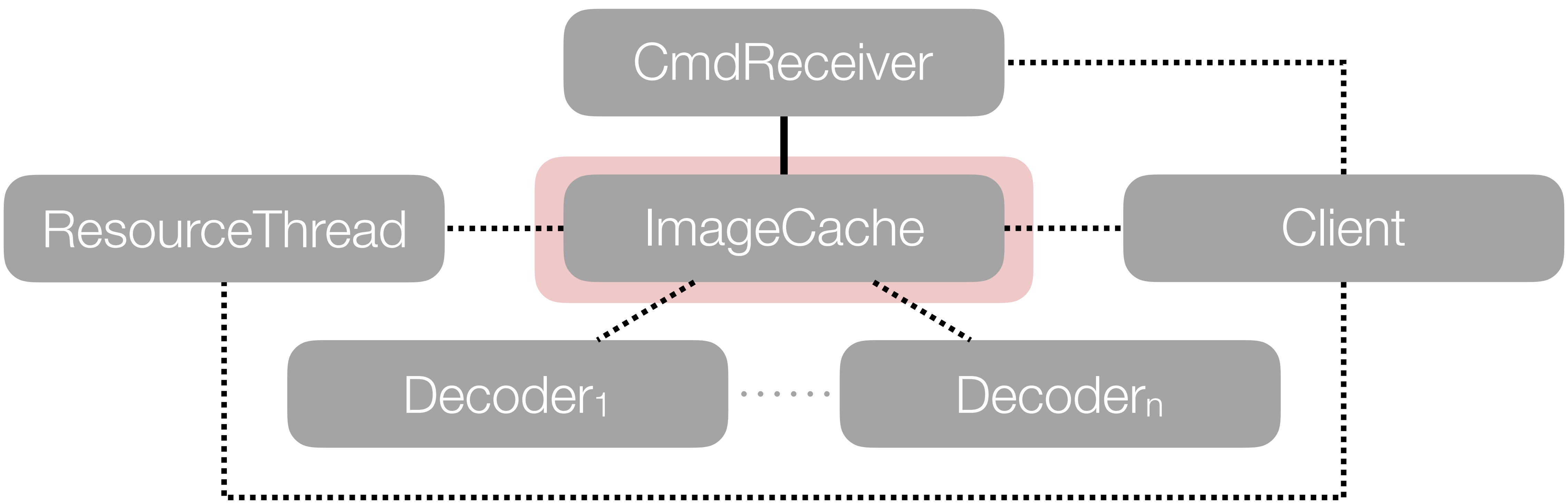

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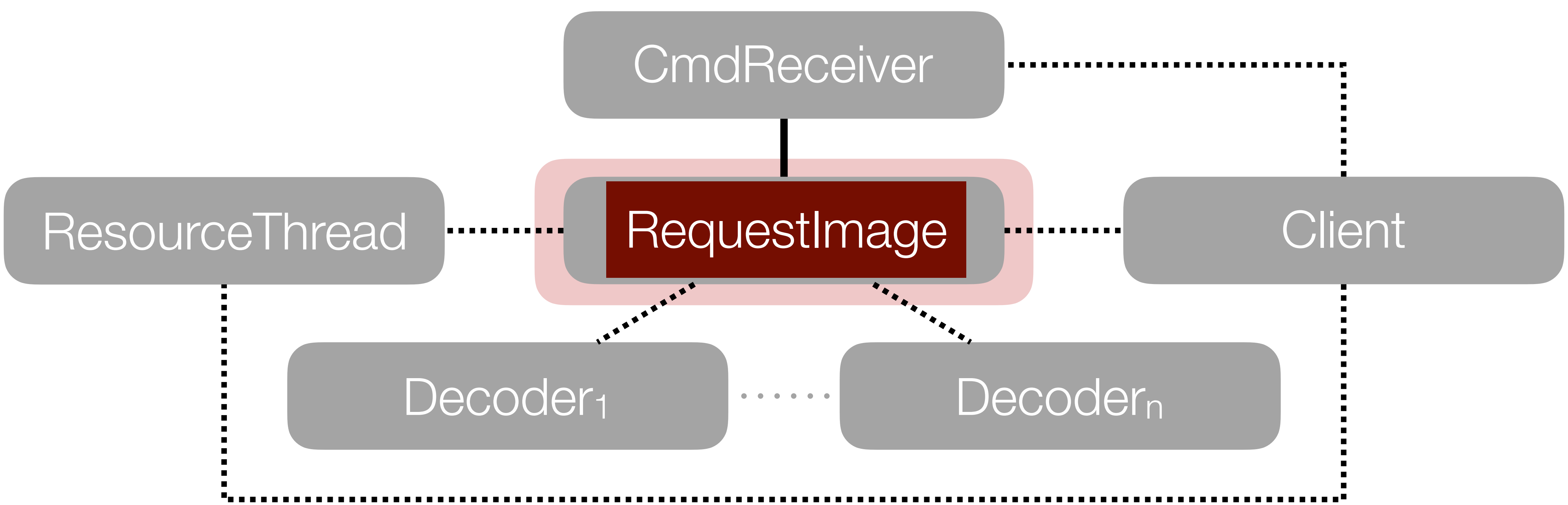

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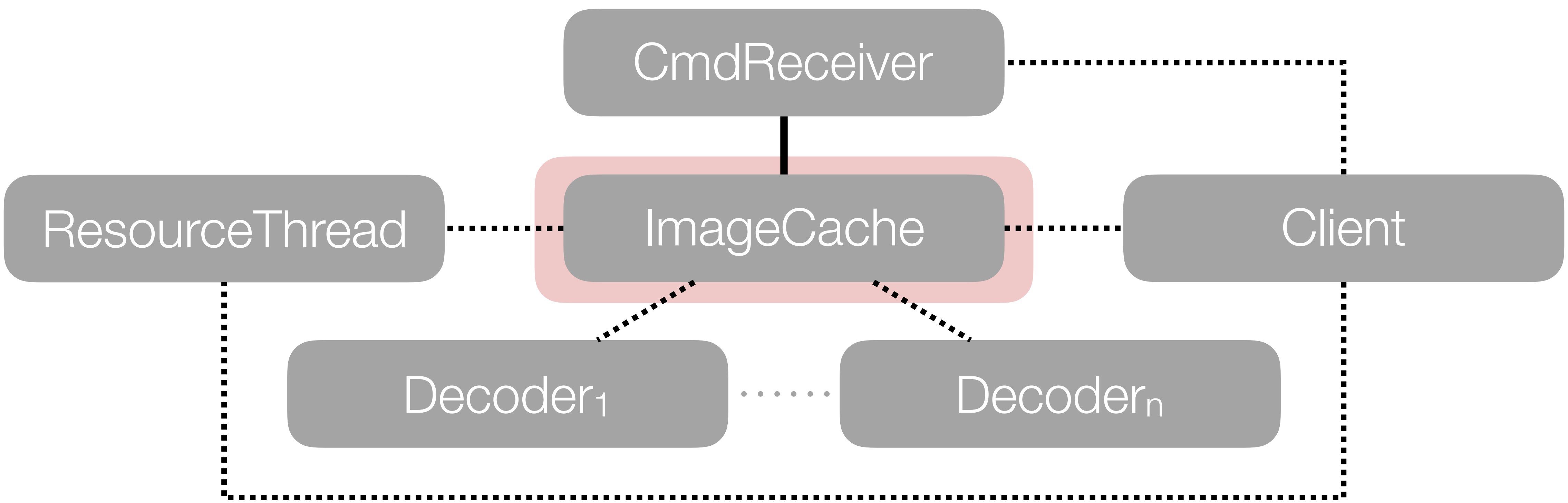

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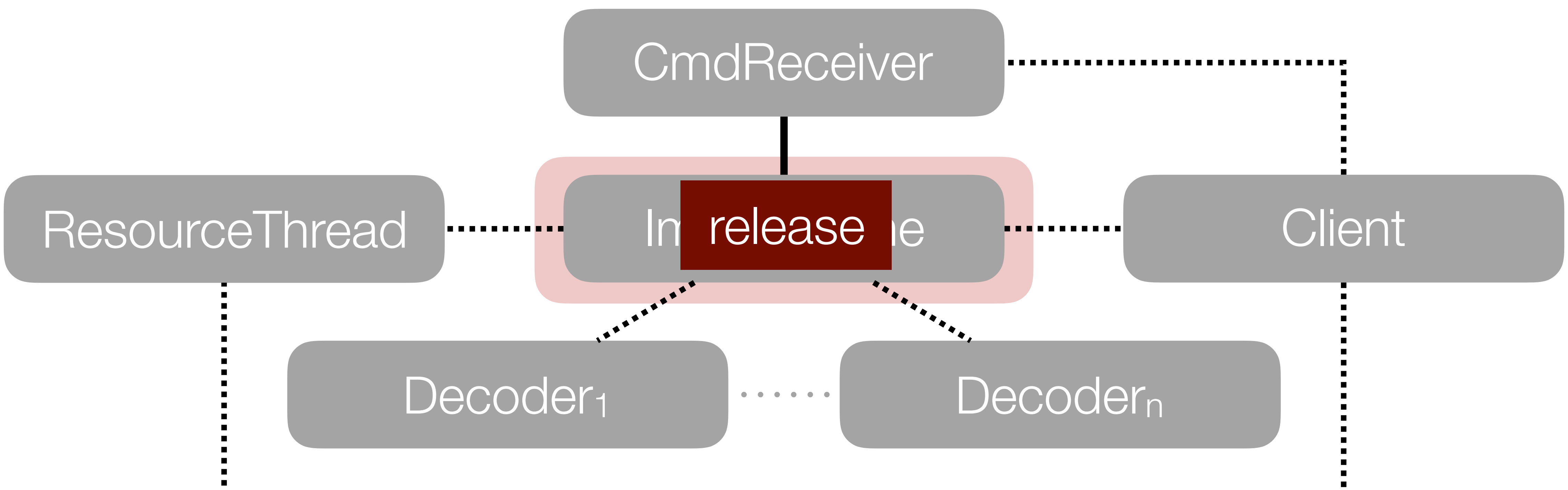

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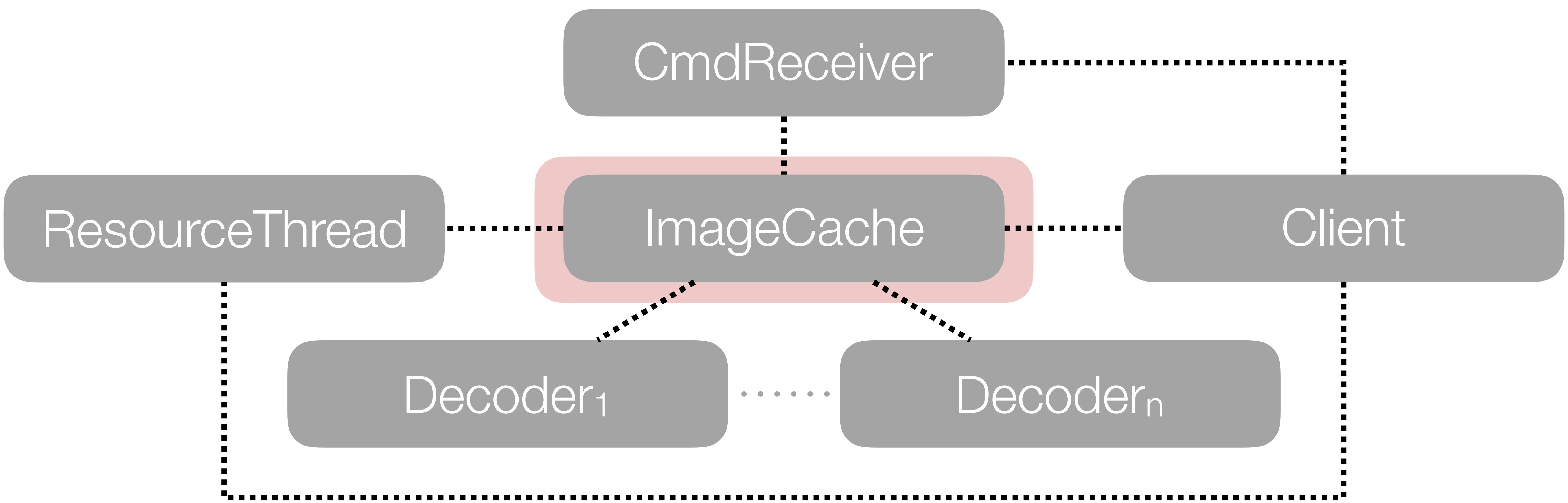

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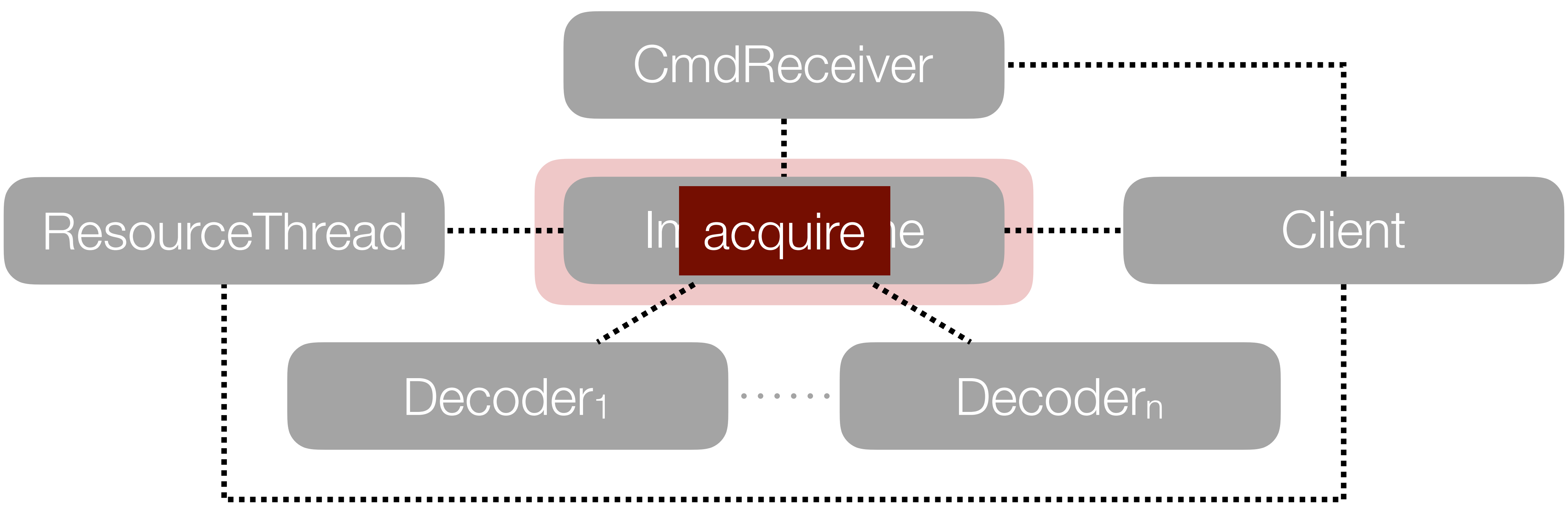

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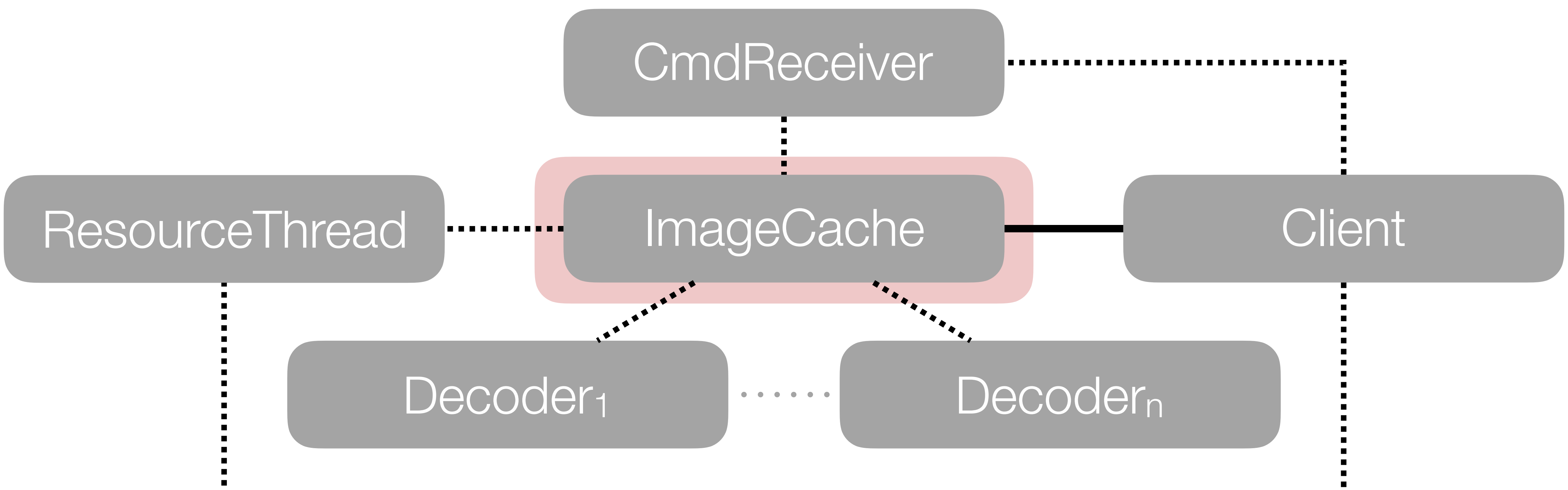

