Tracking Heaps that Hop with Heap-Hop

Jules Villard[1,3] Étienne Lozes[2,3] Cristiano Calcagno[4,5]

[1]Queen Mary, University of London

[2]RWTH Aachen, Germany

[3]LSV, ENS Cachan, CNRS

[4]Monoidics, Inc.

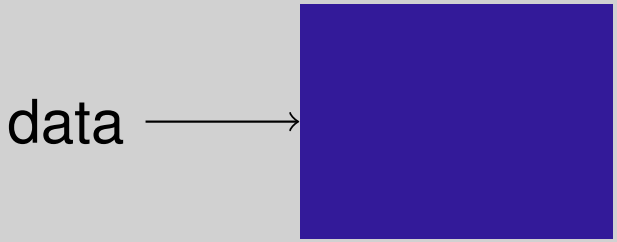
[5]Imperial College, London

Message Passing in Multicore Systems

- Concurrent programs are hard to write **correctly** and **efficiently**
- Paradigm: message passing over a shared memory
- Leads to **efficient**, copyless message passing
- May be more error-prone (than message passing with copies)

To Copy or not to Copy?

Copyful




```
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```
d = receive(struct,f);
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- `(e,f)`: channel
- `data` points to a big struct
- `struct`: type of message

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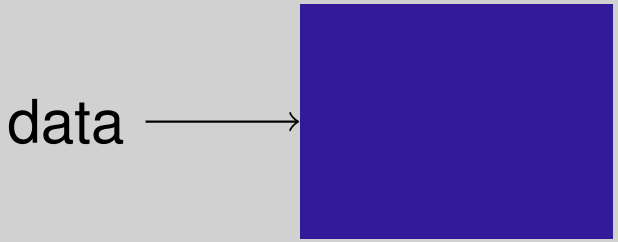

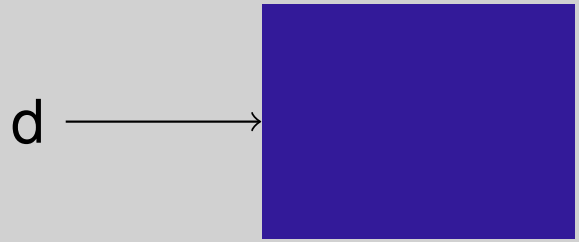


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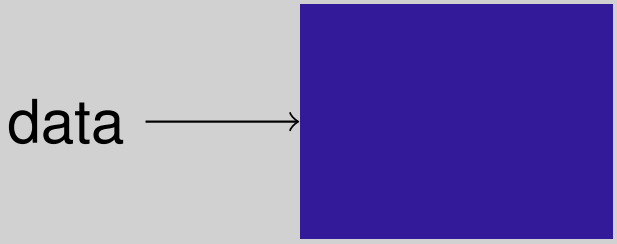

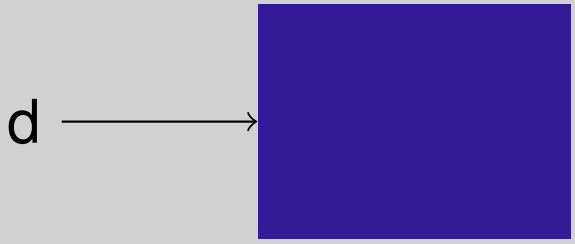


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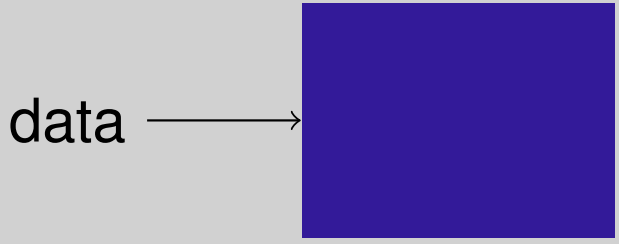
Copyless



d

```
send(pointer,e,data);
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d = receive(pointer,f);
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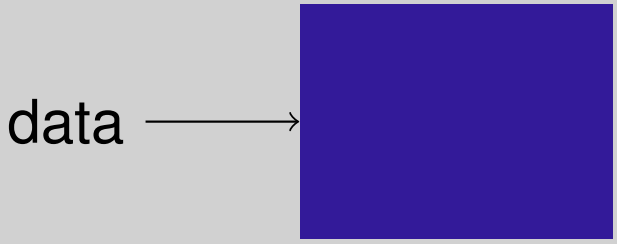

