Exception Handling for Copyless Messaging

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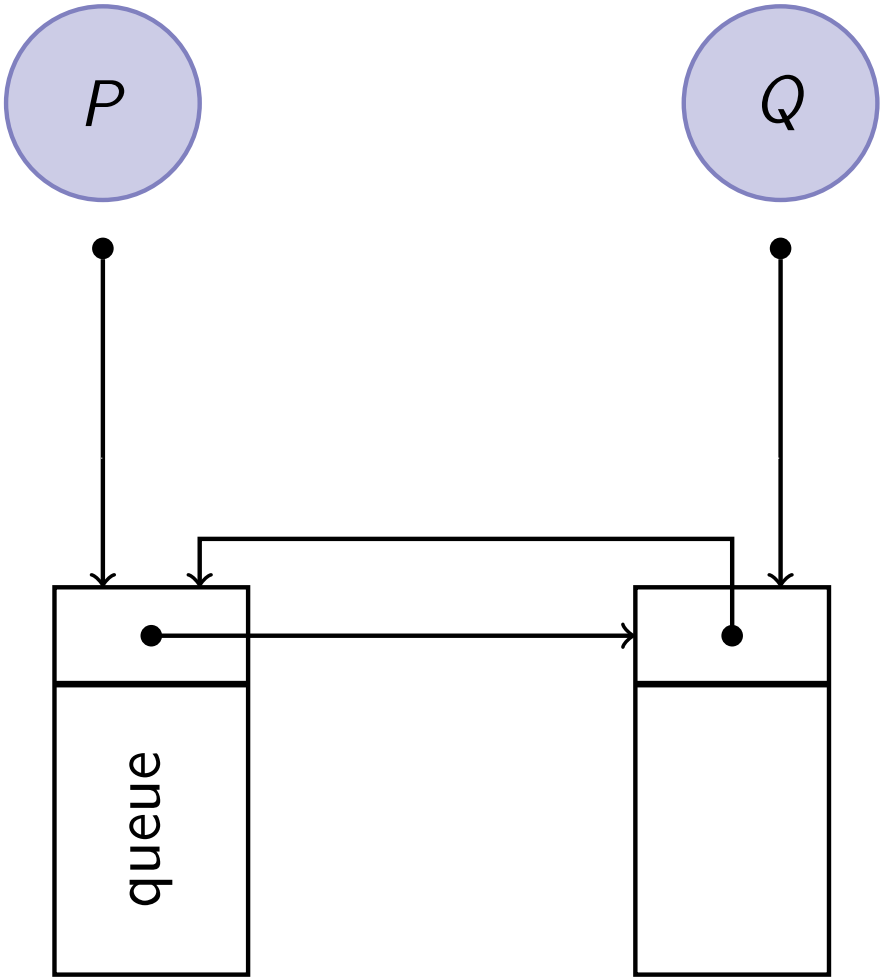
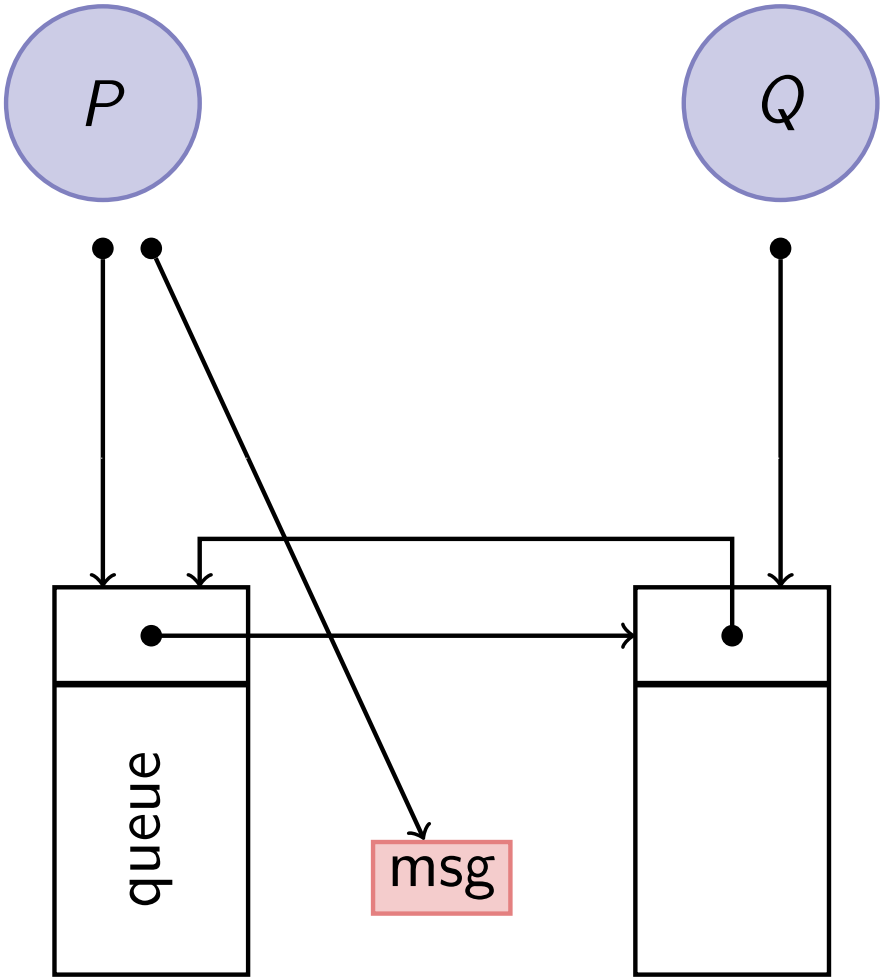
Copyful messaging