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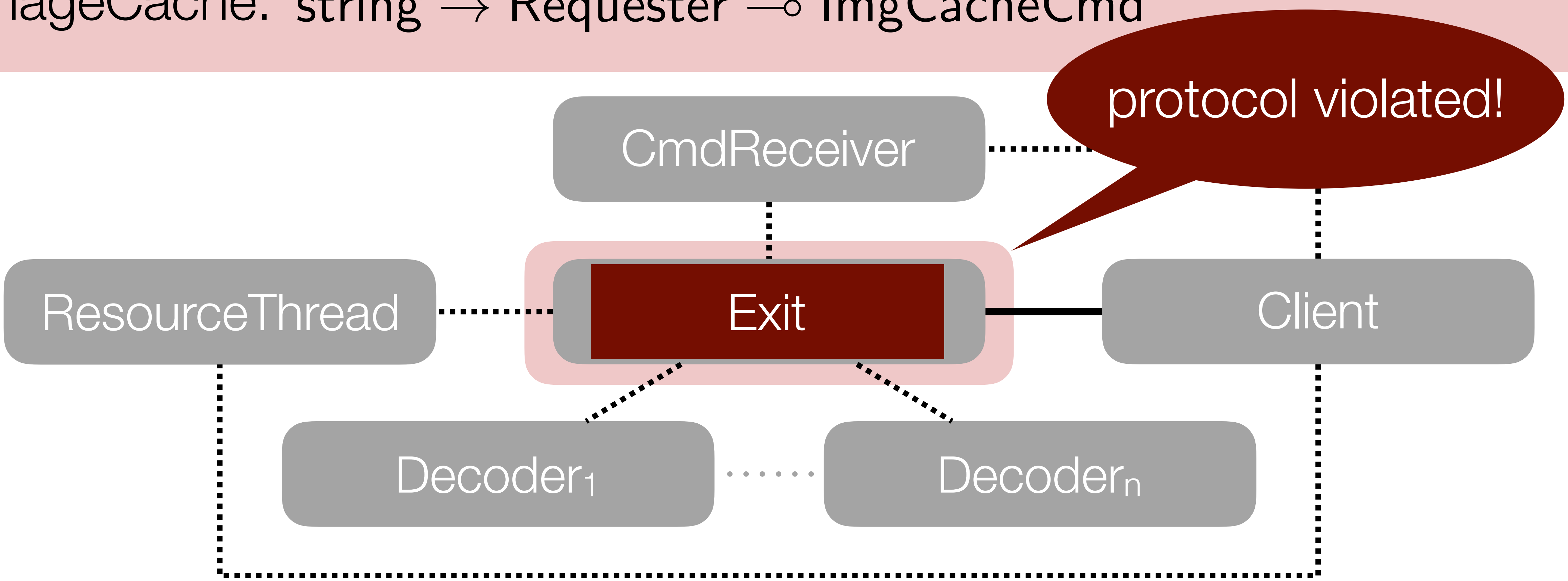

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$$
\begin{aligned}
\mathsf{ImgCacheCmd} = \overset{\text{acquire}}{\downarrow}\!\!\& \{ &\mathsf{RequestImage} : \mathsf{string} \rightarrow \mathsf{Requester} \multimap \mathsf{ImgCacheCmd}, \\
&\mathsf{Exit} : \oplus \{\mathsf{Done} : \mathsf{ResourceThread} \otimes \mathbf{1}, \\
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\end{aligned}
$$

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$$\mathsf{ImgCacheCmd} = \underset{\uparrow}{\overset{\text{acquire}}{}}\&\{\mathsf{RequestImage} : \mathsf{string} \rightarrow \mathsf{Requester} \multimap \overset{\text{release}}{\downarrow}\ \mathsf{ImgCacheCmd},\\ \mathsf{Exit} : \oplus\{\mathsf{Done} : \mathsf{ResourceThread} \otimes \mathbf{1},\\ \mathsf{Running} : \mathsf{ImgCacheCmd}\}\}$$

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acquire ... release ✓

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release

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$$\mathsf{ImgCacheCmd} = \overset{\text{acquire}}{\downarrow}\&\{\mathsf{RequestImage} : \mathsf{string} \rightarrow \mathsf{Requester} \multimap \overset{\text{release ✓}}{\downarrow}\mathsf{ImgCacheCmd},$$
$$\mathsf{Exit} : \oplus\{\mathsf{Done} : \mathsf{ResourceThread} \otimes \mathbf{1},$$
$$\mathsf{Running} : \underset{\text{release ✓}}{\uparrow}\mathsf{ImgCacheCmd}\}\}$$

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release ✓

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acquire ↓ release ✗ ↓ release ✓ ↓

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↑ release ✓

Taking stock

Taking stock

Acquire-release + equi-synchronizing:

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Taking stock

- Acquire-release + equi-synchronizing:
  - restore protocol adherence;
  - guarantee freedom of (high-level) data races because execution between acquire-release is atomic.
- We could state the policy of acquire-release and equi-synchronizing as a programming methodology.
- But, why not lift this policy to the type level and have it enforced statically?

Manifest sharing

Manifest sharing

Manifest sharing

acquire

release

$$
\begin{aligned}
\mathsf{ImgCacheCmd} = \&\{&\mathsf{RequestImage} : \mathsf{string} \rightarrow \mathsf{Requester} \multimap \mathsf{ImgCacheCmd},\\
&\mathsf{Exit} : \oplus\,\{\mathsf{Done} : \mathsf{ResourceThread} \otimes \mathbf{1},\\
&\qquad\qquad \mathsf{Running} : \mathsf{ImgCacheCmd}\}\}
\end{aligned}
$$

release

Manifest sharing

$$\begin{array}{l} \text{ImgCacheCmd} = \underset{\text{acquire}}{\&}\{\text{RequestImage} : \text{string} \to \text{Requester} \multimap \underset{\text{release}}{\text{ImgCacheCmd}}, \\ \qquad\qquad\qquad \text{Exit} : \oplus\{\text{Done} : \text{ResourceThread} \otimes \mathbf{1}, \\ \qquad\qquad\qquad\qquad\qquad \text{Running} : \underset{\text{release}}{\text{ImgCacheCmd}}\}\} \end{array}$$

Legend: shared phase linear phase

Manifest sharing

Manifest sharing

Stratify session types into a linear and shared layer

Manifest sharing

Stratify session types into a linear and shared layer

$$A_{\mathsf{S}} \triangleq$$

$$\begin{aligned} A_{\mathsf{L}}, B_{\mathsf{L}} \triangleq \; & \oplus\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \otimes B_{\mathsf{L}} \mid \mathbf{1} \mid \\ & \&\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \multimap B_{\mathsf{L}} \end{aligned}$$

Manifest sharing

Stratify session types into a linear and shared layer

Connect layers with modalities going back and forth

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$$A_{\mathsf{L}}, B_{\mathsf{L}} \triangleq \oplus\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \otimes B_{\mathsf{L}} \mid \mathbf{1} \mid \&\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \multimap B_{\mathsf{L}}$$

Manifest sharing

- Stratify session types into a linear and shared layer
- Connect layers with modalities going back and forth

$$
\begin{array}{lcl}
A_{\mathsf{S}} & \triangleq & \uparrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{L}} \\
A_{\mathsf{L}}, B_{\mathsf{L}} & \triangleq & \oplus\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \otimes B_{\mathsf{L}} \mid \mathbf{1} \mid \\
 & & \&\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \multimap B_{\mathsf{L}} \mid \downarrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{S}}
\end{array}
$$

Manifest sharing

Stratify session types into a linear and shared layer

Connect layers with modalities going back and forth

$$A_{\mathsf{S}} \triangleq \uparrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{L}}$$

$$\begin{aligned} A_{\mathsf{L}}, B_{\mathsf{L}} \triangleq\ & \oplus\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \otimes B_{\mathsf{L}} \mid \mathbf{1} \mid \\ & \&\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \multimap B_{\mathsf{L}} \mid \downarrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{S}} \end{aligned}$$

Support communication of shared channels

Manifest sharing

Stratify session types into a linear and shared layer

Connect layers with modalities going back and forth

$$A_{\mathsf{S}} \triangleq \uparrow^{\mathsf{S}}_{\mathsf{L}} A_{\mathsf{L}}$$

$$\begin{array}{lll} A_{\mathsf{L}}, B_{\mathsf{L}} & \triangleq & \oplus\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \otimes B_{\mathsf{L}} \mid \mathbf{1} \mid \exists x{:}A_{\mathsf{S}}.\, B_{\mathsf{L}} \mid \\ & & \&\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \multimap B_{\mathsf{L}} \mid \downarrow^{\mathsf{S}}_{\mathsf{L}} A_{\mathsf{S}} \mid \Pi x{:}A_{\mathsf{S}}.\, B_{\mathsf{L}} \end{array}$$

Support communication of shared channels

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\begin{array}{lcl}
A_{\mathsf{S}} & \triangleq & \uparrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{L}} \\
A_{\mathsf{L}}, B_{\mathsf{L}} & \triangleq & \oplus\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \otimes B_{\mathsf{L}} \mid \mathbf{1} \mid \exists x{:}A_{\mathsf{S}}.\, B_{\mathsf{L}} \mid \\
 & & \&\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \multimap B_{\mathsf{L}} \mid \downarrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{S}} \mid \Pi x{:}A_{\mathsf{S}}.\, B_{\mathsf{L}}
\end{array}
$$

Manifest sharing

$$A_{\mathsf{S}} \triangleq \uparrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{L}}$$

$$\begin{aligned} A_{\mathsf{L}}, B_{\mathsf{L}} \triangleq\ & \oplus\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \otimes B_{\mathsf{L}} \mid \mathbf{1} \mid \exists x{:}A_{\mathsf{S}}.\, B_{\mathsf{L}} \mid \\ & \&\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \multimap B_{\mathsf{L}} \mid \downarrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{S}} \mid \Pi x{:}A_{\mathsf{S}}.\, B_{\mathsf{L}} \end{aligned}$$

$$\begin{aligned} \mathsf{ImgCacheCmd} = \ & \&\{\mathsf{RequestImage} : \mathsf{string} \rightarrow \mathsf{Requester} \multimap \mathsf{ImgCacheCmd}, \\ & \quad \mathsf{Exit} : \oplus \{\mathsf{Done} : \mathsf{ResourceThread} \otimes \mathbf{1}, \\ & \qquad \mathsf{Running} : \mathsf{ImgCacheCmd}\}\} \end{aligned}$$

Manifest sharing

$$A_{\mathsf{S}} \triangleq \uparrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{L}}$$

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Up and down shifts denote acquire and release, resp.

Typing judgments

$$A_{\mathsf{S}} \triangleq \uparrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{L}}$$

$$\begin{aligned} A_{\mathsf{L}}, B_{\mathsf{L}} \triangleq\ & \oplus\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \otimes B_{\mathsf{L}} \mid \mathbf{1} \mid \exists x{:}A_{\mathsf{S}}.\, B_{\mathsf{L}} \mid \\ & \&\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \multimap B_{\mathsf{L}} \mid \downarrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{S}} \mid \Pi x{:}A_{\mathsf{S}}.\, B_{\mathsf{L}} \end{aligned}$$

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Based on correspondence between intuitionistic linear logic and session-typed pi-calculus:

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Based on correspondence between intuitionistic linear logic and session-typed pi-calculus:

$$\Gamma \vdash_{\Sigma} P :: (x_{\mathsf{S}} : A_{\mathsf{S}})$$

$$\Gamma;\ \Delta \vdash_{\Sigma} P :: (x_{\mathsf{L}} : A_{\mathsf{L}})$$

Typing judgments

A_{S}	$\triangleq$	$\uparrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{L}}$
$A_{\mathsf{L}}, B_{\mathsf{L}}$	$\triangleq$	$\oplus\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \otimes B_{\mathsf{L}} \mid \mathbf{1} \mid \exists x{:}A_{\mathsf{S}}.\, B_{\mathsf{L}} \mid$
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"Process P provides session of type A_m along x_m using channels in (Γ and) Δ."

Typing judgments

A_{S}	$\triangleq$	$\uparrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{L}}$
$A_{\mathsf{L}}, B_{\mathsf{L}}$	$\triangleq$	$\oplus\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \otimes B_{\mathsf{L}} \mid \mathbf{1} \mid \exists x{:}A_{\mathsf{S}}.\, B_{\mathsf{L}} \mid$
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Based on correspondence between intuitionistic linear logic and session-typed pi-calculus:

shared (structural) context

$$\Gamma \vdash_{\Sigma} P :: (x_{\mathsf{S}} : A_{\mathsf{S}})$$

$$\Gamma;\ \Delta \vdash_{\Sigma} P :: (x_{\mathsf{L}} : A_{\mathsf{L}})$$

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Typing judgments

A_{S}	$\triangleq$	$\uparrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{L}}$
$A_{\mathsf{L}}, B_{\mathsf{L}}$	$\triangleq$	$\oplus\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \otimes B_{\mathsf{L}} \mid \mathbf{1} \mid \exists x{:}A_{\mathsf{S}}.\, B_{\mathsf{L}} \mid$
		$\&\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \multimap B_{\mathsf{L}} \mid \downarrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{S}} \mid \Pi x{:}A_{\mathsf{S}}.\, B_{\mathsf{L}}$

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"Process P provides session of type A_m along x_m using channels in (Γ and) Δ."

Typing judgments

$$A_{\mathsf{S}} \triangleq {\uparrow}^{\mathsf{S}}_{\mathsf{L}} A_{\mathsf{L}}$$

$$\begin{aligned} A_{\mathsf{L}}, B_{\mathsf{L}} \triangleq\ & \oplus\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \otimes B_{\mathsf{L}} \mid \mathbf{1} \mid \exists x{:}A_{\mathsf{S}}.\, B_{\mathsf{L}} \mid \\ & \&\{\overline{l : A_{\mathsf{L}}}\} \mid A_{\mathsf{L}} \multimap B_{\mathsf{L}} \mid {\downarrow}^{\mathsf{S}}_{\mathsf{L}} A_{\mathsf{S}} \mid \Pi x{:}A_{\mathsf{S}}.\, B_{\mathsf{L}} \end{aligned}$$

Based on correspondence between intuitionistic linear logic and session-typed pi-calculus:

linear (substructural) context

$$\Gamma \vdash_{\Sigma} P :: (x_{\mathsf{S}} : A_{\mathsf{S}})$$

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"Process P provides session of type A_m along x_m using channels in (Γ and) Δ."

Typing of acquire

Typing of acquire

$$\frac{\Gamma, x_{\mathsf{S}} : \uparrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{L}};\ \Delta, x_{\mathsf{L}} : A_{\mathsf{L}} \vdash_{\Sigma} Q_{x_{\mathsf{L}}} :: (z_{\mathsf{L}} : C_{\mathsf{L}})}{\Gamma, x_{\mathsf{S}} : \uparrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{L}};\ \Delta \vdash_{\Sigma} x_{\mathsf{L}} \leftarrow \mathsf{acquire}\ x_{\mathsf{S}}\ ; Q_{x_{\mathsf{L}}} :: (z_{\mathsf{L}} : C_{\mathsf{L}})}\ (\mathrm{T}\text{-}{\uparrow_{\mathsf{L}}^{\mathsf{S}}}\mathrm{L})$$

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$$\frac{\Gamma;\ \cdot \vdash_{\Sigma} P_{x_{\mathsf{L}}} :: (x_{\mathsf{L}} : A_{\mathsf{L}})}{\Gamma \vdash_{\Sigma} x_{\mathsf{L}} \leftarrow \mathsf{accept}\ x_{\mathsf{S}}\ ; P_{x_{\mathsf{L}}} :: (x_{\mathsf{S}} : \uparrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{L}})} \ (\text{T-}\uparrow_{\mathsf{L}}^{\mathsf{S}}\text{R})$$

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Typing of release

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$$\frac{\Gamma, x_{\mathsf{S}} : A_{\mathsf{S}};\ \Delta \vdash_{\Sigma} Q_{x_{\mathsf{S}}} :: (z_{\mathsf{L}} : C_{\mathsf{L}})}{\Gamma;\ \Delta, x_{\mathsf{L}} : \downarrow^{\mathsf{S}}_{\mathsf{L}} A_{\mathsf{S}} \vdash_{\Sigma} x_{\mathsf{S}} \leftarrow \mathsf{release}\ x_{\mathsf{L}}\ ; Q_{x_{\mathsf{S}}} :: (z_{\mathsf{L}} : C_{\mathsf{L}})} \ (\mathrm{T}\text{-}\downarrow^{\mathsf{S}}_{\mathsf{L}}\mathrm{L})$$

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$$\frac{\Gamma \vdash_\Sigma P_{x_{\mathsf{S}}} :: (x_{\mathsf{S}} : A_{\mathsf{S}})}{\Gamma;\ \cdot \vdash_\Sigma x_{\mathsf{S}} \leftarrow \mathsf{detach}\ x_{\mathsf{L}}\ ; P_{x_{\mathsf{S}}} :: (x_{\mathsf{L}} : \downarrow_{\mathsf{L}}^{\mathsf{S}} A_{\mathsf{S}})}\ (\mathrm{T}\text{-}\downarrow_{\mathsf{L}}^{\mathsf{S}}\mathrm{R})$$

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Taking stock

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- We have a session type system that allows shared and linear channels to coexist and guarantees:
  - data-race-freedom (low-level and high-level)
  - protocol adherence

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- We have a session type system that allows shared and linear channels to coexist and guarantees:
  - data-race-freedom (low-level and high-level)
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- What about deadlock-freedom?

Why are linear session types deadlock-free?

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Linearity (“exactly one client”) turns process graph into a tree.