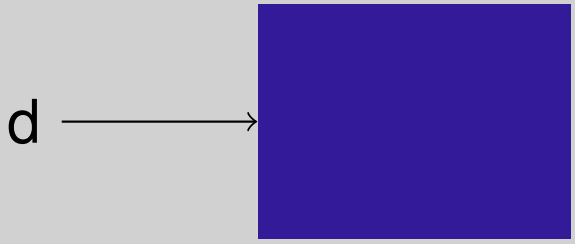


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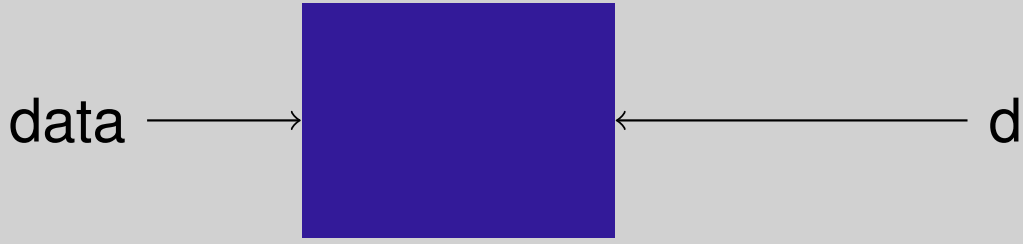


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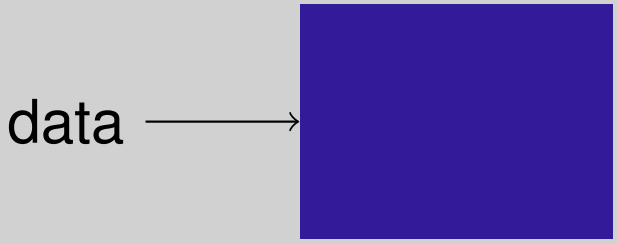

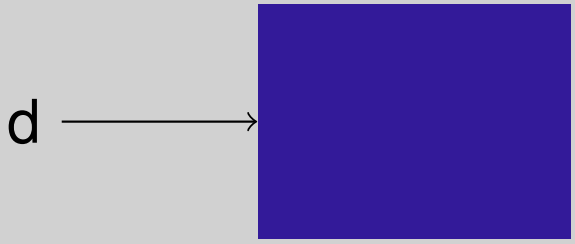


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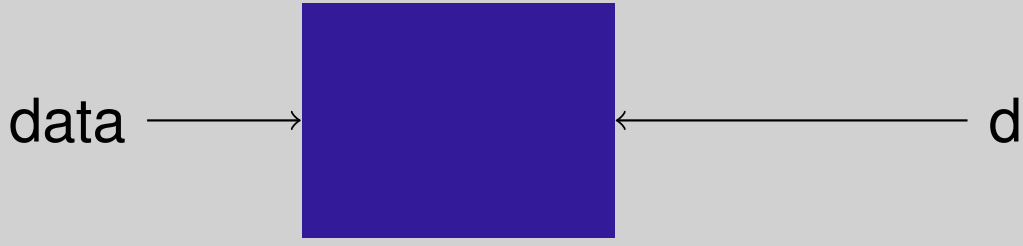
Copyless

Race!

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dispose(data);
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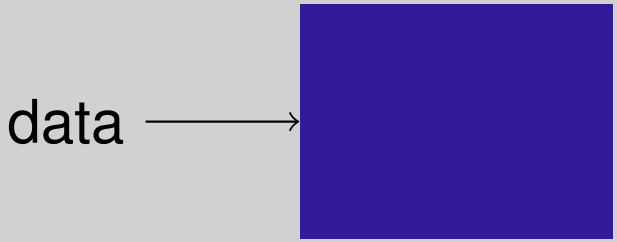

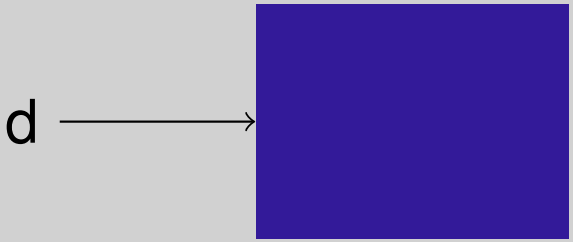


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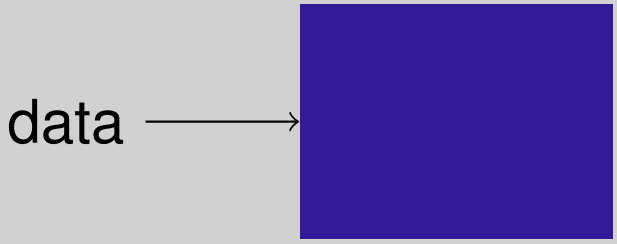