Copyful messaging



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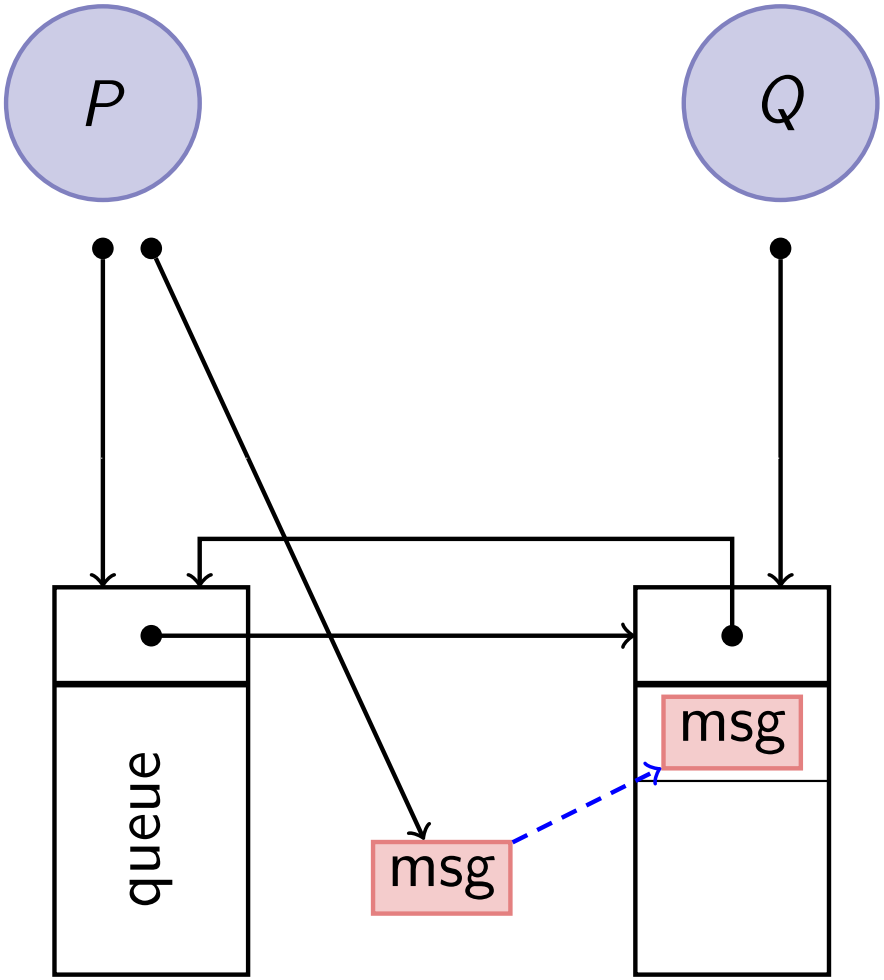