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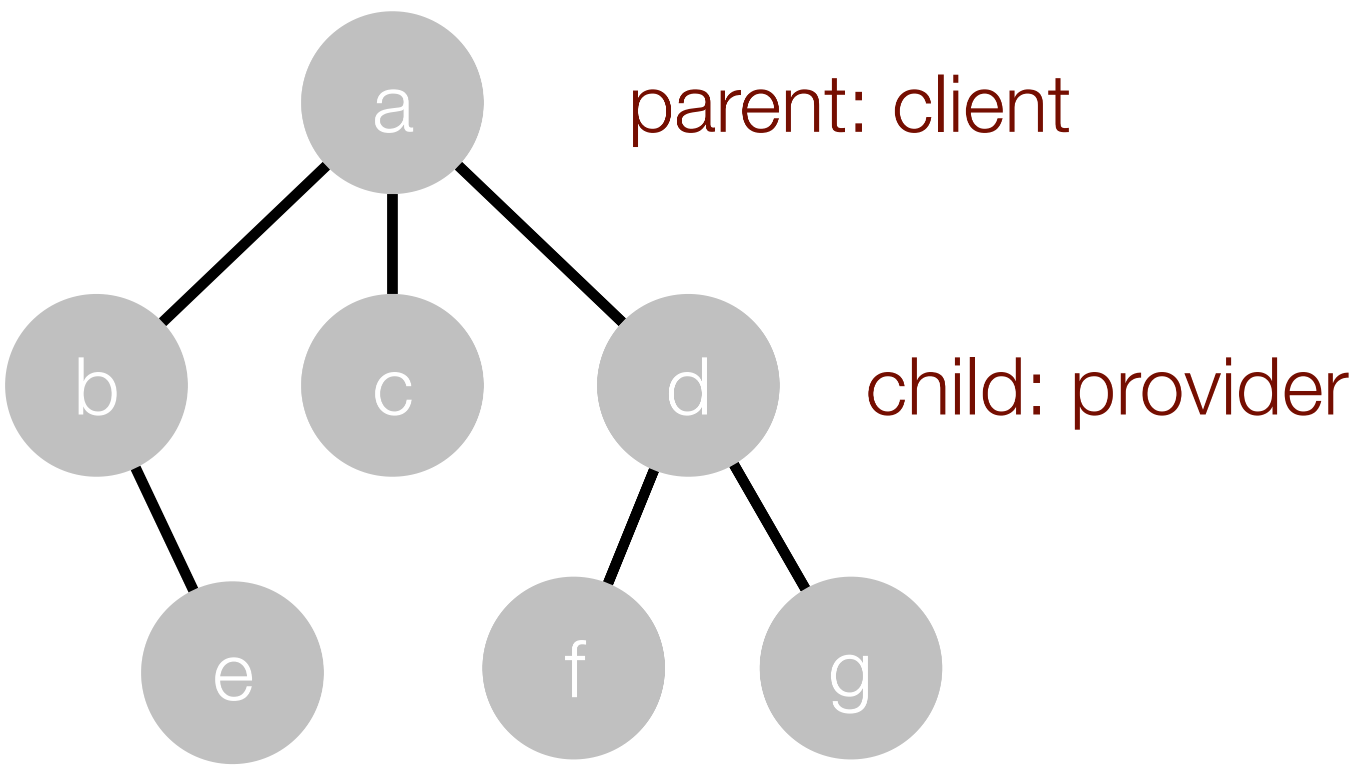

Legend: —— linear channel

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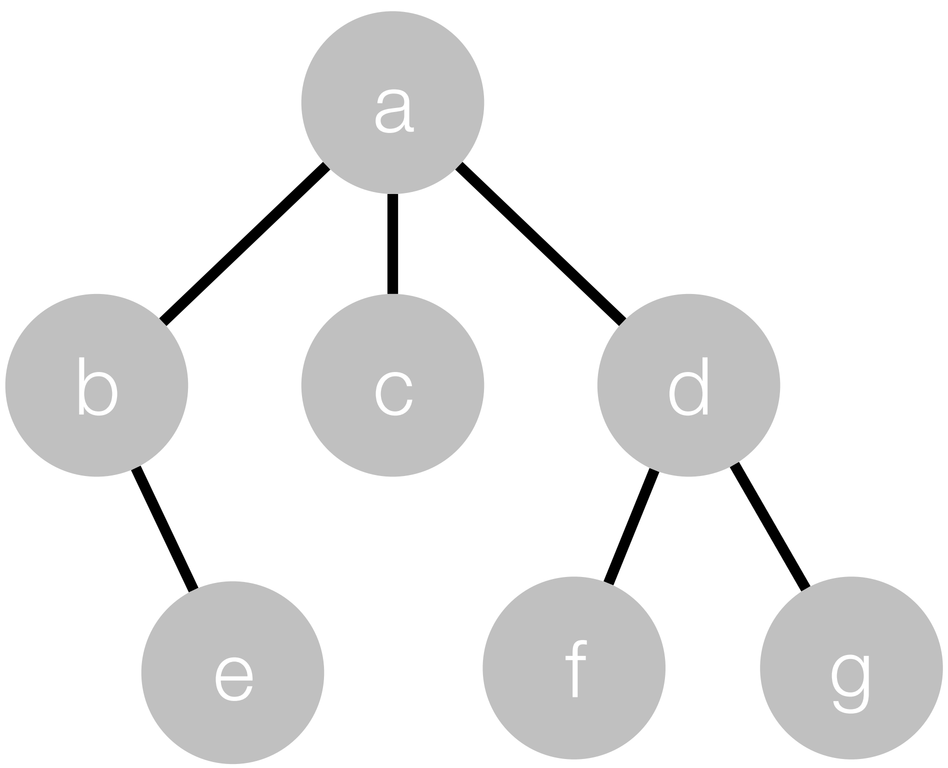

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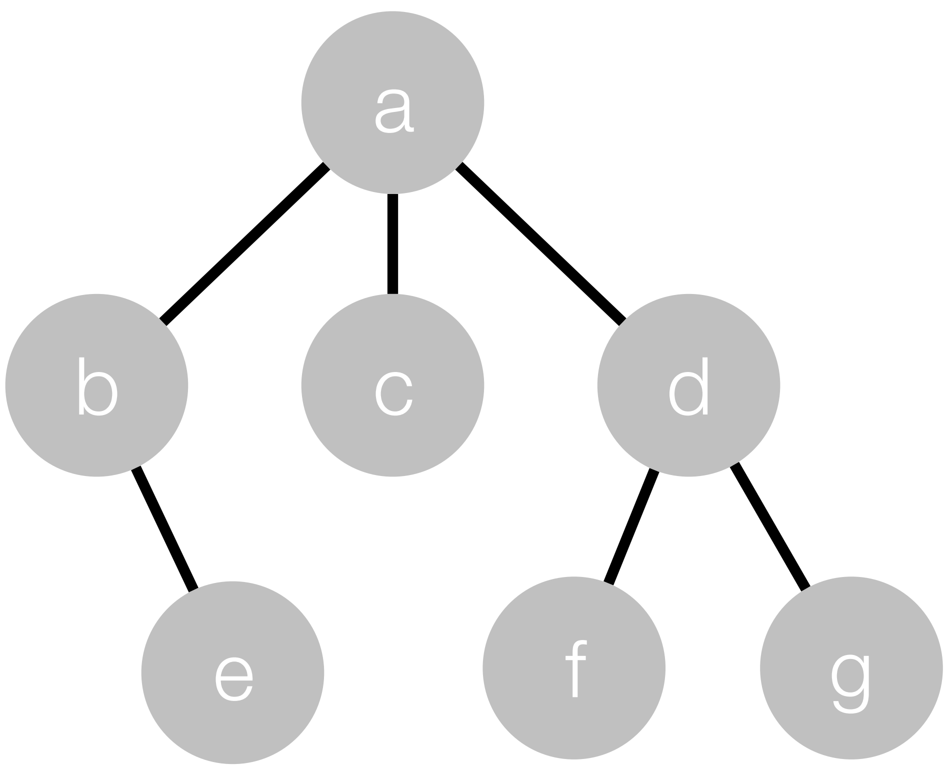

What are the threats to progress?

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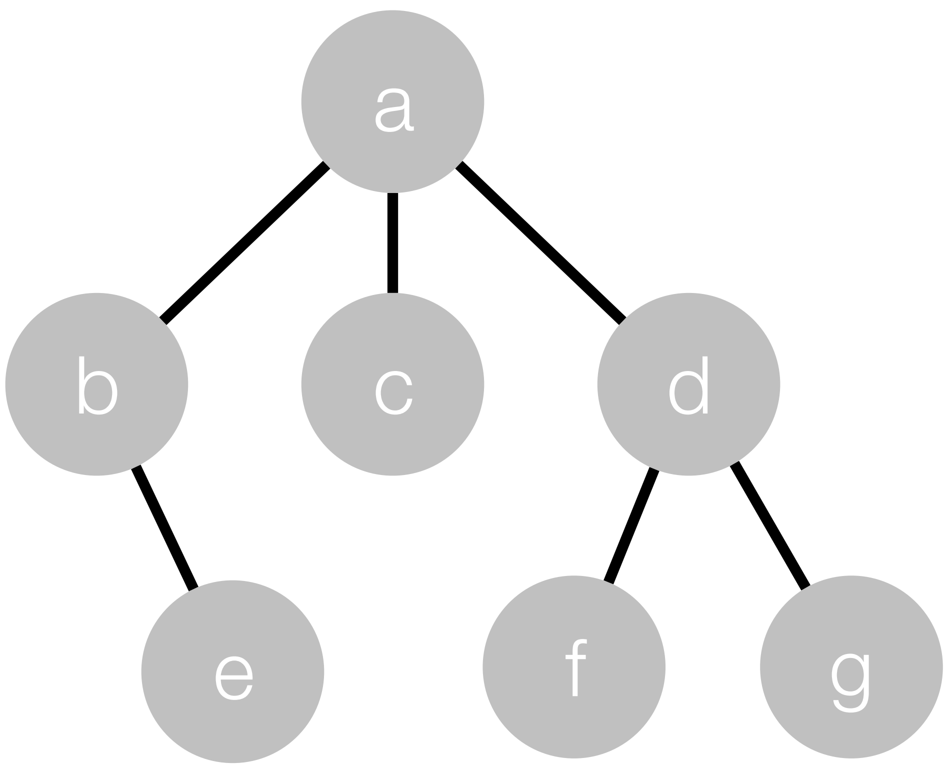

What are the threats to progress?

- Two scenarios:

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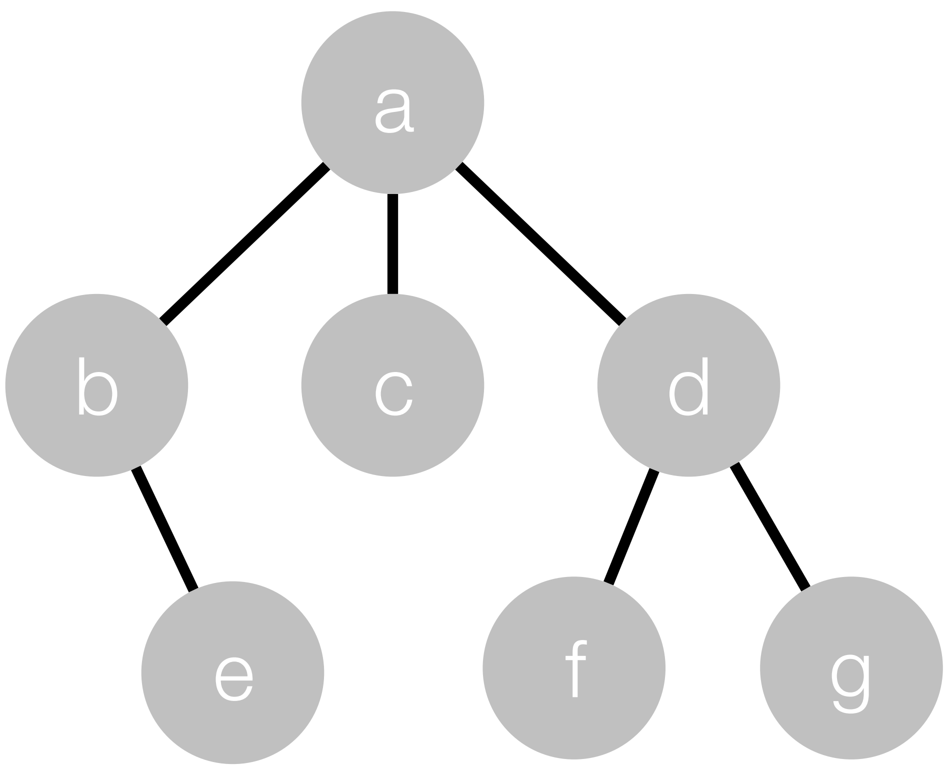

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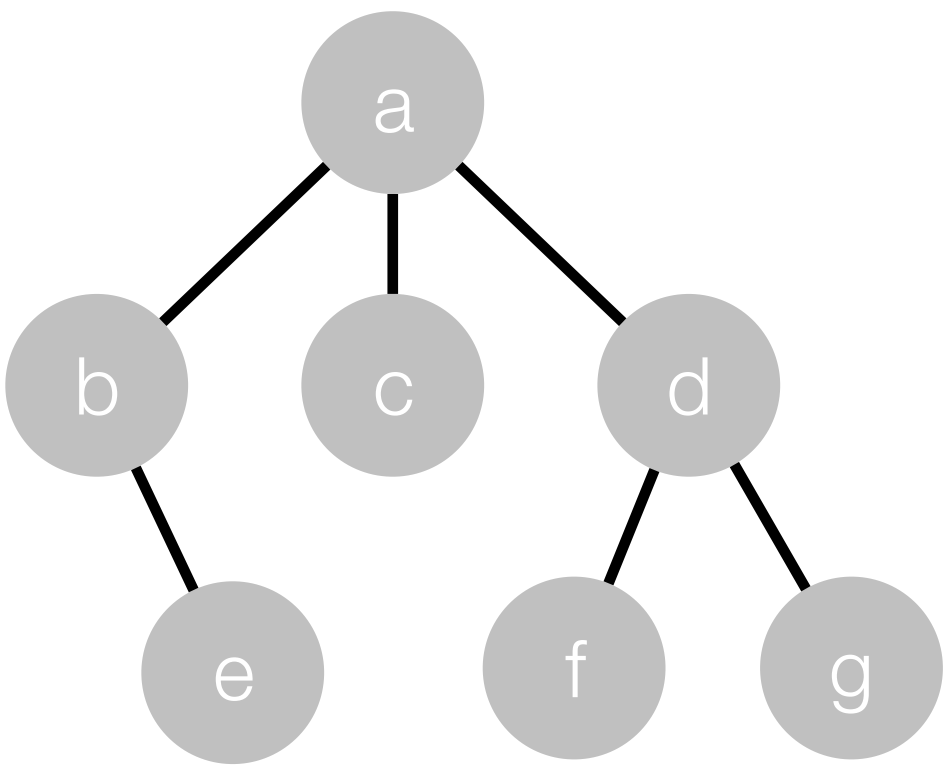

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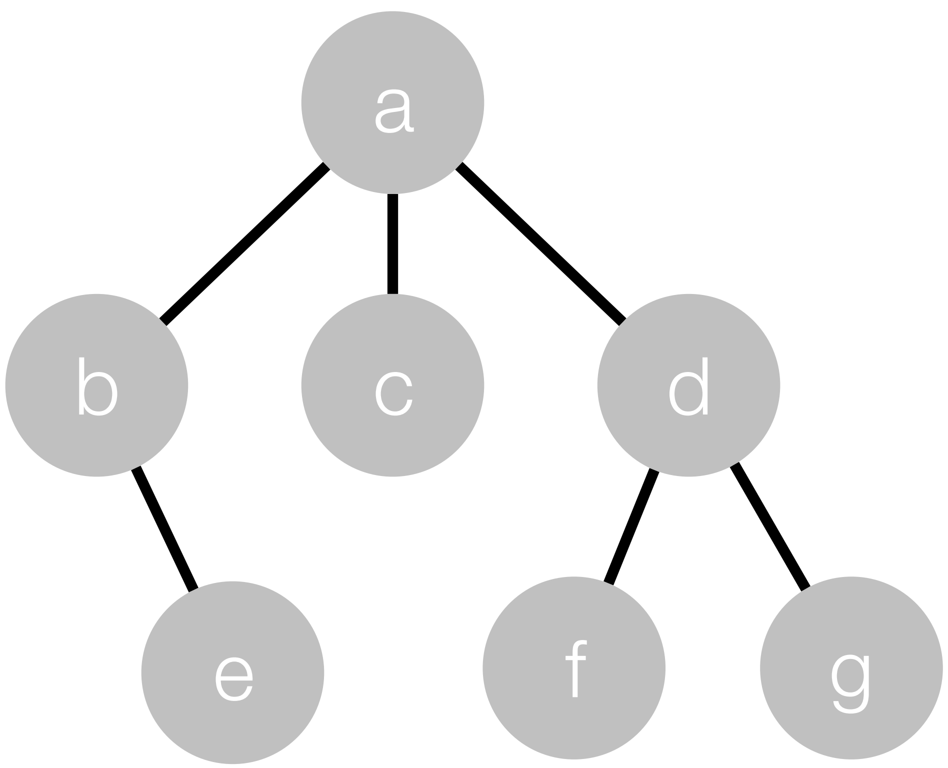

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- Let's visualize this waiting dependency with a green arrow