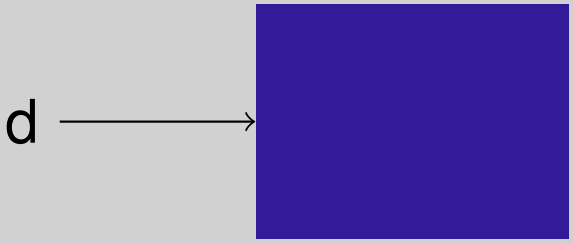


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Copyless

No race

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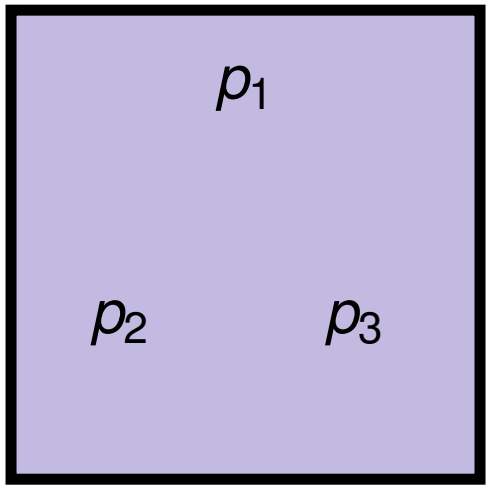
Singularity OS

Singularity: a research project and an operating system.

- No hardware memory protection
- Sing♯ language
- Isolation is verified at compile time
- Invariant: each memory cell is owned by at most one thread
- No shared resources
- Copyless message passing



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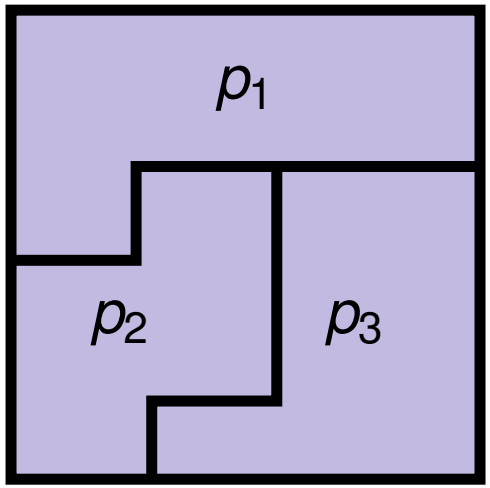