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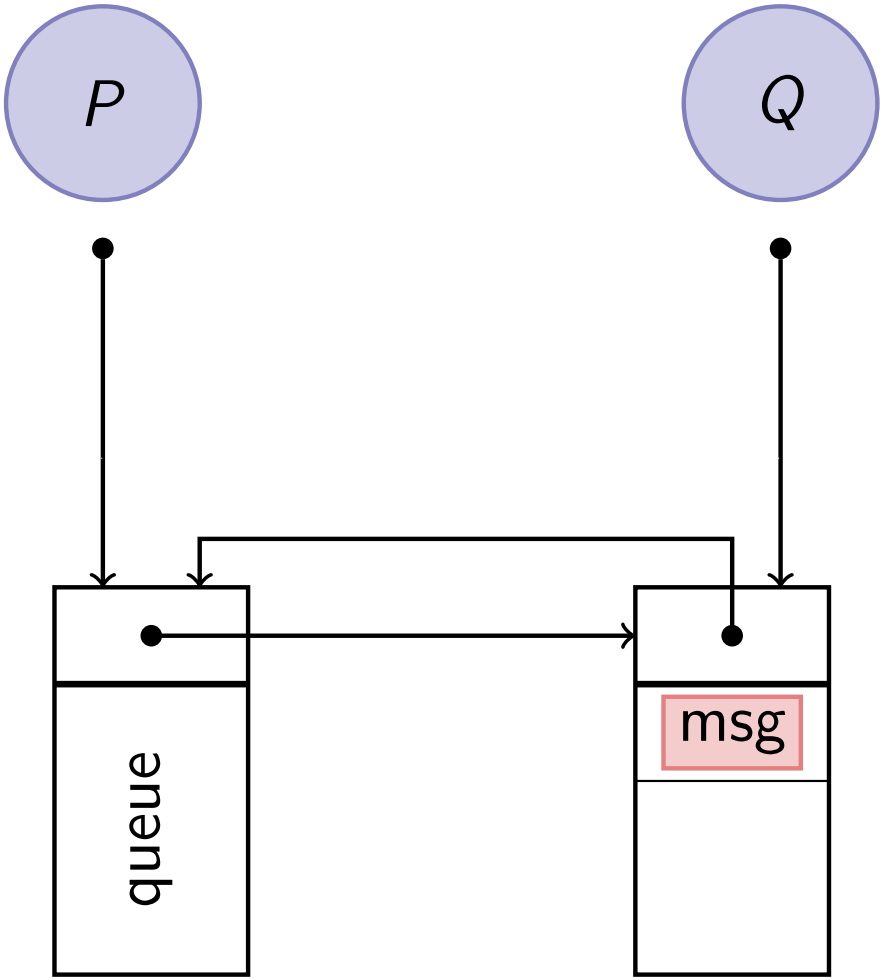
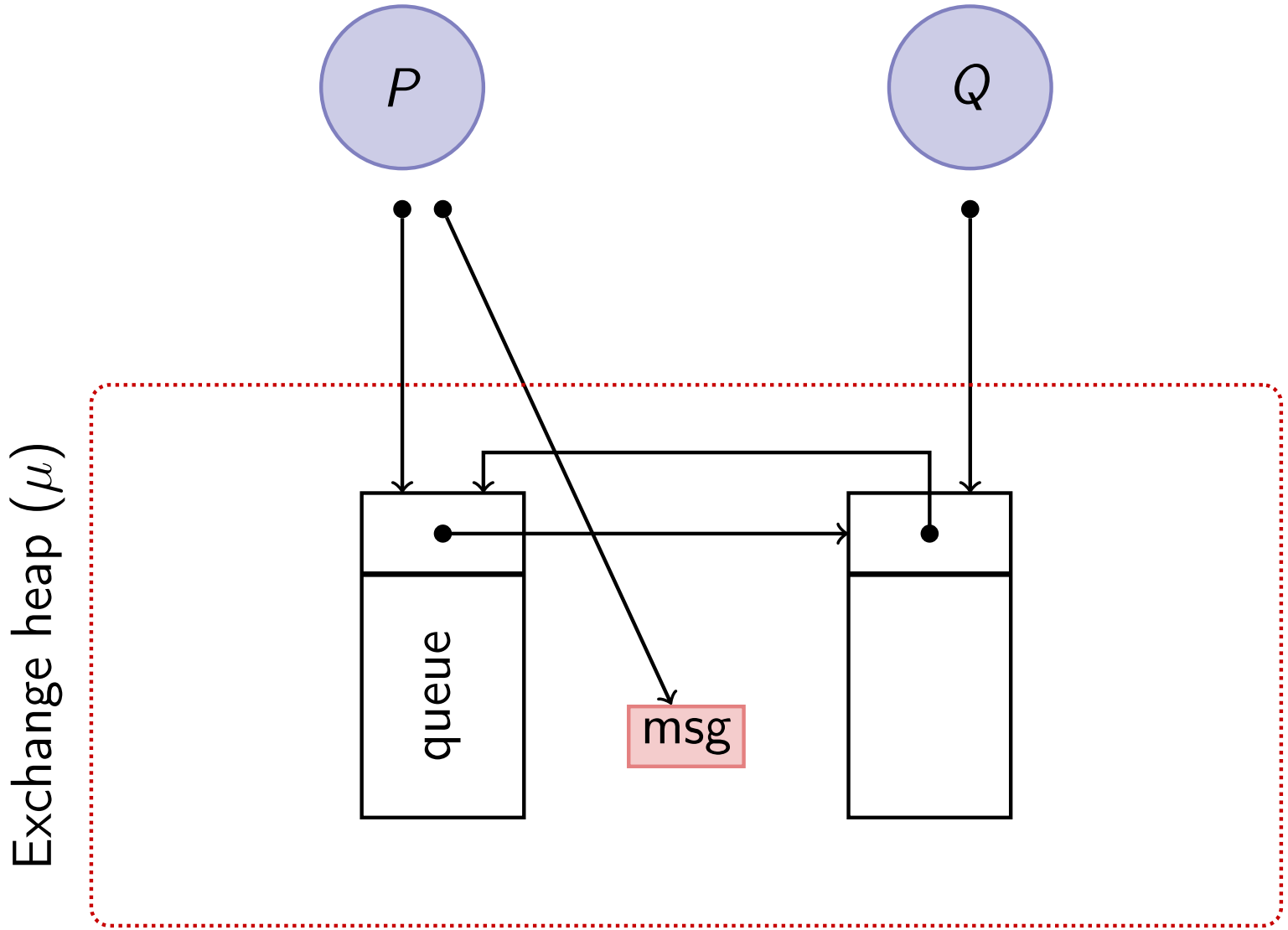