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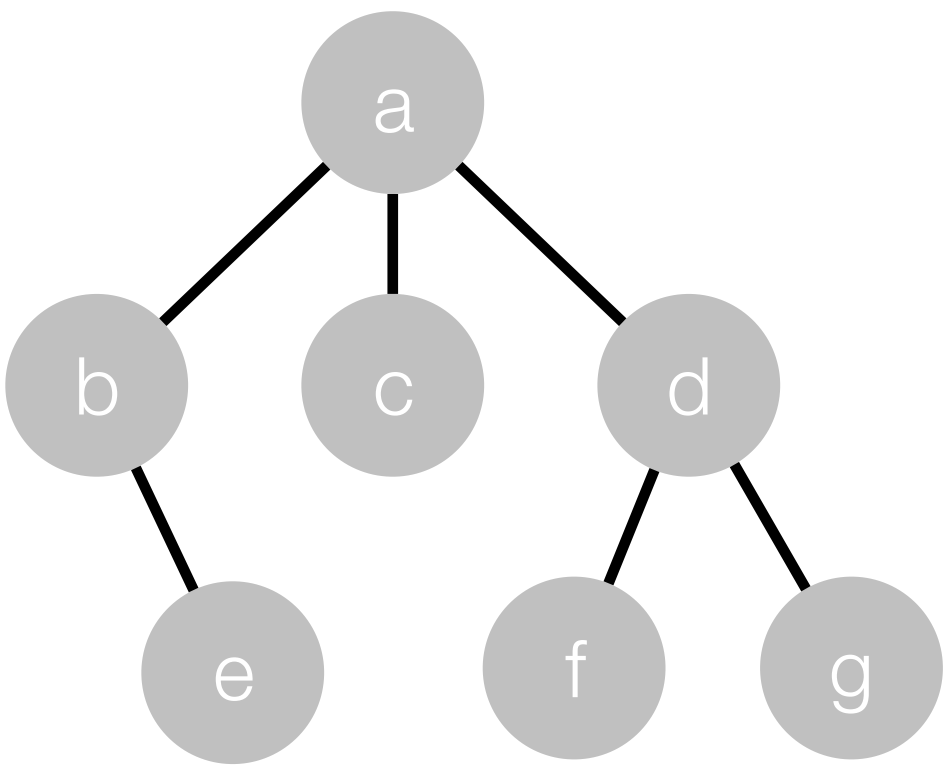

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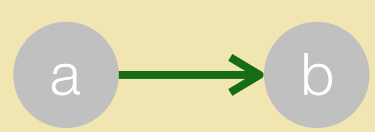
Legend: —— linear channel 

"a waits for b"

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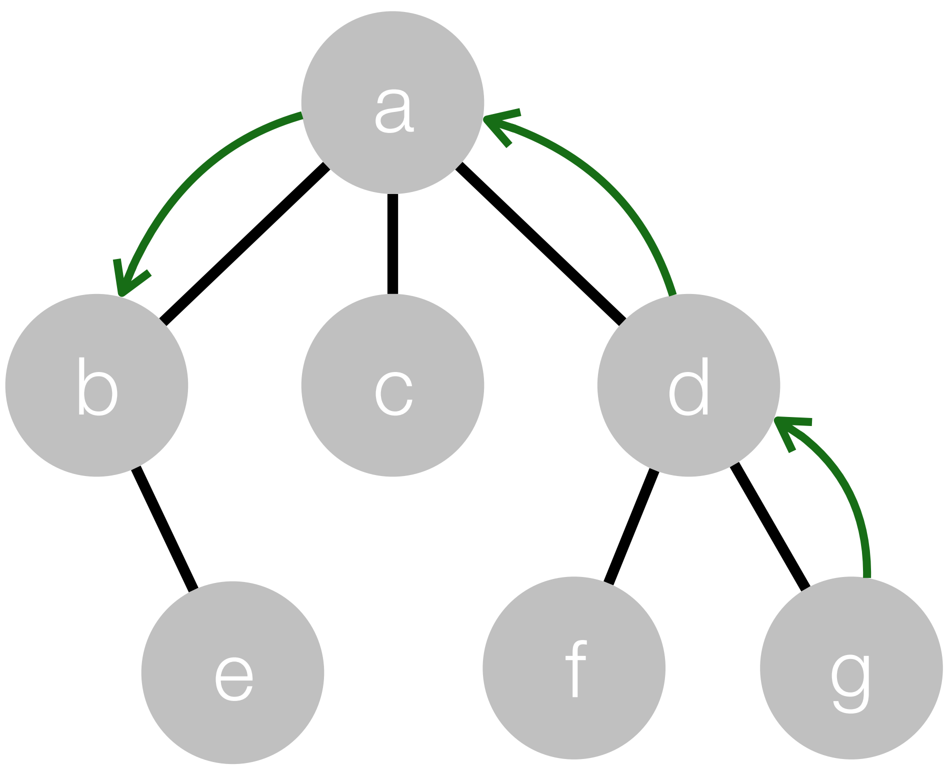

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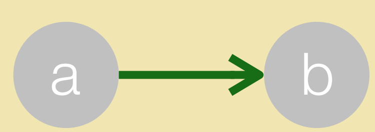

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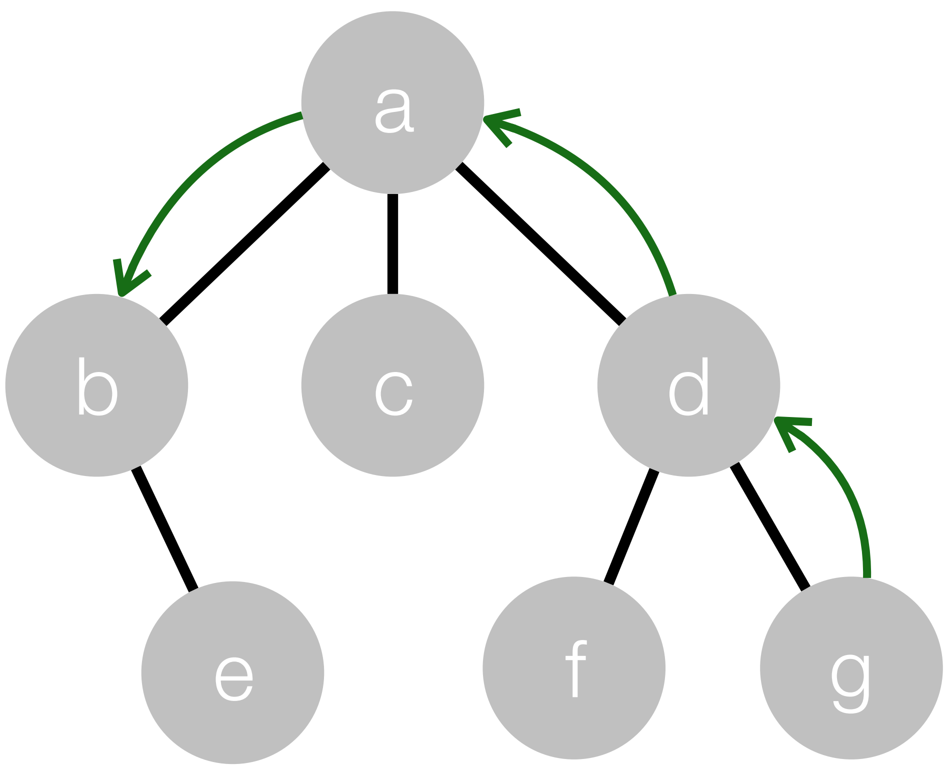

What are the threats to progress?

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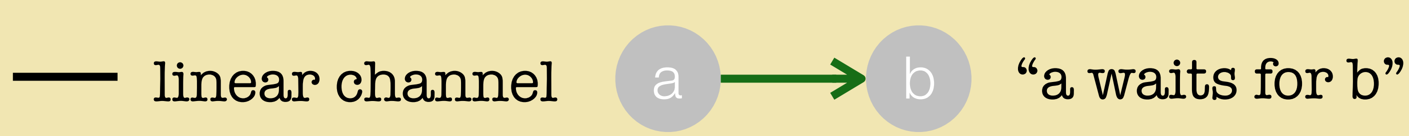
  - client ready to synchronize, provider not
- Let's visualize this waiting dependency with a green arrow

No green cycles: green arrows can only go along linear channels, and client and provider cannot both be waiting for each other.

Legend: 

Let's add sharing

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We get a graph of linear and shared processes, with a linear tree inside.

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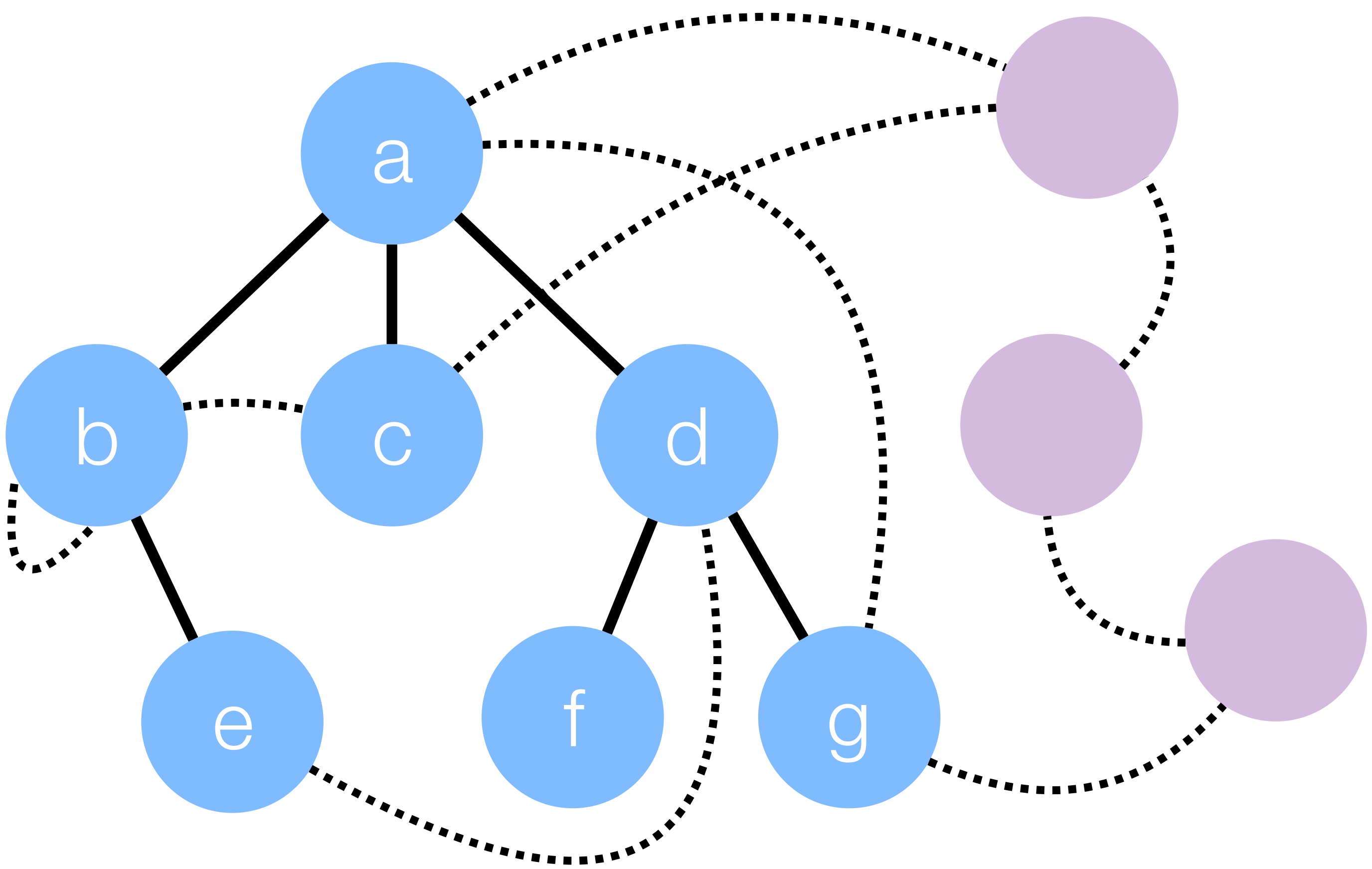
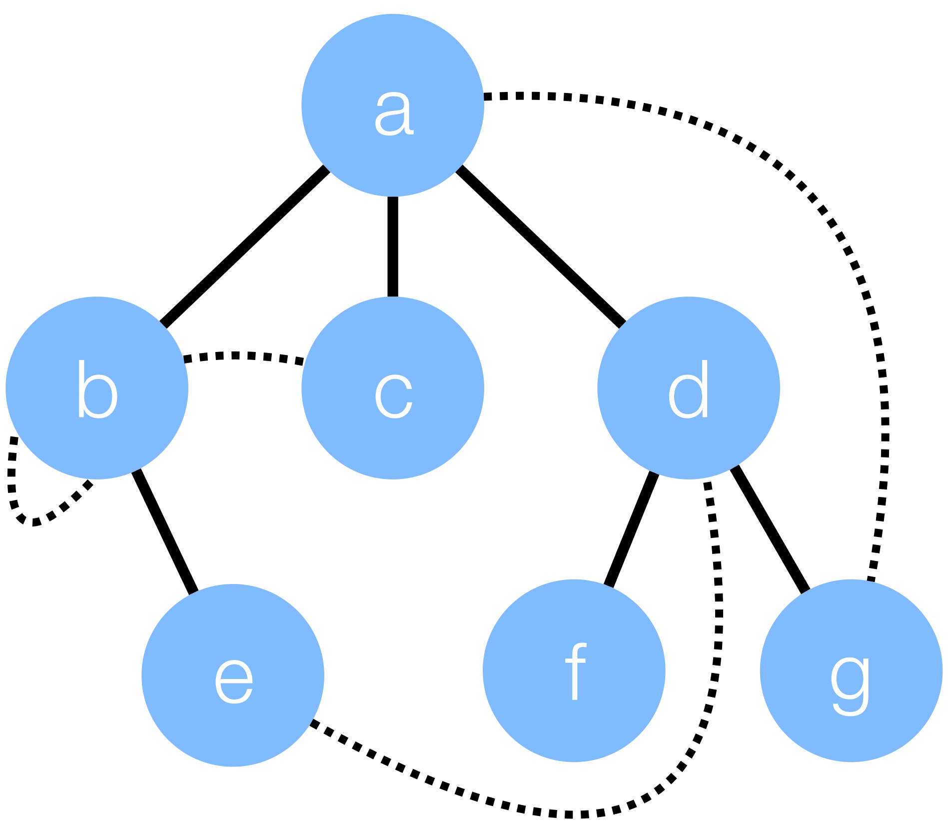


Legend: linear channel · shared channel · linear process · shared process

Let's add sharing

We get a graph of linear and shared processes, with a linear tree inside.



Legend: — linear channel ● linear process ● shared process

······ shared channel

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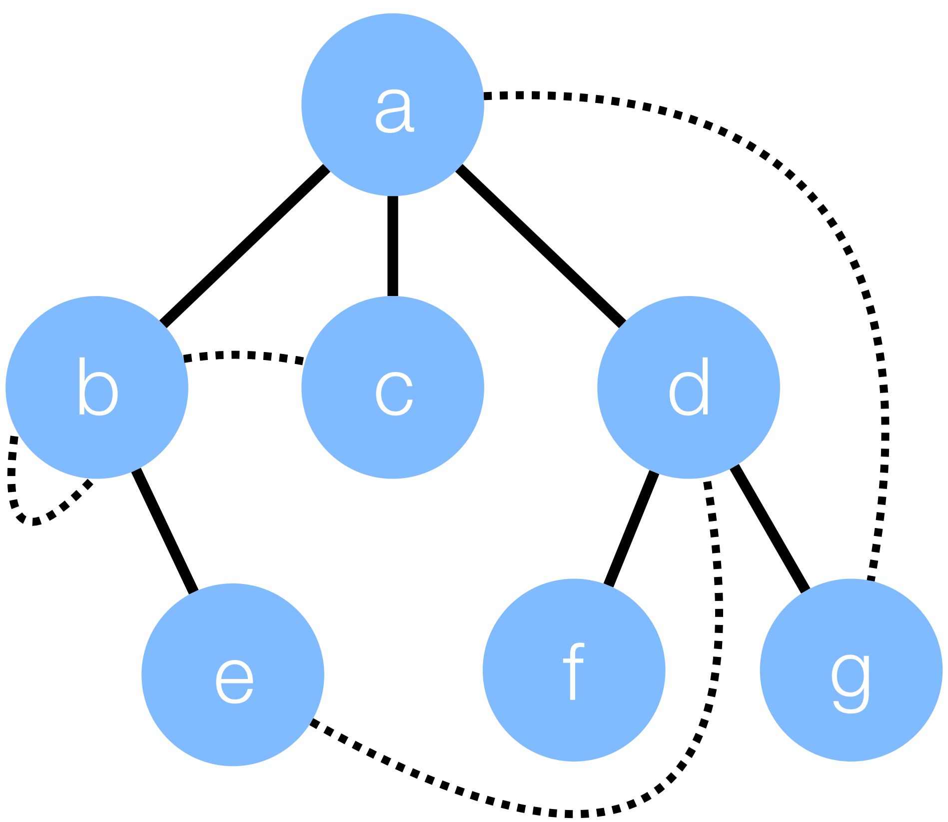