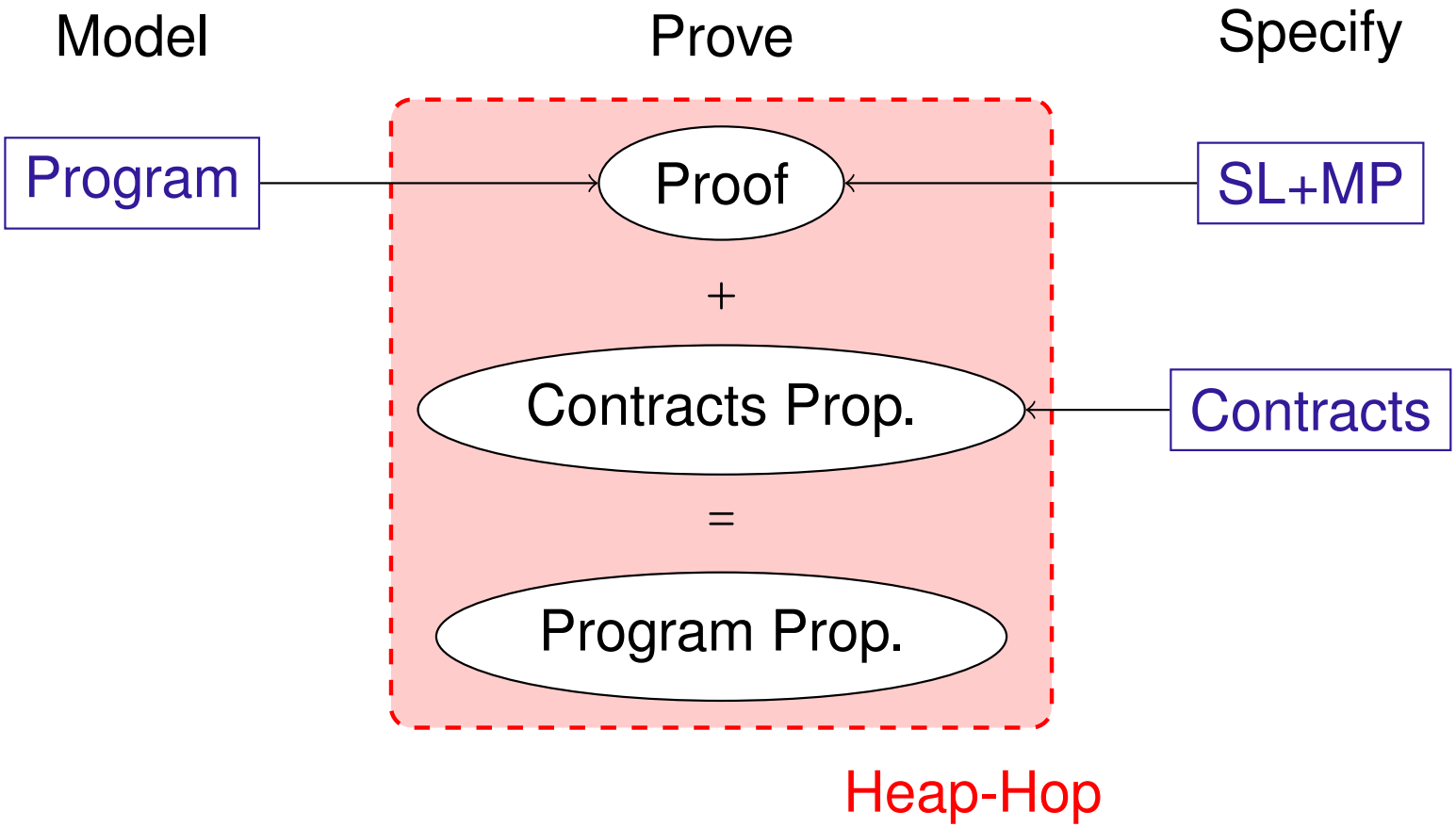
Singularity Features

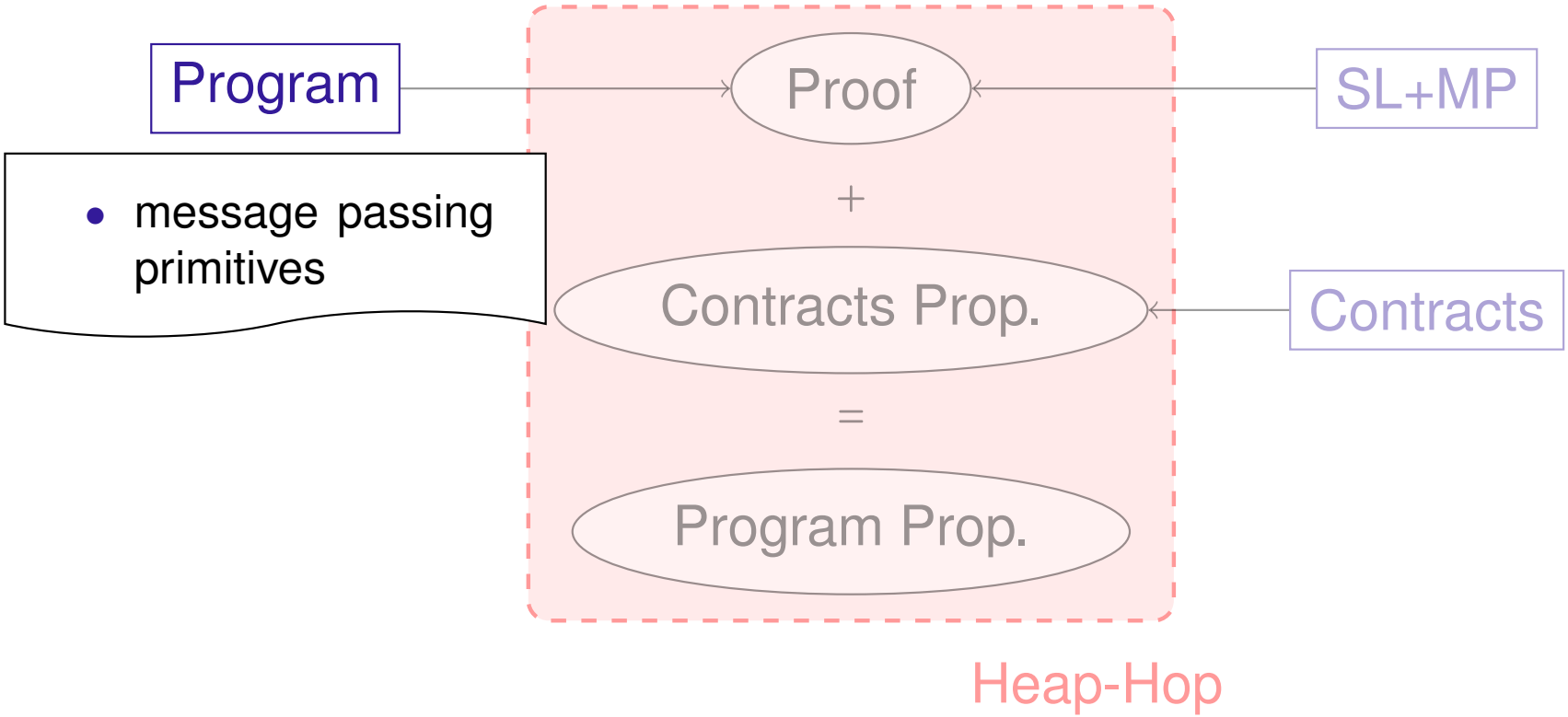
[Fähndrich et al. '06]