Copyless messaging



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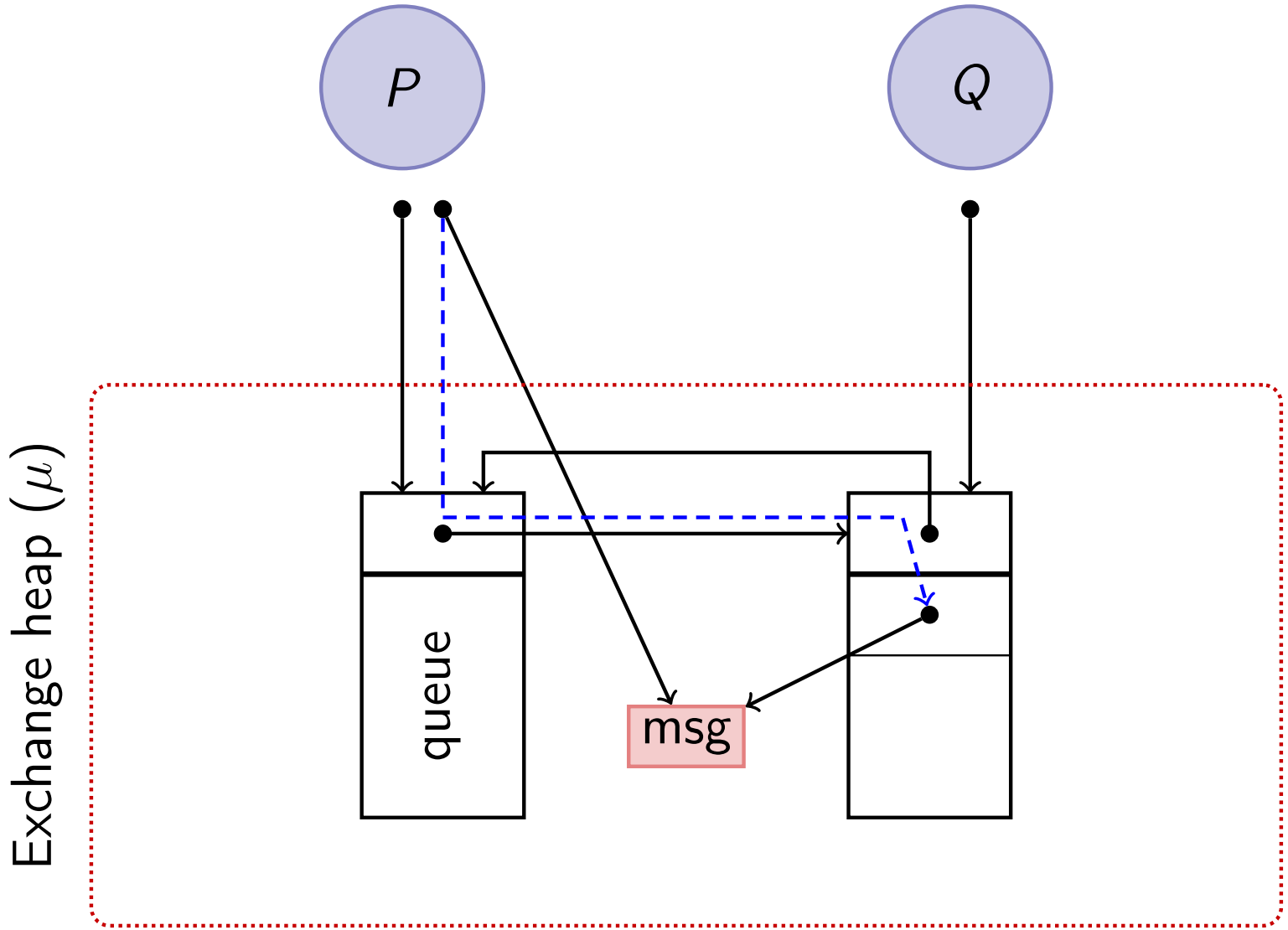