Legend: linear channel; shared channel; linear process; shared process

Let's add sharing

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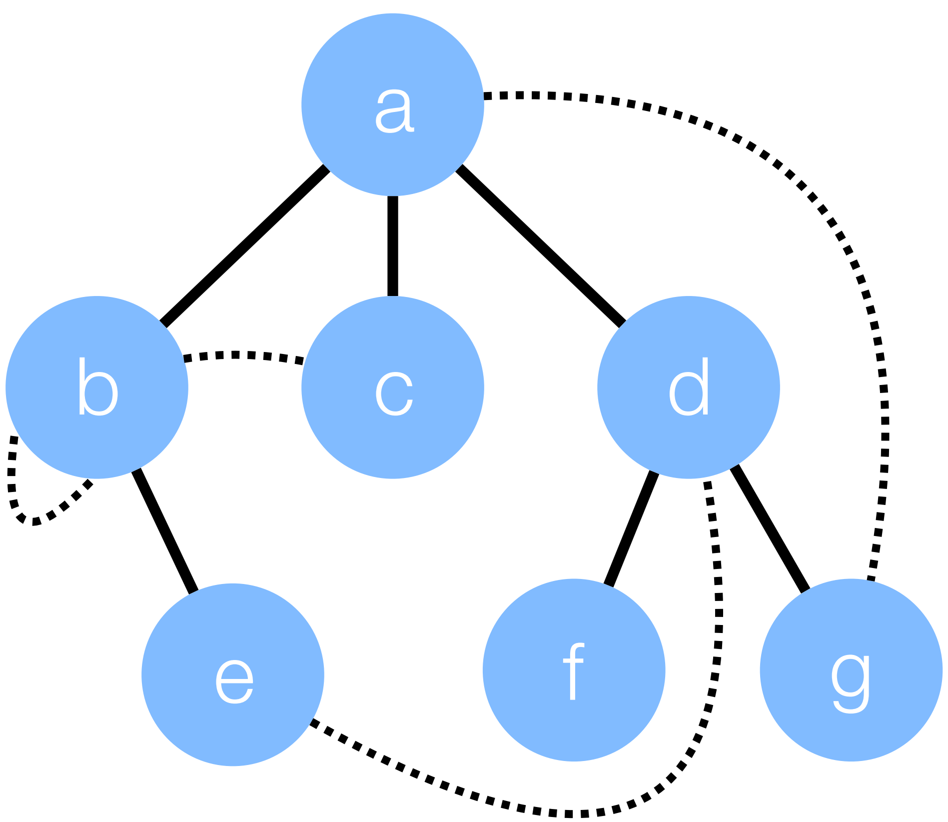

Acquire-release amounts to "locking"

Legend: linear channel · shared channel · linear process · shared process

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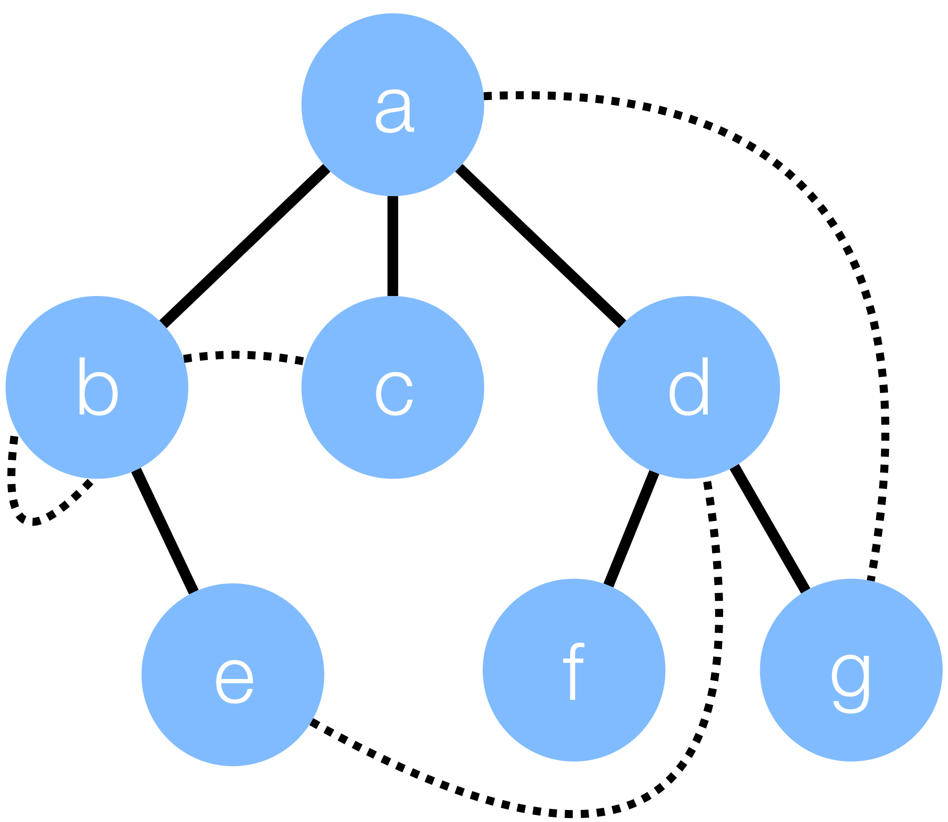
We get a graph of linear and shared processes, with a linear tree inside.



Acquire-release amounts to "locking"

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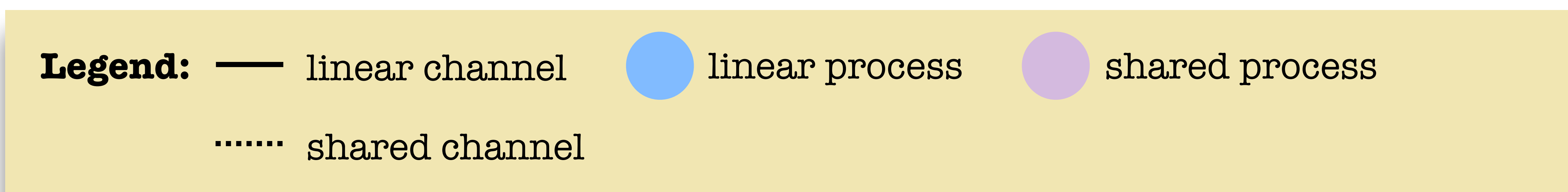

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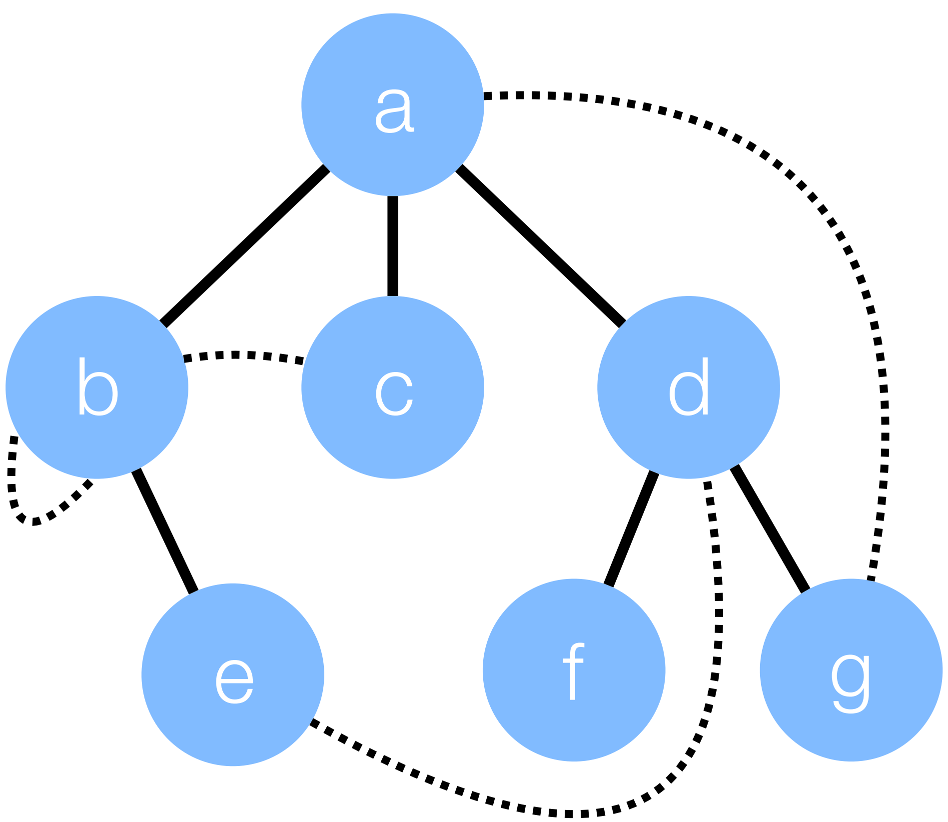

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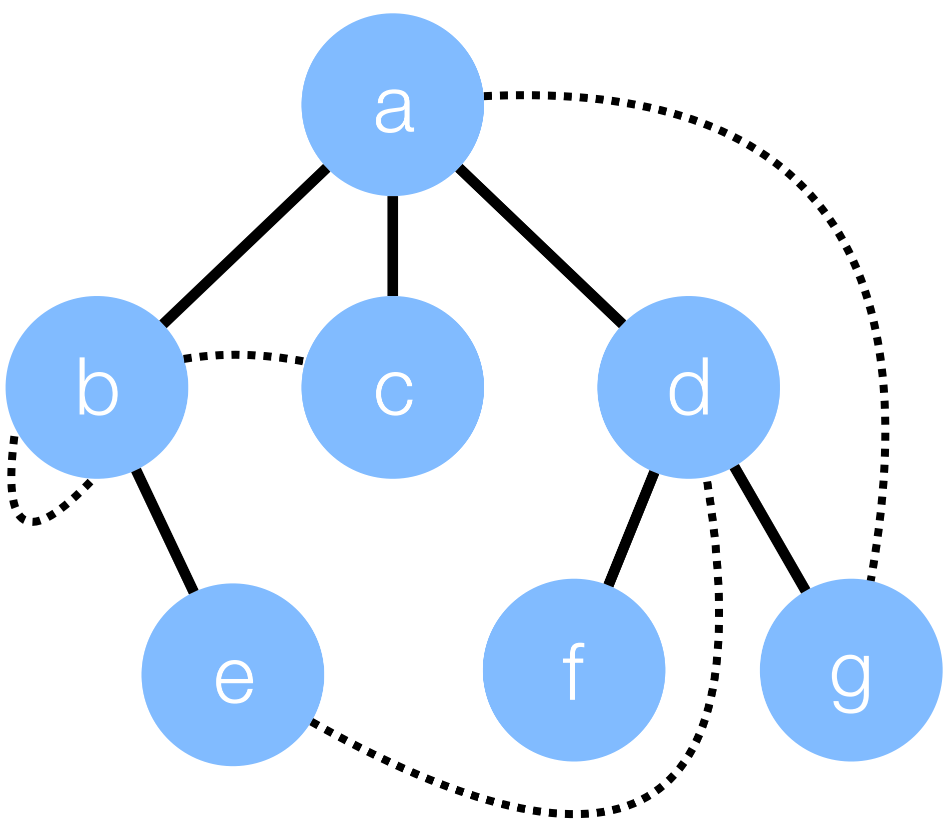

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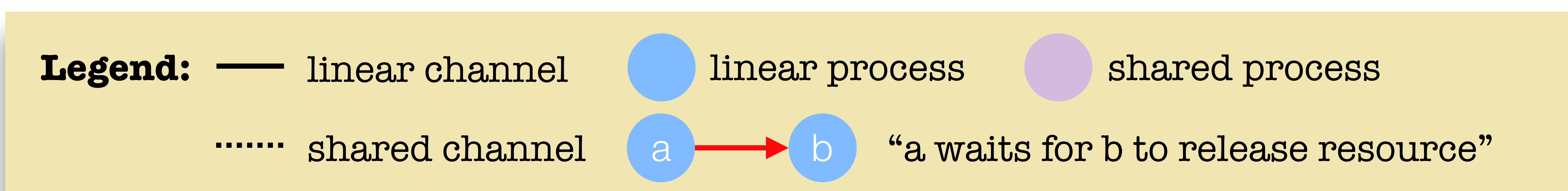

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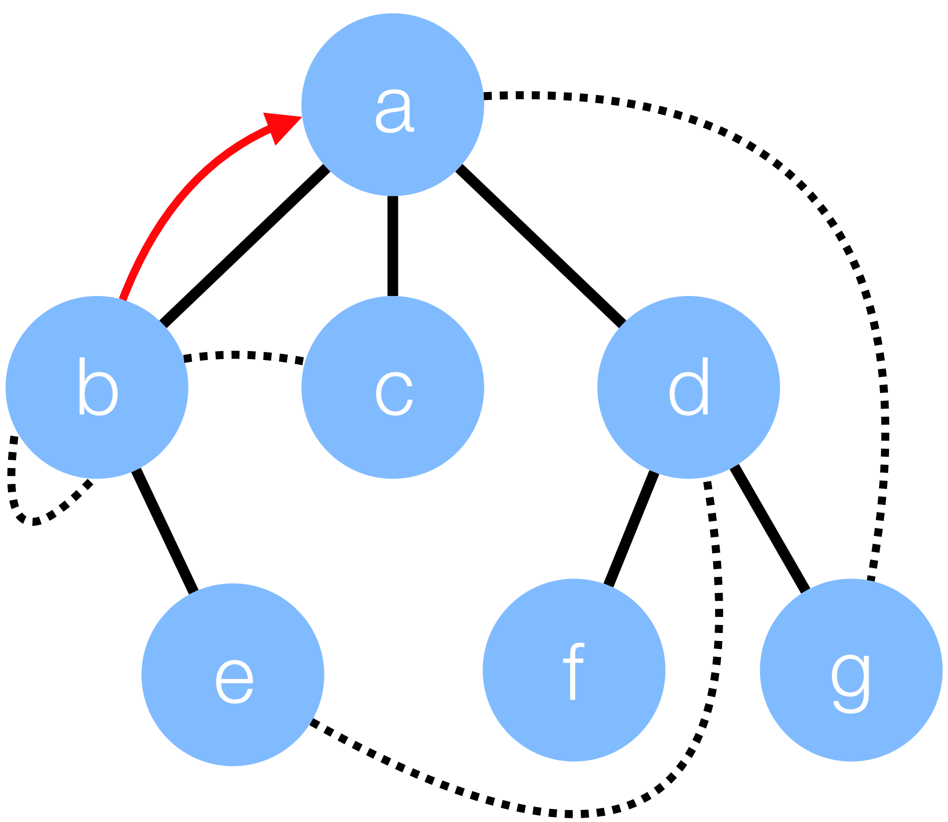

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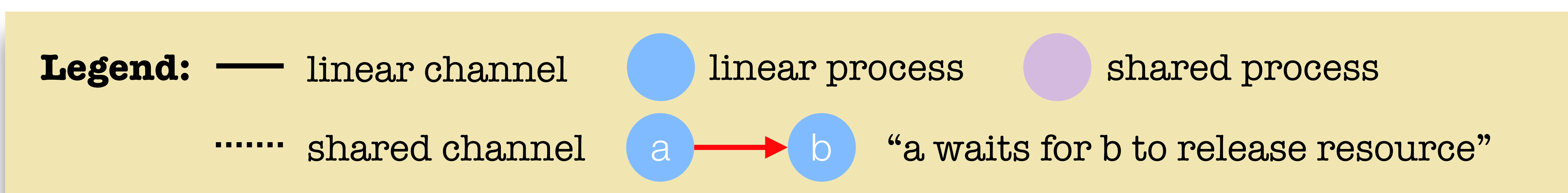

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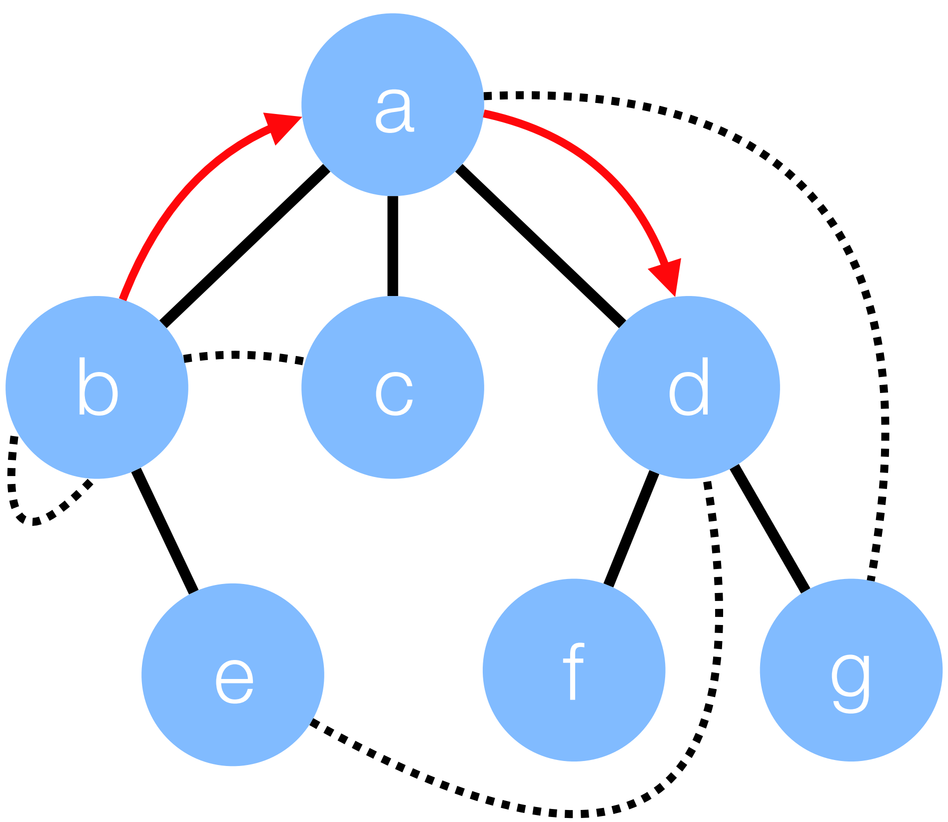