- Channels are **bidirectional** and **asynchronous**
  channel = pair of FIFO queues
- Channels are made of two **endpoints**
  similar to the socket model
- Endpoints can be allocated, disposed of, and communicated through channels
  similar to the π-calculus
- Communications are ruled by user-defined **contracts**
  similar to session types

⊖ No formalisation
  How to ensure the absence of bugs?

Analysis


Model
Prove
Specify
Program
Proof
SL+MP
+
Contracts Prop.
Contracts
=
Program Prop.
Heap-Hop


Program
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Message Passing Primitives

- `(e,f) = open()` Creates a bidirectional channel between endpoints `e` and `f`
- `close(e,f)` Closes the channel `(e,f)`
- `send(a,e,x)` Sends message starting with value `x` on endpoint `e`. The message has type/tag `a`
- `x = receive(a,e)` Receives message of type `a` on endpoint `e` and stores its value in `x`

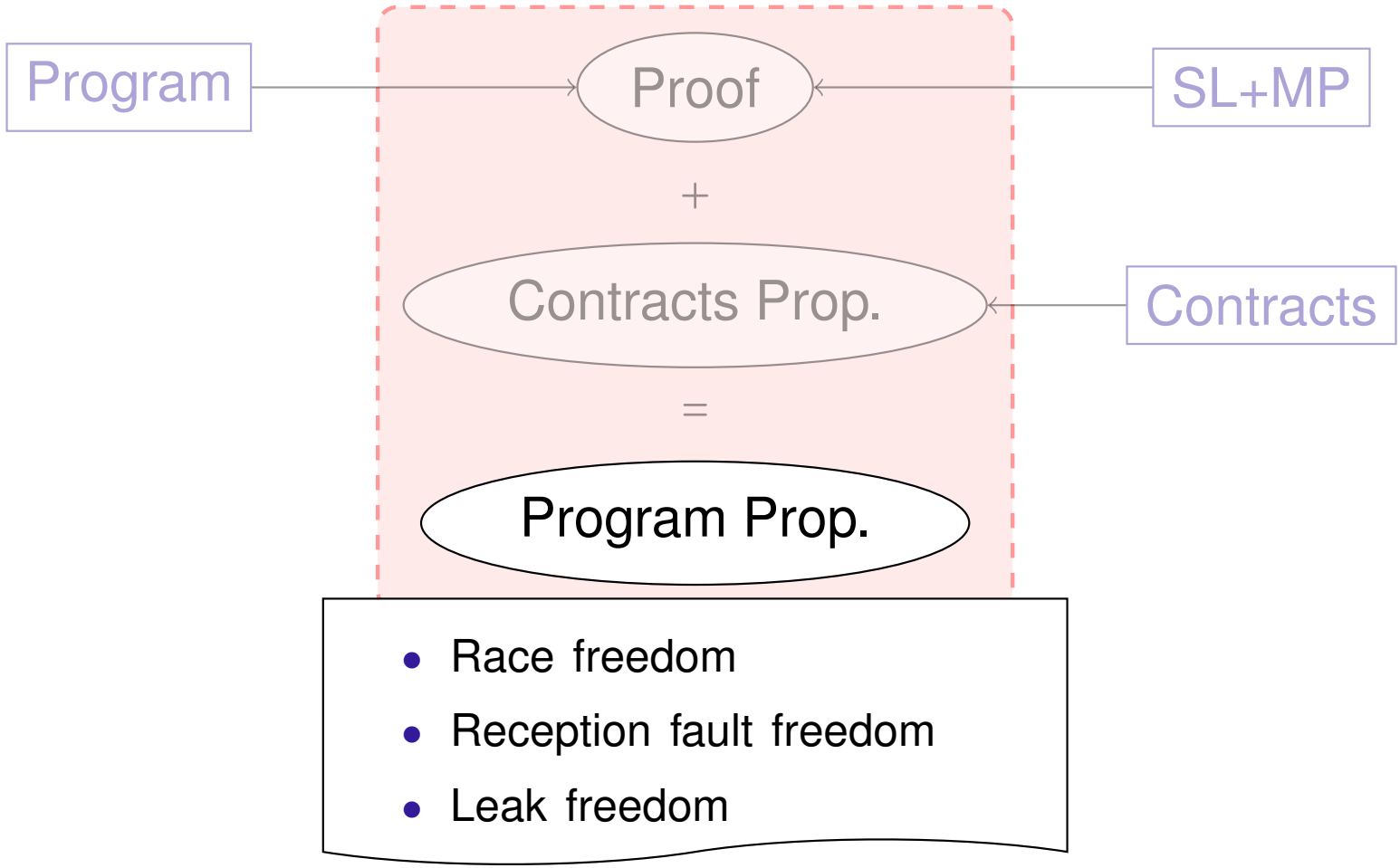
```
1 set_to_ten(x) {
2   local e,f;
3   (e,f) = open();
4   send(integer,e,10);
5   x = receive(integer,f);
6   close(e,f);
7 }
```