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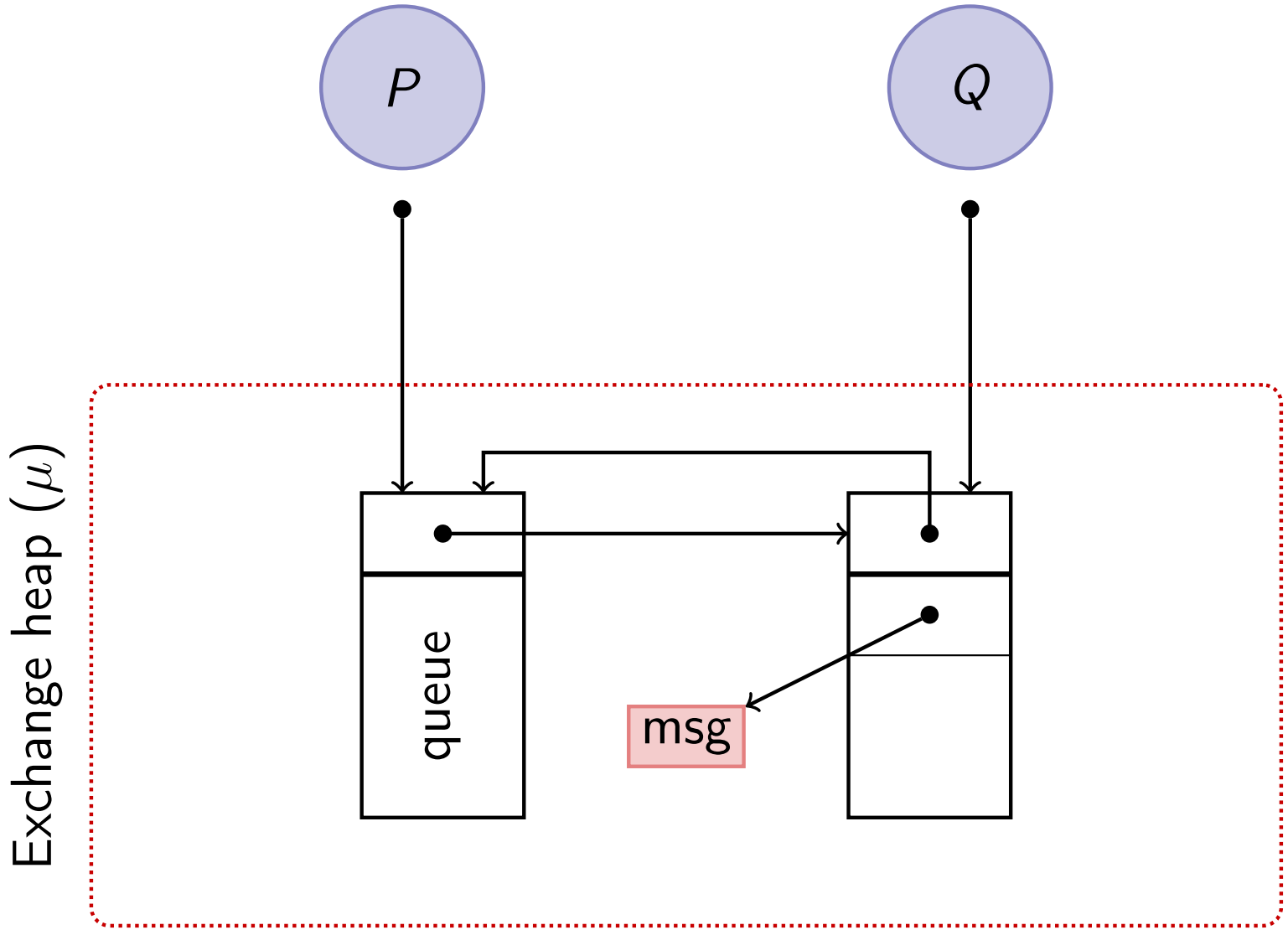