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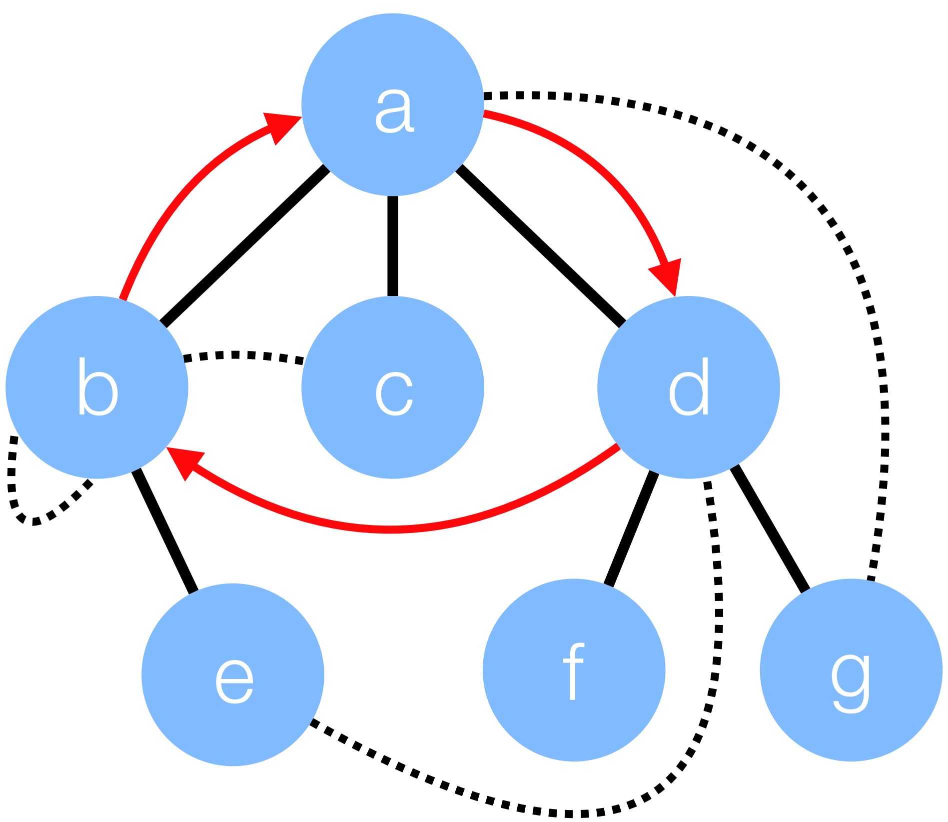

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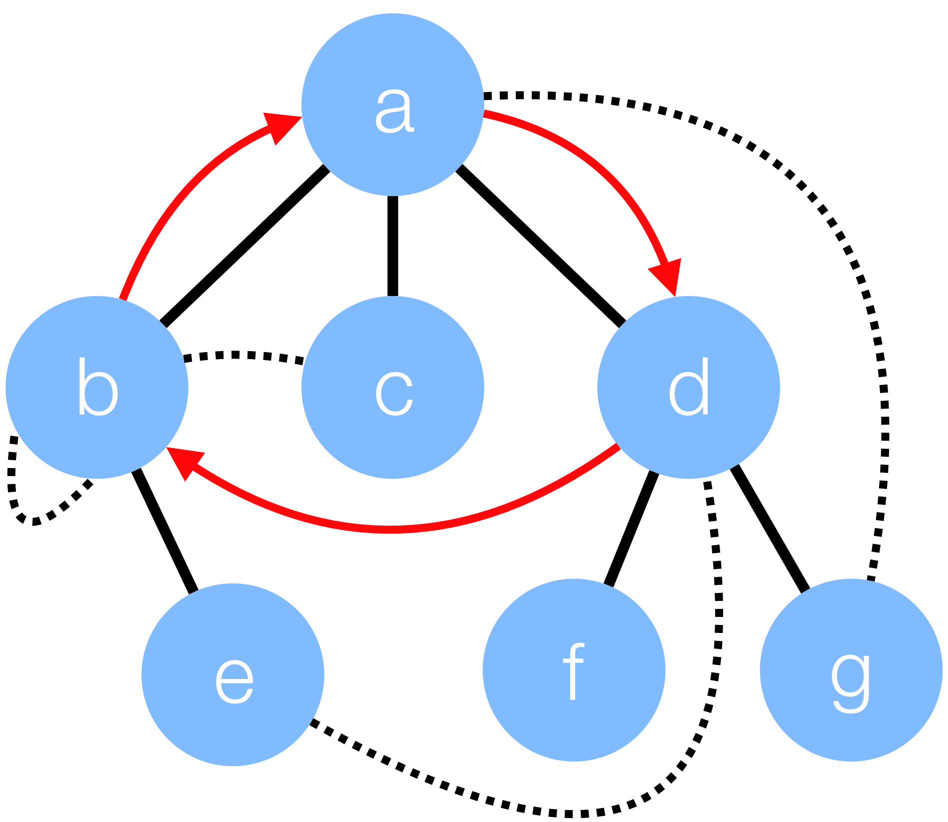

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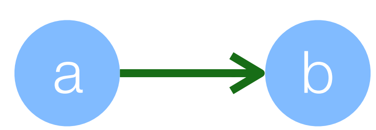
- waiting to synchronize: 

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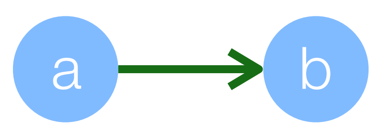
- waiting to synchronize: 

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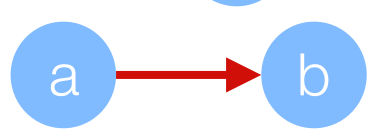
- waiting to release: 

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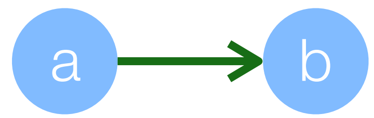
- waiting to synchronize: 

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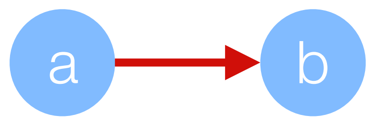
- waiting to release: 

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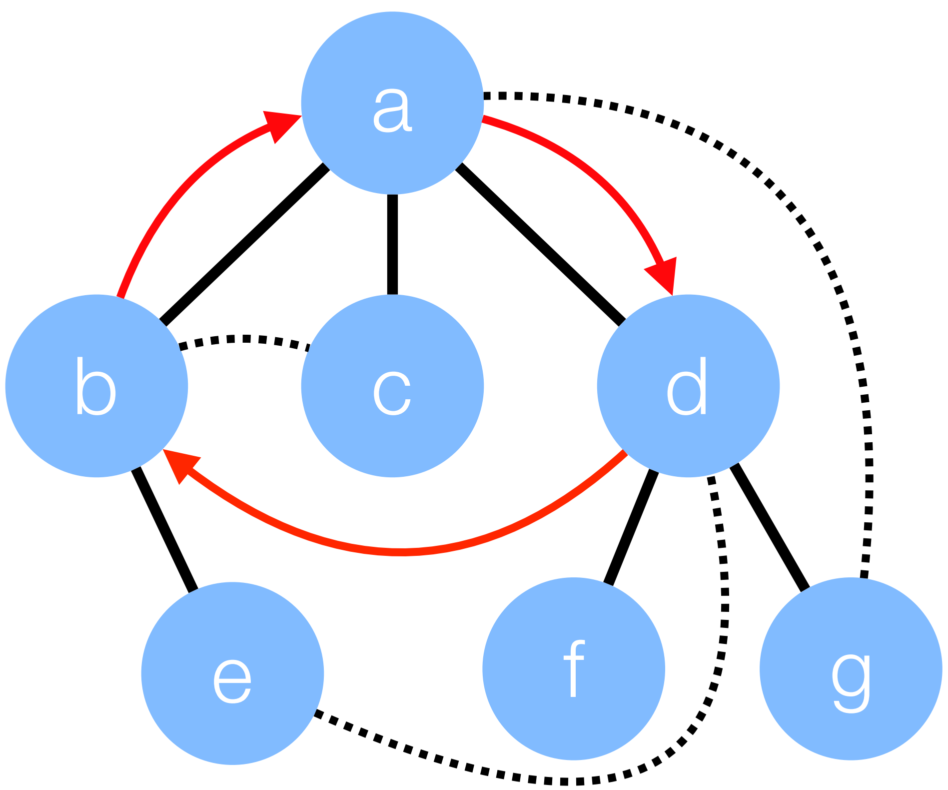

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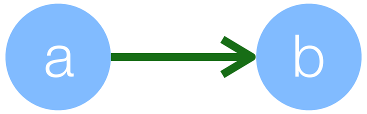
- waiting to synchronize: 

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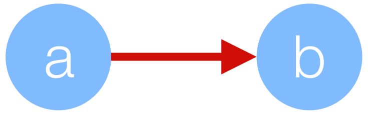
- waiting to release: 

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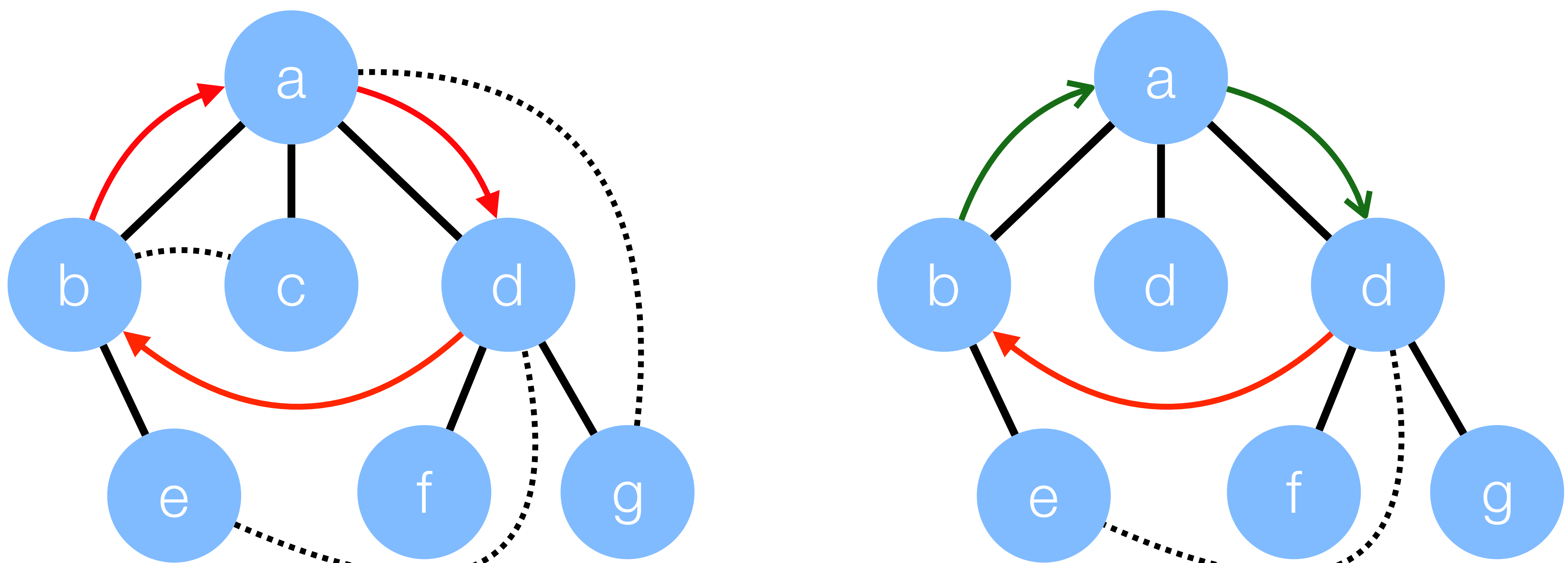

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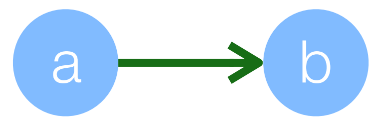
- waiting to synchronize: 

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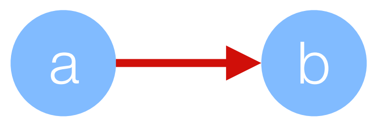
- waiting to release: 

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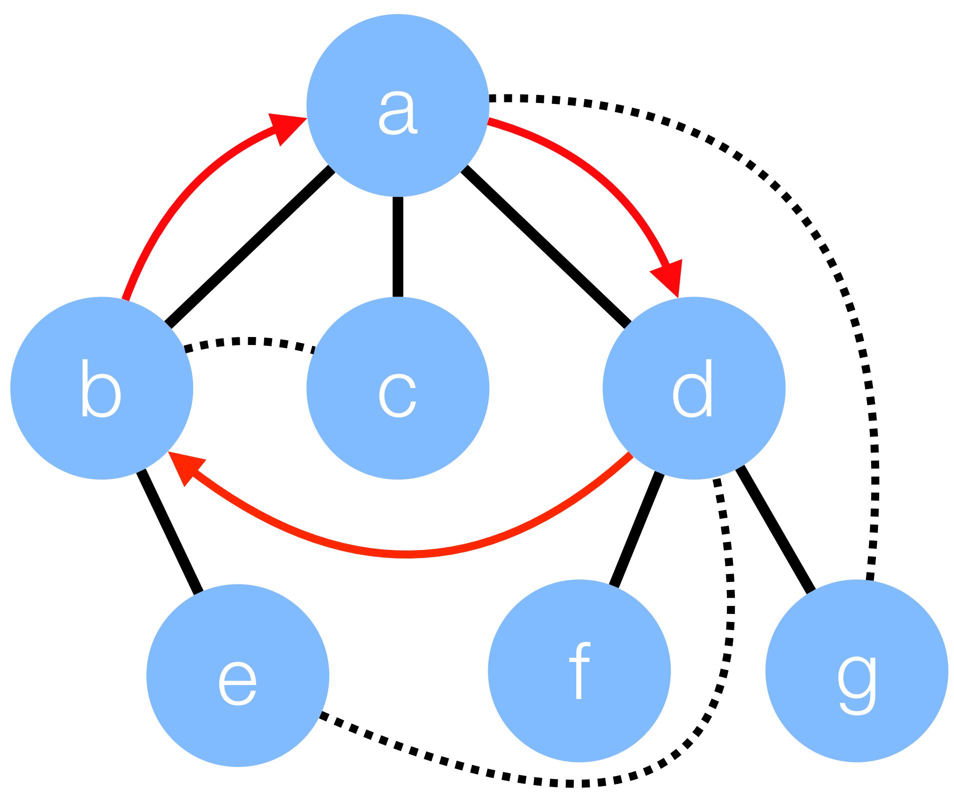

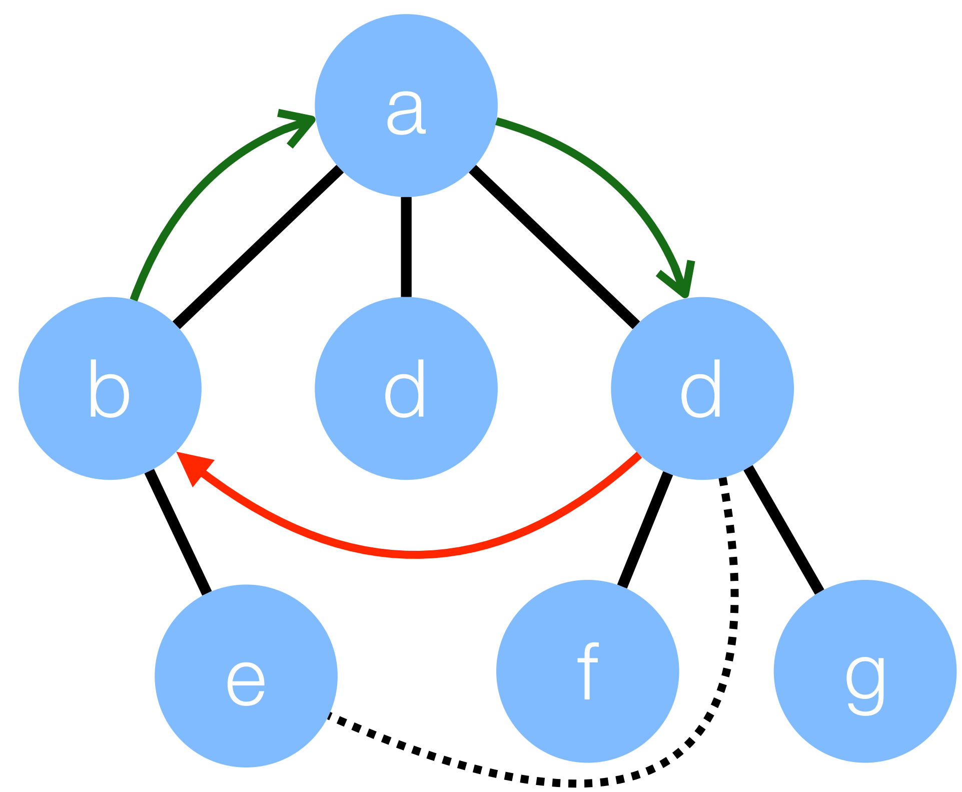

Cycles can consist of red arrows only or a combination of red and green arrows.