Switch Receive

- `switch receive` selects a receive branch depending on availability of messages

```
if( x ) {
  send(cell,e,x);
} else {
  send(integer,e,0);
}
```

```
switch receive {
  y = receive(cell,f): {dispose(y);}
  z = receive(integer,f): {}
}
```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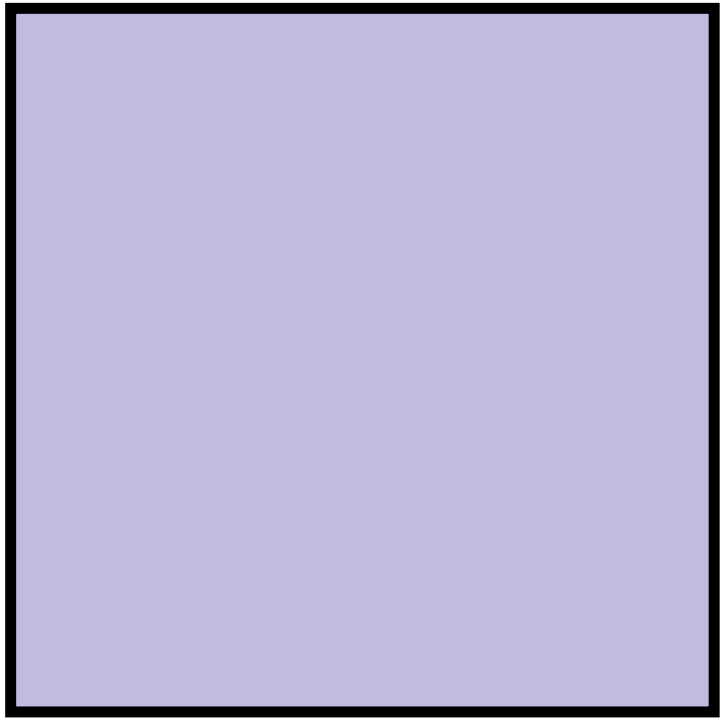
Program Prop.
• Race freedom
• Reception fault freedom
• Leak freedom

Separation property

At each point in the execution, the state can be **partitioned** into what is owned by each program and each message in transit.

- Programs access only what they own.
- Prevents races.