An example from Singularity OS

```
ns = DS.NewClientEndpoint();
try {
  while (true) {
    NewChannel(out imp, out exp);
    ns.SendRegister(imp);
    switch receive {
      case ns.AckRegister():
        return exp;
      case ns.NakRegister(nakImp, error):
        if (error != AlreadyExists)
          throw new Exception();
        delete exp;
        delete nakImp;
    }
  }
} finally { delete ns; }
```

Safety properties

Safety is...

- no communication errors
- no memory faults
- no memory leaks

Recipe for safety

- use channel contracts (aka session types)
- impose linear ownership of pointers (+ a little more)

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Preventing communication errors

```
contract DSContract { // default is exporting view
  state Ready {
    Register? → DoRegister;
    CreateDirectory? → ...
    // ...more transitions
  }
  state DoRegister {
    AckRegister! → Stop;
    NakRegister! → Ready;
  }
  state Stop { }
}
```

$$\texttt{DSContract.Exp} : \texttt{Ready} = \texttt{rec}\ \alpha.?\texttt{Register}.(!\texttt{AckRegister.end} \oplus !\texttt{NakRegister}.\alpha)$$

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Preventing memory faults and leaks

Each pointer is owned by exactly one process

- Process isolation = no faults
- Single ownership = no leaks

Preventing memory faults and leaks

```
ns = DS.NewClientEndpoint();
try {
  while (true) {
    NewChannel(out imp, out exp); { imp, exp }
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      case ns.NakRegister(nakImp, error): { exp, nakImp }
        if (error != AlreadyExists)
          throw new Exception(); // leak
        delete exp; { nakImp }
        delete nakImp; { }
    }
  }
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```

Dealing with exceptions (damage control)

Dynamic type checking