Idea: competitors and collaborators

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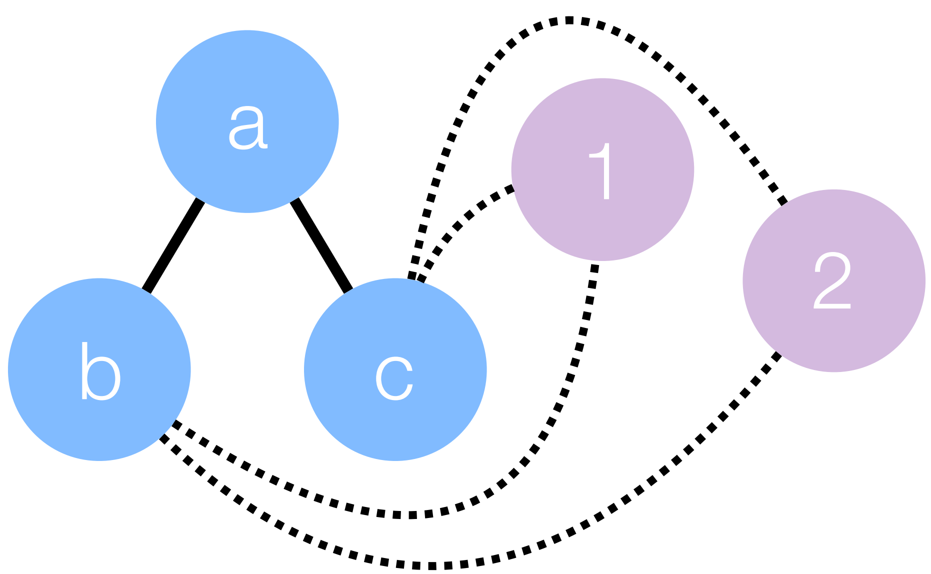

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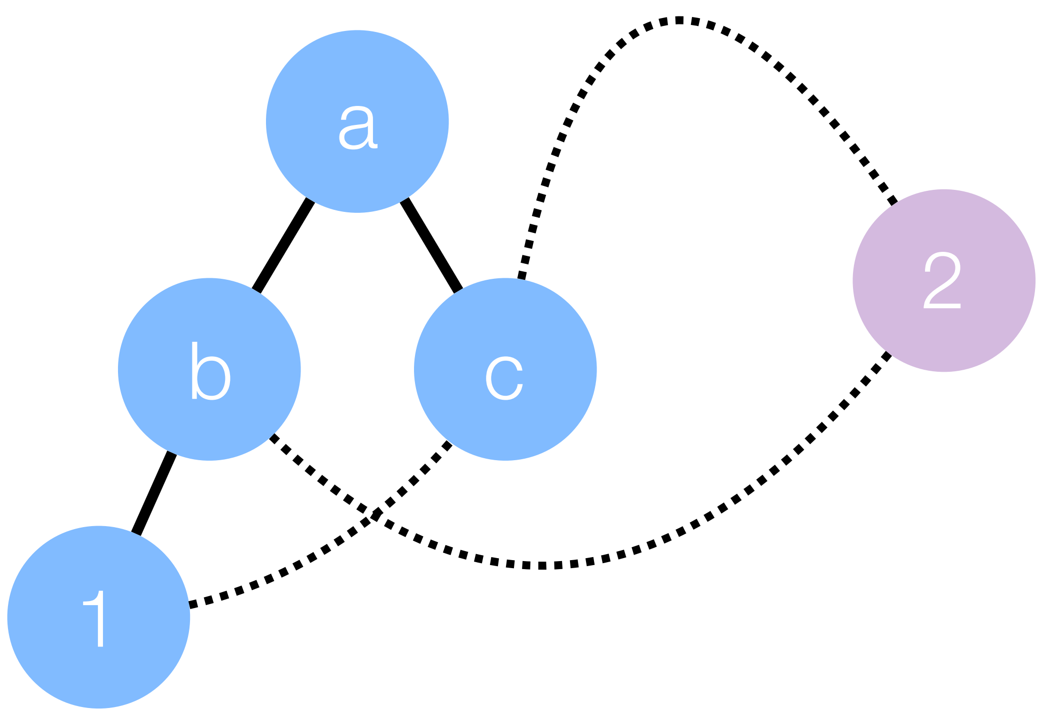

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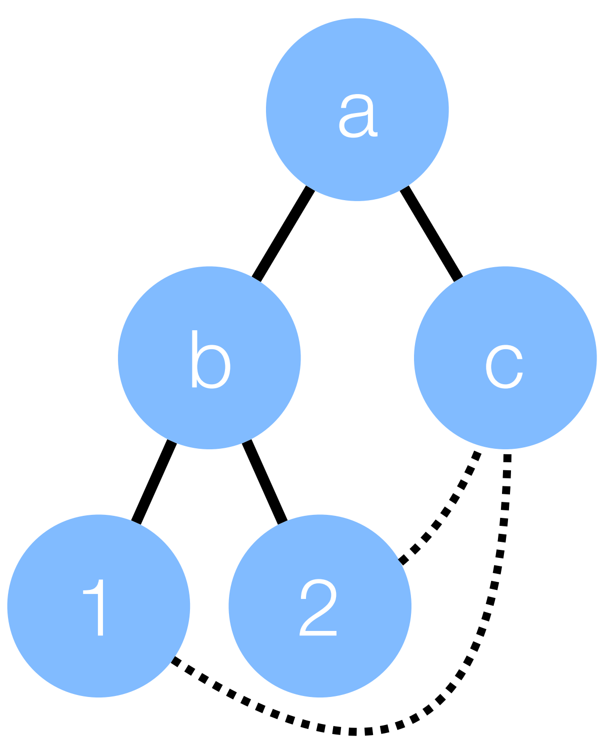

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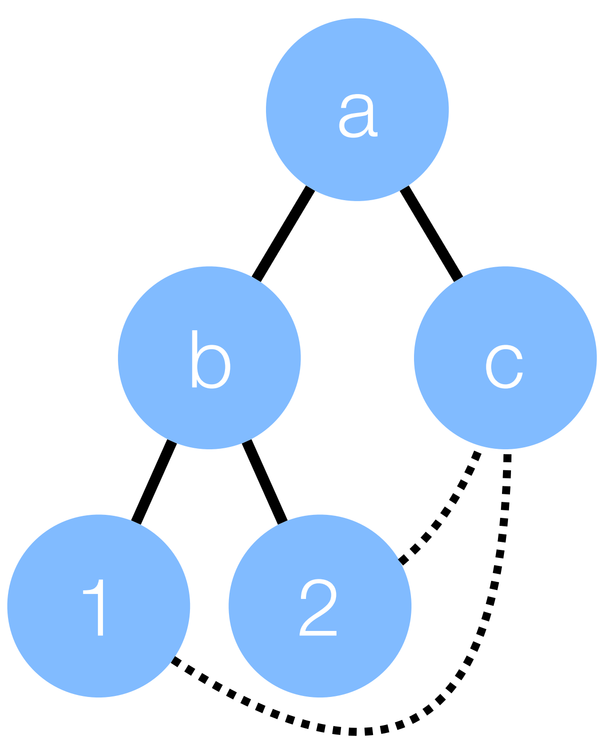

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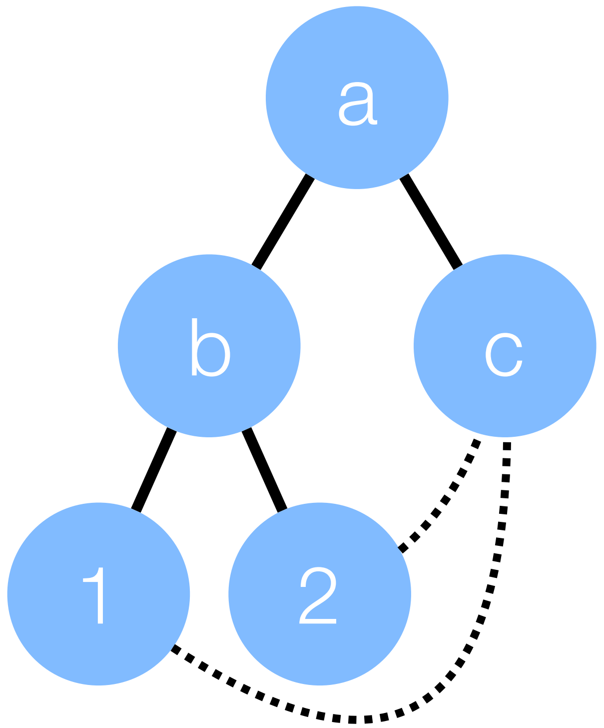

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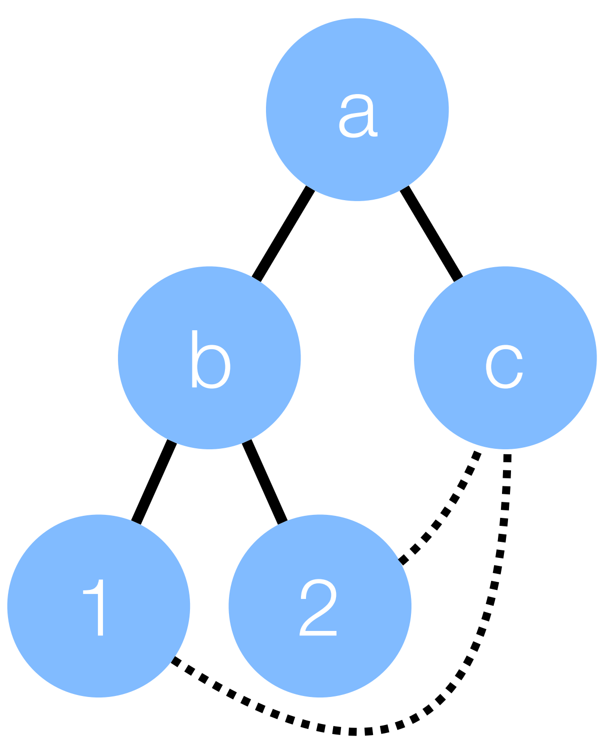

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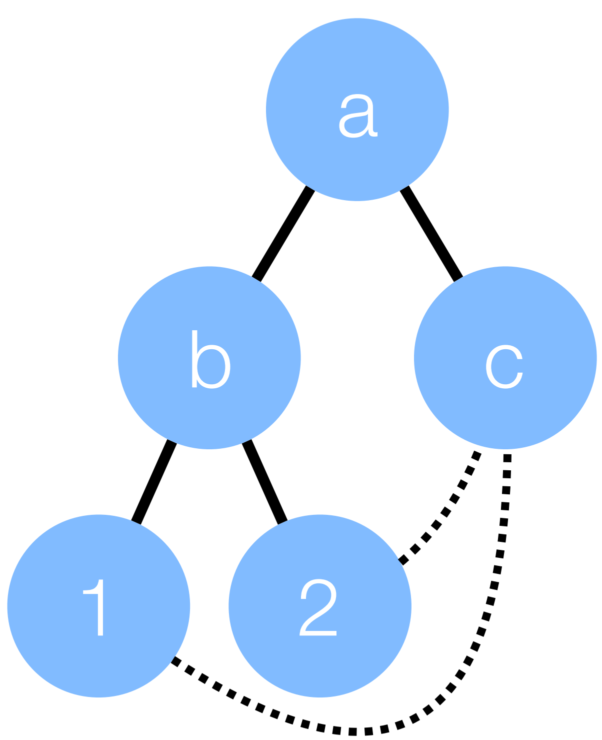

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{a, b, 1} {a, b, 2} {a, c}

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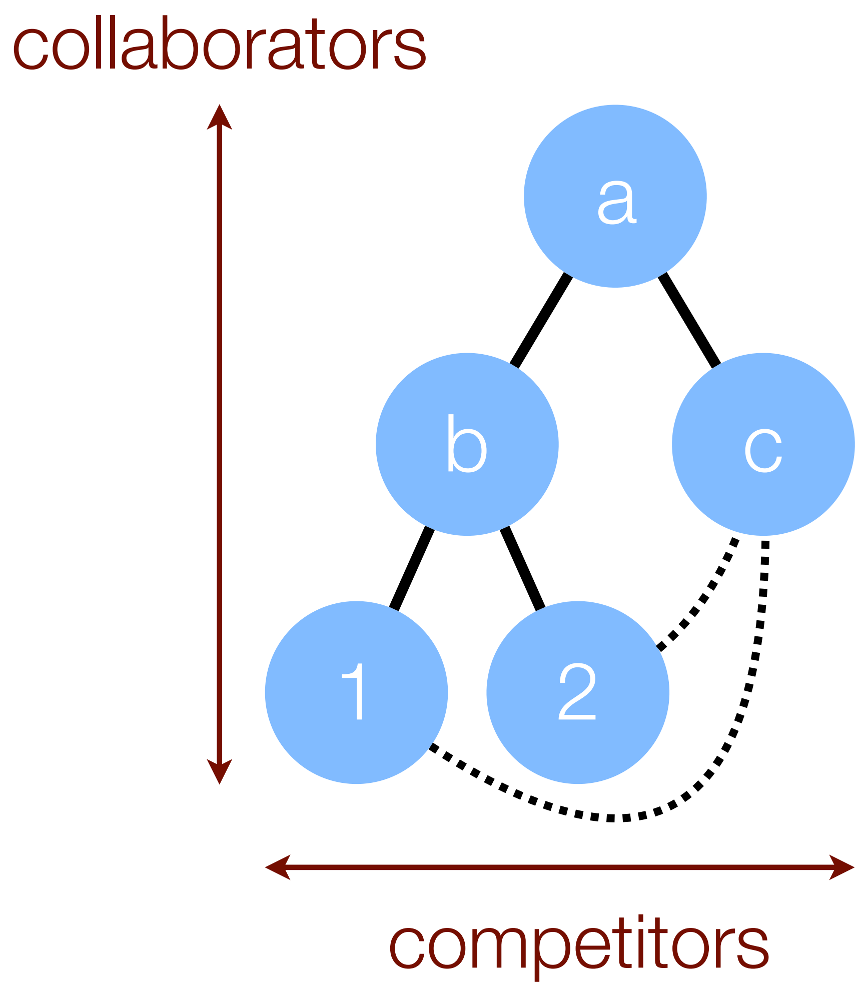
Define type system enforcing the following invariants:



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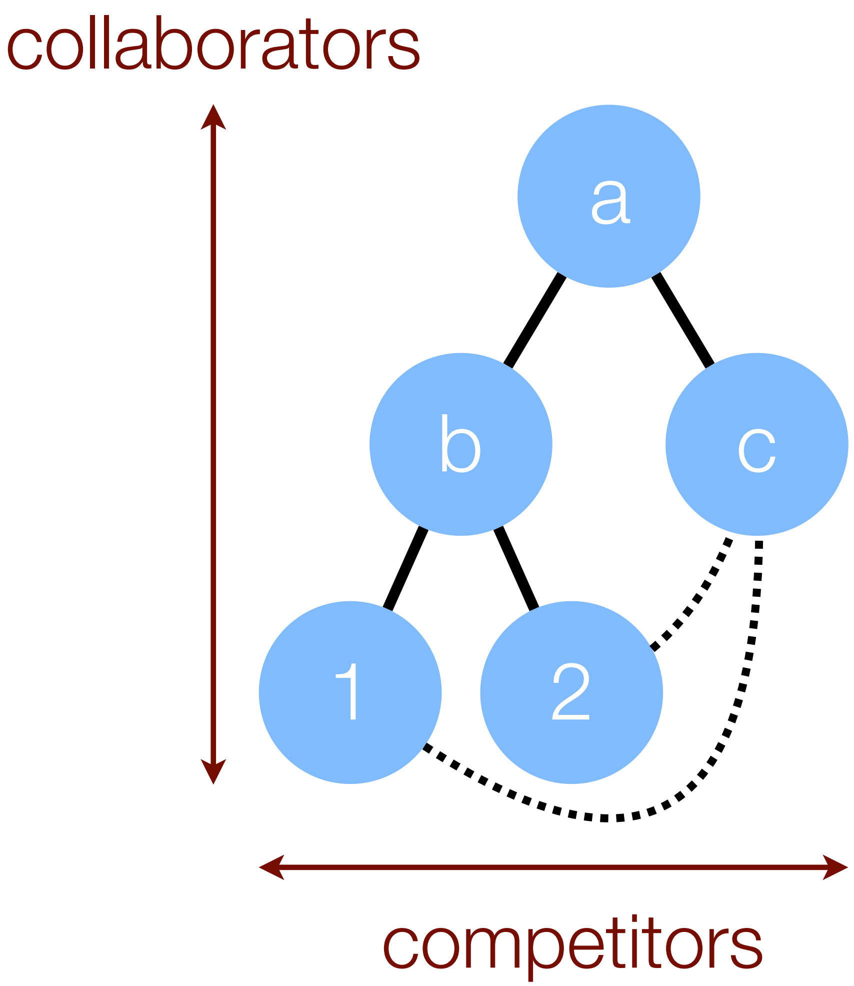

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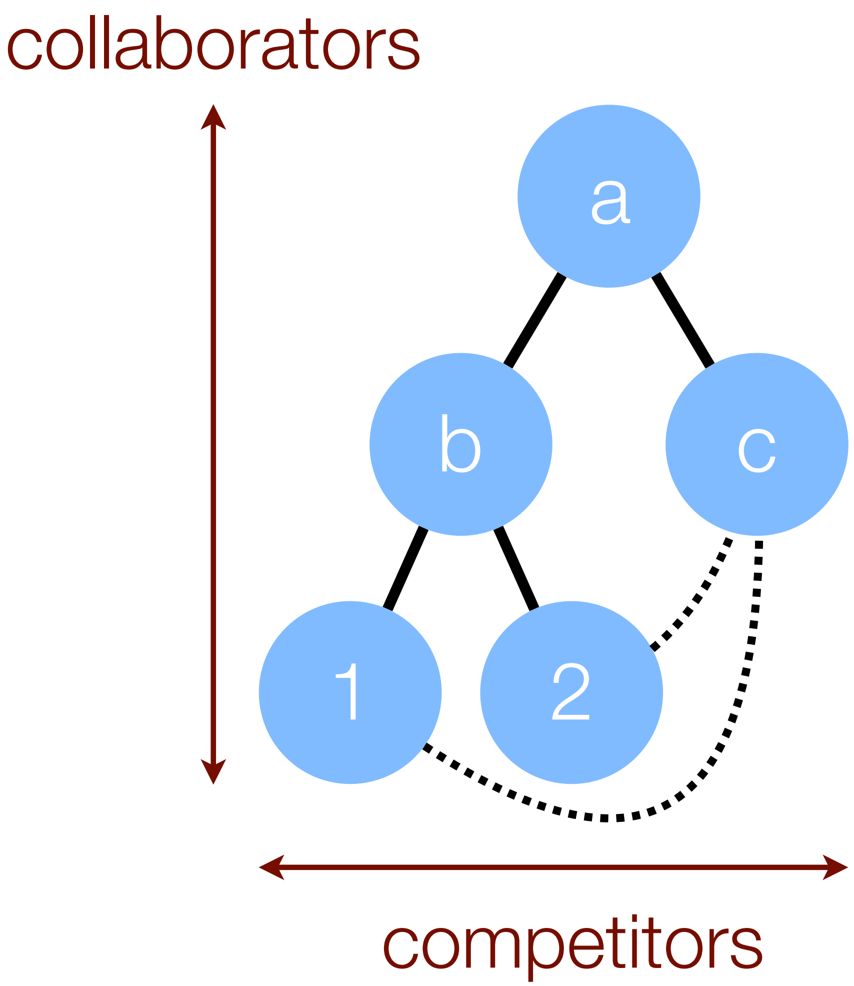