memory

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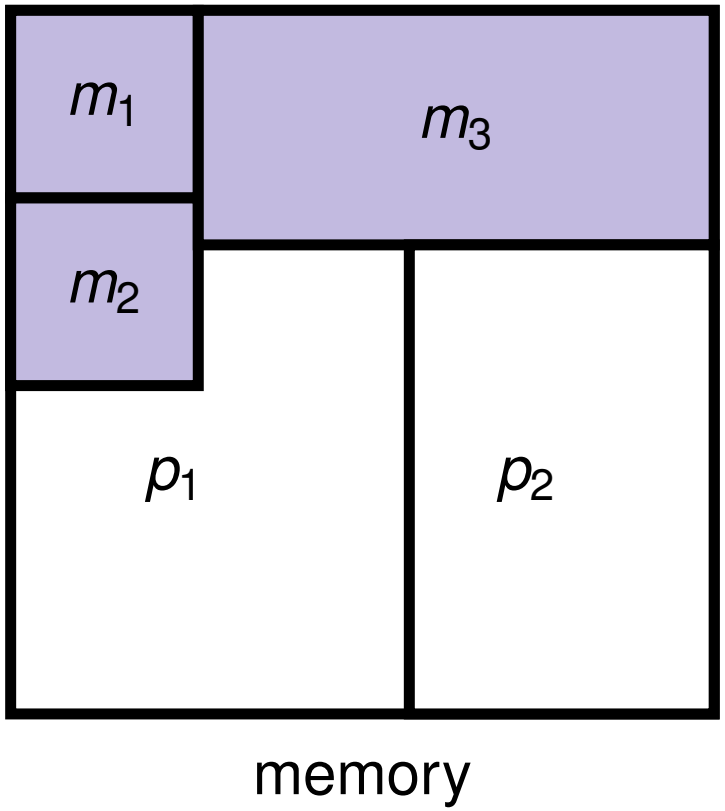

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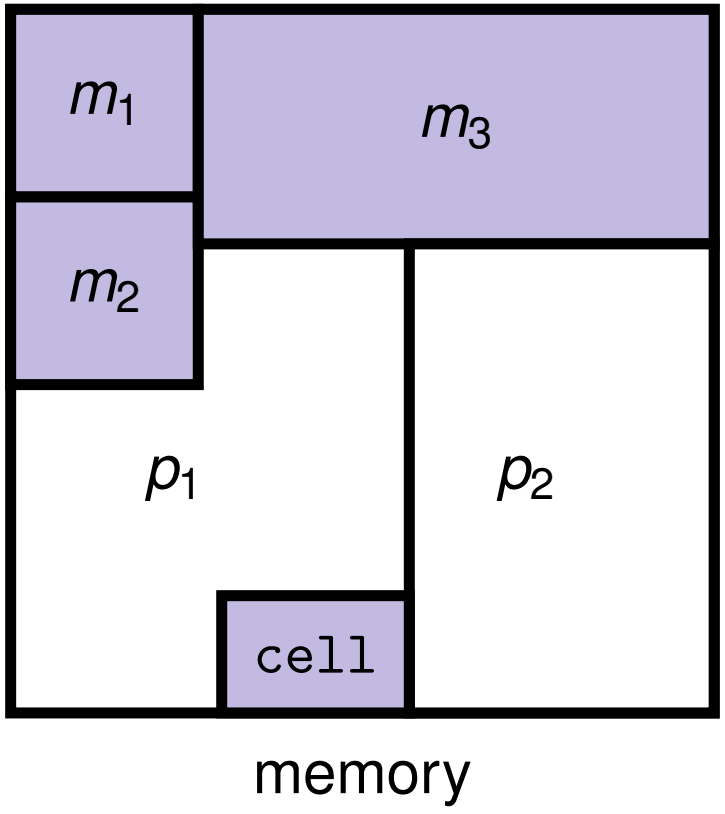

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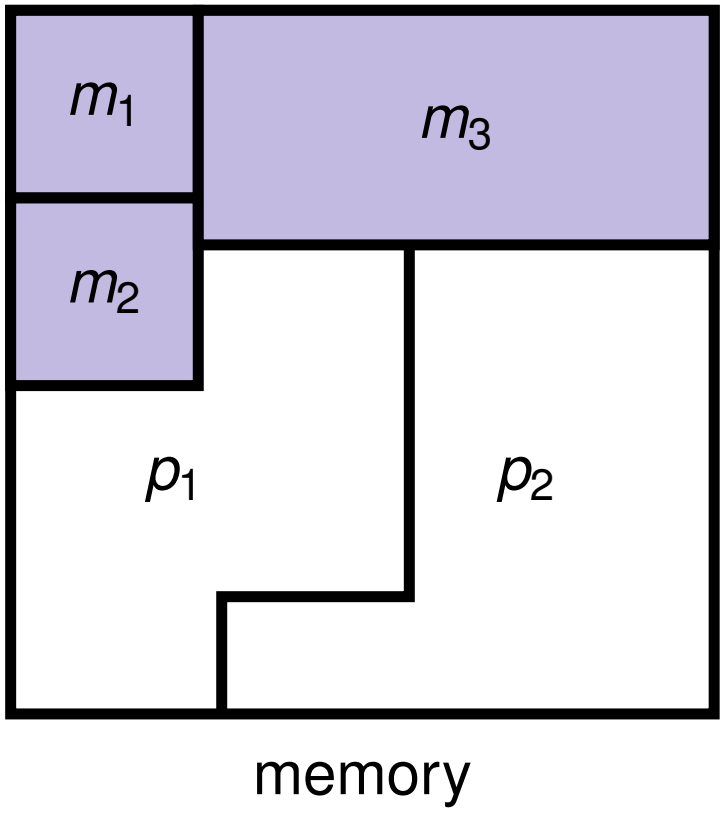