```
if (ns.InState(DSContract.Imp:Ready)) ...
```

- ☹ error prone
- ☹ defeats the purpose of static type checking

Careful placement of `delete`

- ☹ error prone
- ☹ sometimes impossible (scoping rules)

Our proposal: `try` block = transaction

When the transaction starts...

- synchronize affected processes
- save state of the heap

If an exception is thrown...

- undo heap changes
- notify affected processes and run handlers

If the transaction completes...

- discard handlers
- commit heap changes

Our proposal: `try` block = transaction

When the transaction starts...

- synchronize affected processes
- ~~save state of the heap~~ do nothing

If an exception is thrown...

- ~~undo heap changes~~ do some local clean up
- notify affected processes and run handlers

If the transaction completes...

- discard handlers
- ~~commit heap changes~~ do nothing

Modeling processes

P	::=		**Process**
		done	(inaction)
	$\mid$	open$(a, b).P$	(open channel)
	$\mid$	close$(u).P$	(close endpoint)
	$\mid$	$u!\mathtt{m}\langle v\rangle.P$	(send)
	$\mid$	$\sum_{i\in I} u?\mathtt{m}_i\langle x_i\rangle.P_i$	(receive)
	$\mid$	$P \oplus Q$	(conditional)
	$\mid$	$P \mid Q$	(parallel)
	$\mid$	try(u) $\{Q\}P$	(start transaction)
	$\mid$	throw	(exception)
	$\mid$	commit$(u).P$	(commit transaction)

Types and endpoint types

T	$::=$		**Endpoint type**
		$\mathtt{end}$	(to-be-closed)
	$\mid$	$\{!\mathtt{m}_i\langle t_i\rangle.T_i\}_{i\in I}$	(output)
	$\mid$	$\{?\mathtt{m}_i\langle t_i\rangle.T_i\}_{i\in I}$	(input)
	$\mid$	$\{S\}[\![T$	(start transaction)
	$\mid$	$]\!]T$	(commit transaction)
t	$::=$		**Type**
		T	(endpoint type)
	$\mid$	$[t]$	(sealed type)

Typing transactions

$$\frac{[\Delta], u : T \vdash P \qquad \Delta, u : S \vdash Q}{\Delta, u : \{S\}[\![T \vdash \mathsf{try}(u)\ \{Q\}P}$$

$$\Delta \vdash \mathsf{throw} \qquad \text{(guarded by } \texttt{try}\text{)}$$

$$\frac{\mathsf{unsealed}(\Delta_2) \qquad \Delta_1, u : T, \Delta_2 \vdash P}{[\Delta_1], u : [\![T, \Delta_2 \vdash \mathsf{commit}(u).P}$$

Heap properties induced by endpoint types

Well-formedness: $[\![$ and $]\!]$ must be balanced

- read: no `end` within transactions
- prevents deallocation of endpoints in transactions (except for endpoints created within transactions)

Duality: $\overline{\{S\}[\![T}} = \{\overline{S}\}[\![\overline{T}$

- read: no input/output allowed at transaction boundaries
- endpoint queues are empty at transaction boundaries

DSContract revisited

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Transaction semantics

$$\mu; (\mathsf{try}(a)\ \{Q_1\}P_1 \mid \mathsf{try}(b)\ \{Q_2\}P_2) \qquad \mathsf{peers}(a, b)$$