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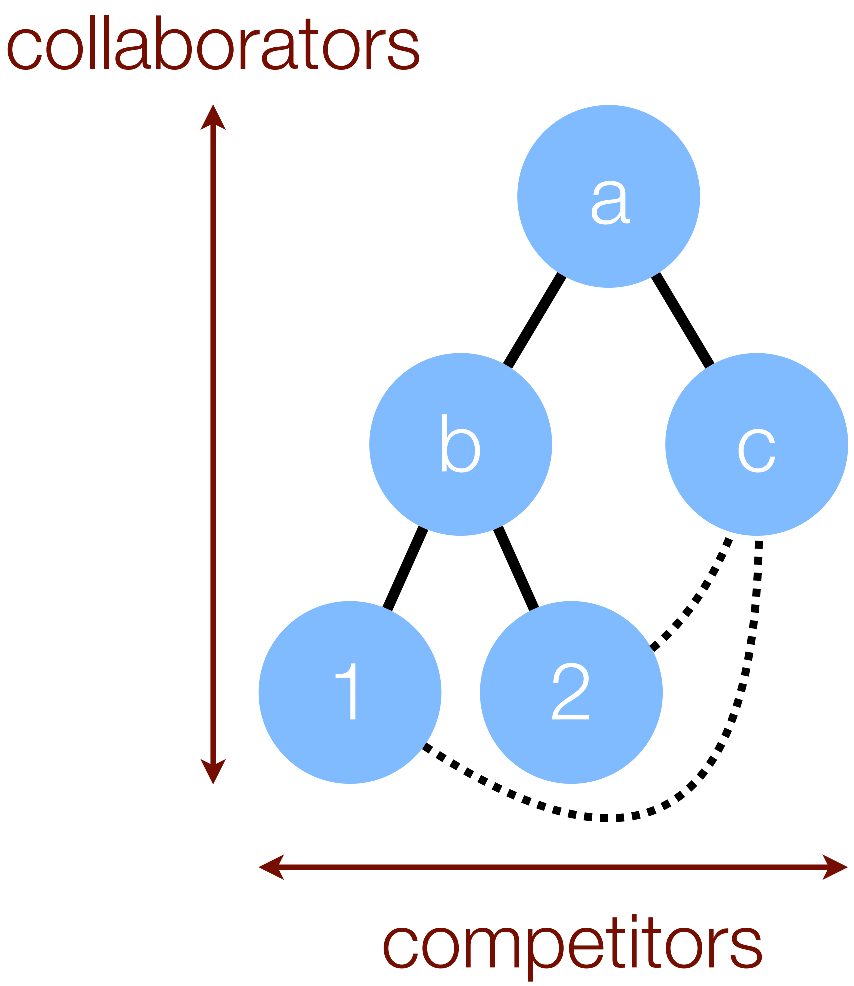

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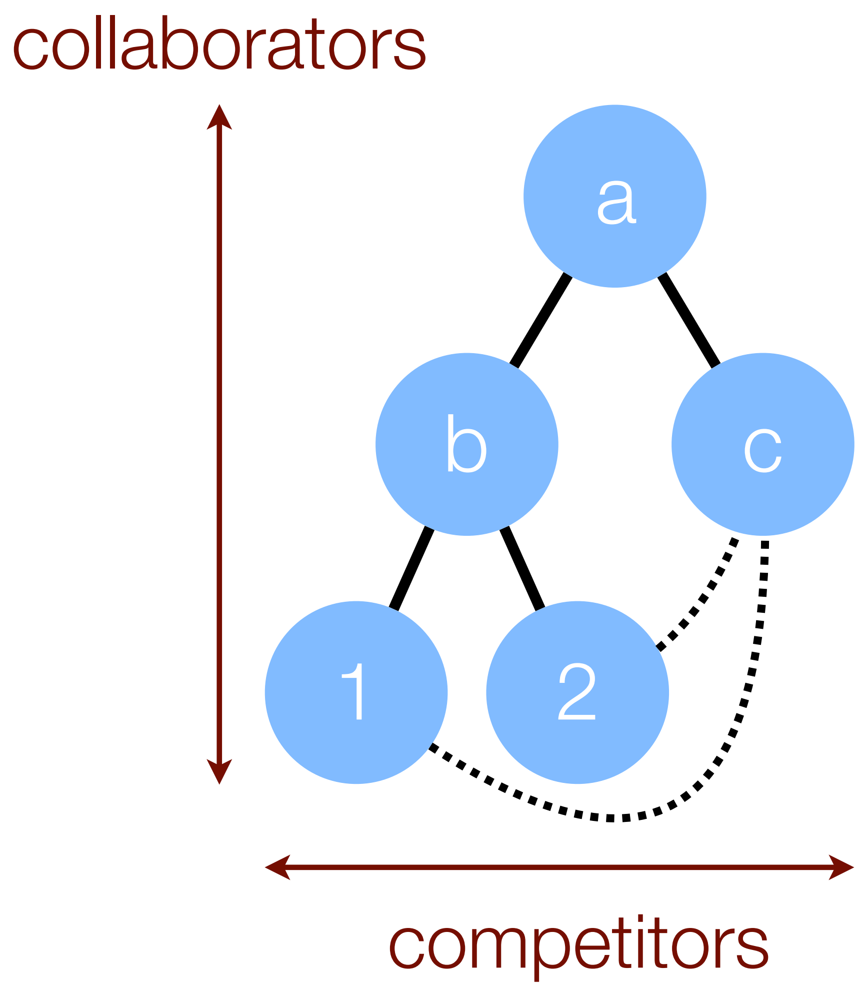

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A rules out red-arrow cycles, B and C rule out red-green-arrow cycles.

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worlds associated with process

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self-world:
world at which process resides

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min-world:
world of minimal resource
to be acquired

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max-world: world
of maximal resource to be
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Manifest deadlock-freedom

- Introduce a world, an abstract value equipped with a partial order.
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world order

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possibly “aliased”
linear channels

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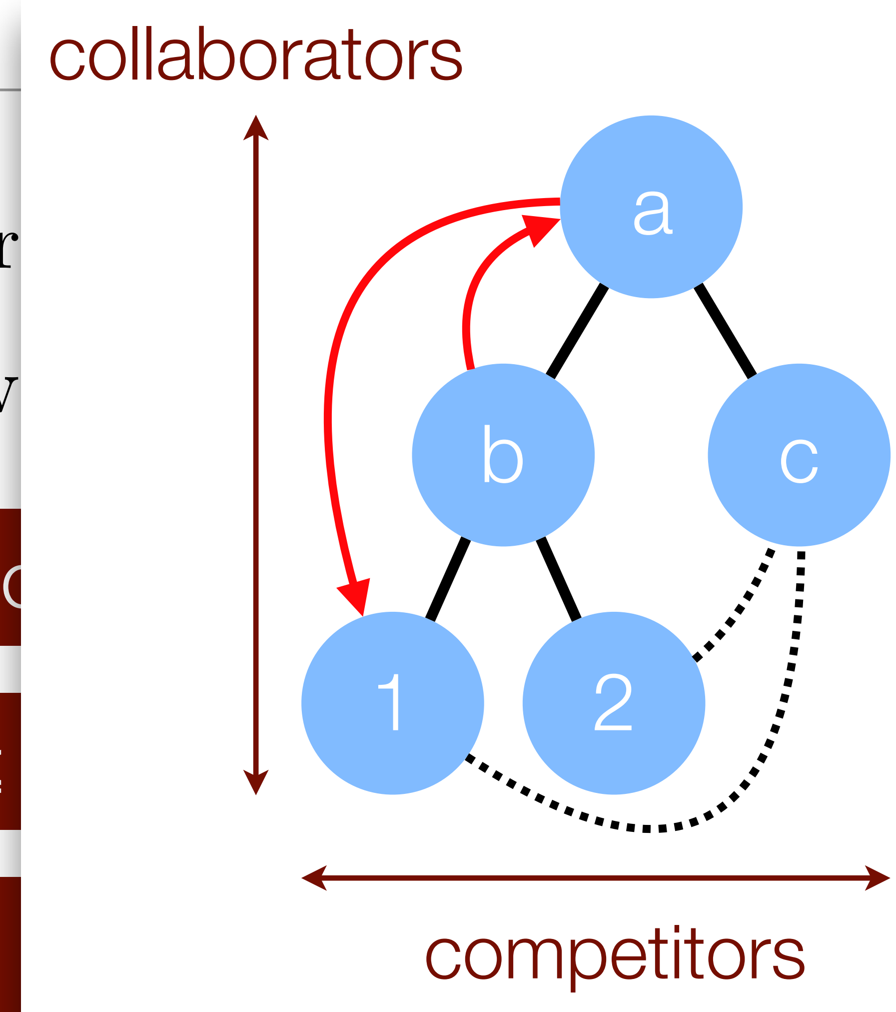

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Manifest deadlock-freedom

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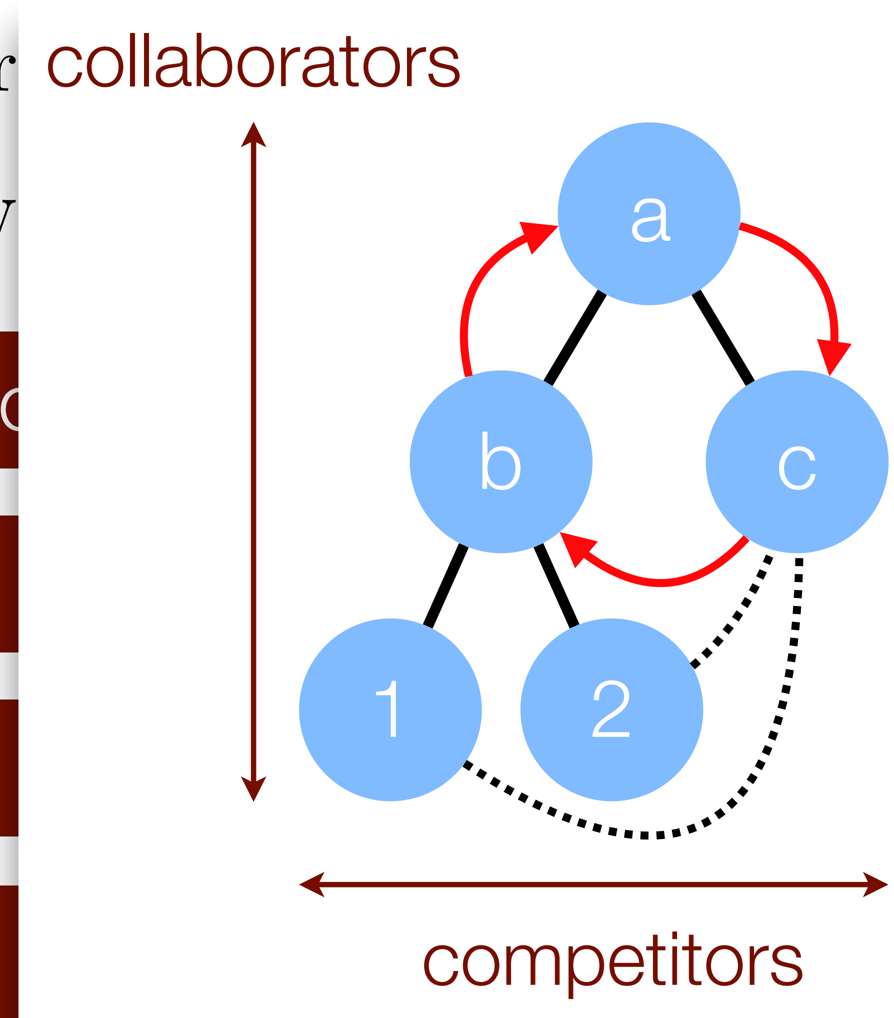

no red cycles

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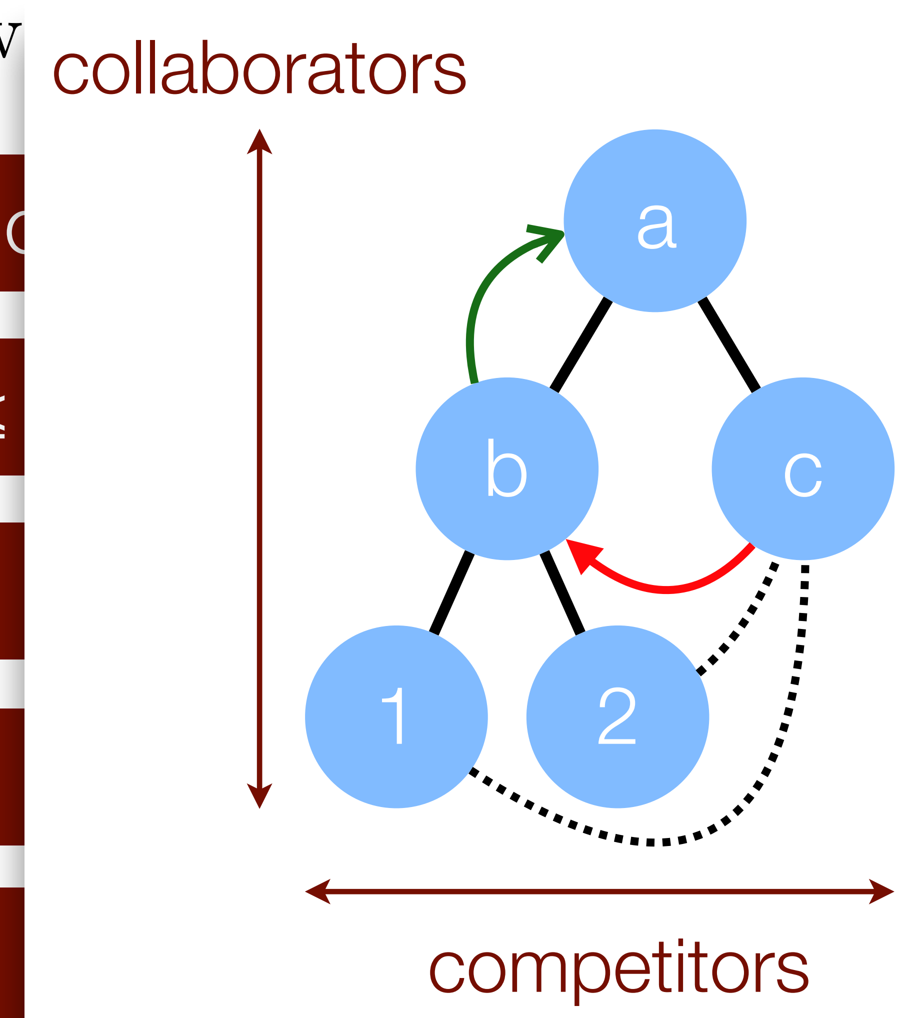

no ingoing red and up-going green arrow

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- These low-level invariants are enforced by typing.

Taking stock

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We have a session type system that allows shared and linear channels to coexist and guarantees:

- data-race-freedom (low-level and high-level)
- protocol adherence
- deadlock-freedom

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- We have a session type system that allows shared and linear channels to coexist and guarantees:
  - data-race-freedom (low-level and high-level)
  - protocol adherence
  - deadlock-freedom
- We have increased practicality of linear session types while maintaining their guarantees.

Current & future work

Digital contracts (with Hoffmann, Pfenning, and Das)

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Unique application field for shared session types:

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\mathsf{auction} = {\uparrow}_{\mathsf{L}}^{\mathsf{S}} \oplus \{&\mathsf{running} : \&\{\mathsf{bid} : \mathsf{id} \to \mathsf{money} \multimap {\downarrow}_{\mathsf{L}}^{\mathsf{S}}\mathsf{auction}, \\
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Resource analysis for static prediction of execution cost.

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Resource analysis for static prediction of execution cost.

Under development: Nomos, a digital contract language based on resource-aware shared session types.

Unifying parallelism and concurrency

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Shared session types recover expressiveness of untyped asynchronous pi-calculus [Balzer et al. CONCUR 2018]

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introduce nondeterminism

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linear logic session types are deterministic

Unifying parallelism and concurrency

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- introduce nondeterminism
- linear logic session types are deterministic

Opportunity for unifying framework that combines both deterministic (parallel) and nondeterministic (concurrent) computation.

Thank you for your attention!

Papers for this talk:

- Stephanie Balzer and Frank Pfenning: Manifest Sharing with Session Types. ICFP 2017.
- Stephanie Balzer, Bernardo Toninho, and Frank Pfenning: Manifest Deadlock-Freedom for Shared Session Types. ESOP 2019.
- Stephanie Balzer, Frank Pfenning, and Bernardo Toninho: A Universal Session Type for Untyped Asynchronous Communication. CONCUR 2019.