$$\to \mu; \langle \{a, b\}, \emptyset, \{Q_1 \mid Q_2\}(P_1 \mid P_2)\rangle$$

$$\mu; \langle \{a, b\}, B, \{Q\}(\mathsf{commit}(a).P_1 \mid \mathsf{commit}(b).P_2)\rangle \to \mu; P_1 \mid P_2$$

$$\frac{\mu; P \to \mu'; P'}{\mu; \langle A, B, \{Q\}P\rangle \to \mu'; \langle A, B', \{Q\}P'\rangle}$$

$$\mu_1, \{a_i \mapsto [b_i, q_i]\}_{i\in 1,2}, \mu_2; \langle \{a_i\}_{i\in 1,2}, \mathrm{dom}(\mu_2), \{Q\}(\mathsf{throw} \mid P)\rangle$$
$$\to \mu_1, \{a_i \mapsto [b_i, \varepsilon]\}_{i\in 1,2}; Q$$

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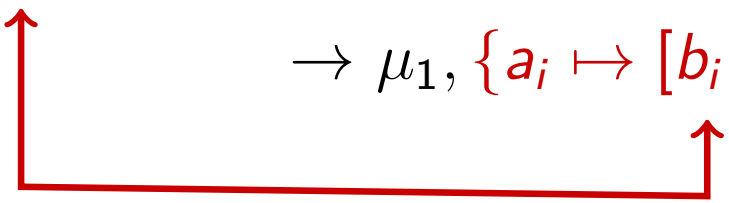

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Well-typed processes are well behaved

P is well behaved if $\emptyset; P \Rightarrow \mu; Q$ implies:

1. $Q \equiv Q_1 \mid Q_2$ and $\mu; Q_1 \not\rightarrow$ where Q_1 is an input from a, then the queue of a is empty
2. $\mathrm{dom}(\mu) = \mu\text{-reach}(\mathrm{fn}(Q))$

Theorem (Subject reduction)

If $\Delta \vdash P$ and $\mu; P \rightarrow \mu'; P'$, then $\Delta' \vdash P'$ for some Δ'.

Theorem (Soundness)

If $\vdash P$, then P is well behaved.

Concluding remarks

Model of copyless messaging with exceptions

- programs $\Rightarrow$ π-like processes
- pointers $\Rightarrow$ names
- `try` blocks $\Rightarrow$ transactions

Endpoint types

- prevent communication errors
- identify transactions in communications
- enable lightweight heap restoration

Related work

On copyless messaging (without exceptions)

- Villard, Lozes, Calcagno, **Proving Copyless Message Passing**, APLAS 2009
- Bono, Padovani, **Typing Copyless Message Passing**, LMCS 2012

On exceptions within sessions (copyful messaging with leaks)

- Carbone, Honda, Yoshida, **Structured interactional exceptions in session types**, CONCUR 2008
- Capecchi, Giachino, Yoshida, **Global escape in multiparty sessions**, FSTTCS 2010

Ongoing work

$$\frac{\Delta, u : T \vdash P}{\Delta, u : !\mathtt{m}\langle S\rangle.T, v : S \vdash u!\mathtt{m}\langle v\rangle.P}$$

- sealed values should be safe to send, but...
- ...this is hard to prove (for us)
- temporary ownership invariant violation

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Linear ownership is too permissive

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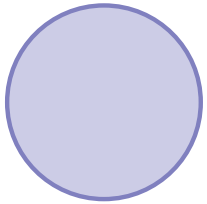

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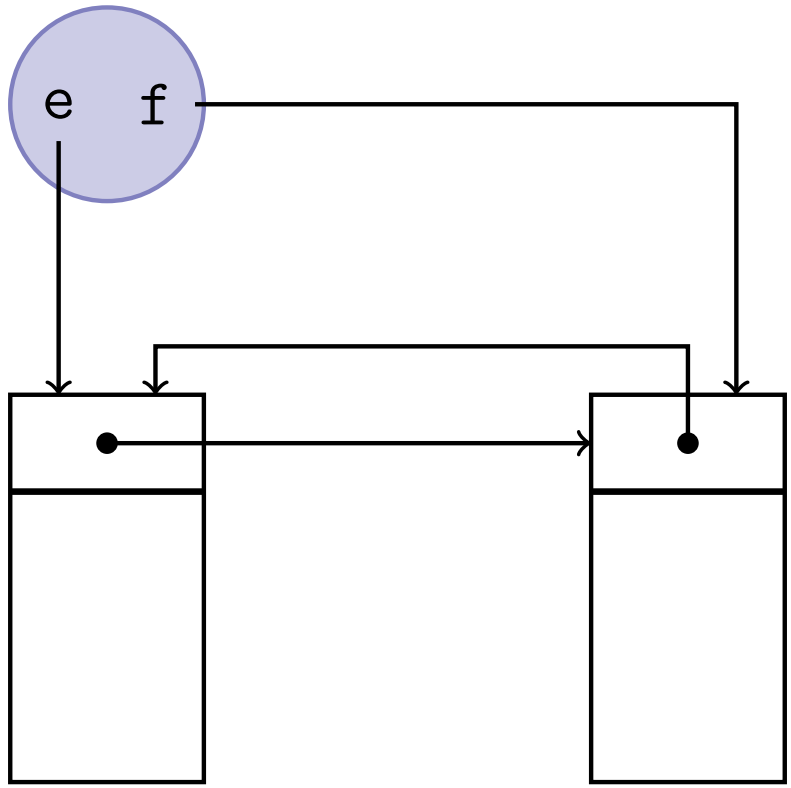

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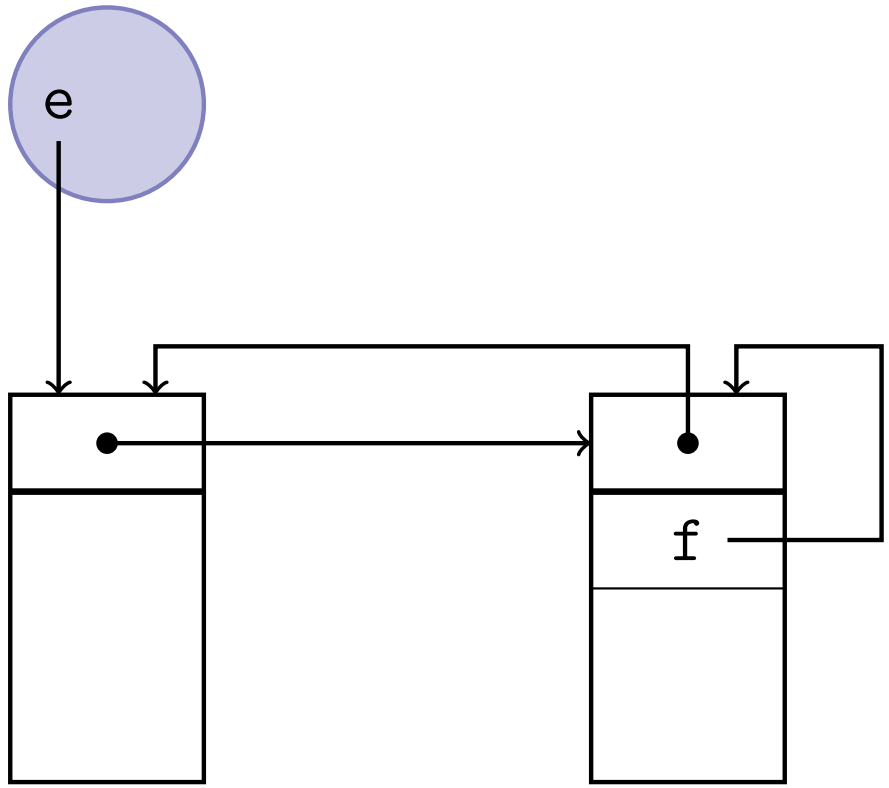

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