Separation property

Invalid receptions freedom

`switch receive` are exhaustive.

```
...
switch receive {
  y = receive(a,f): { ... }
  z = receive(b,f): { ... }
}
...
```

```
...
send(c,e,x);
...
```

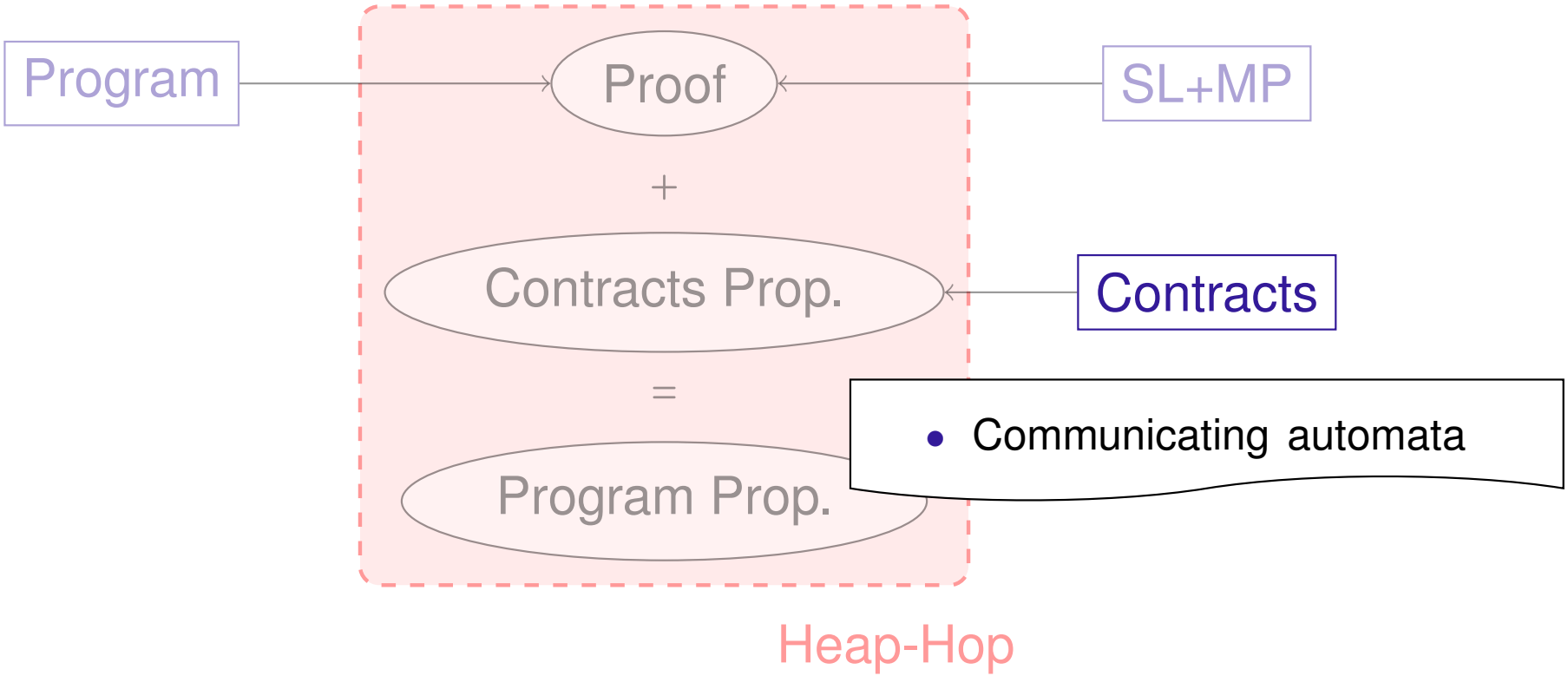
Separation property

Invalid receptions freedom

Leak freedom

The program does not leak memory.

```
1 main() {
2   local x,e,f;
3
4   x = new();
5   (e,f) = open();
6   send(cell,e,x);
7   close(e,f);
8 }
```


Program
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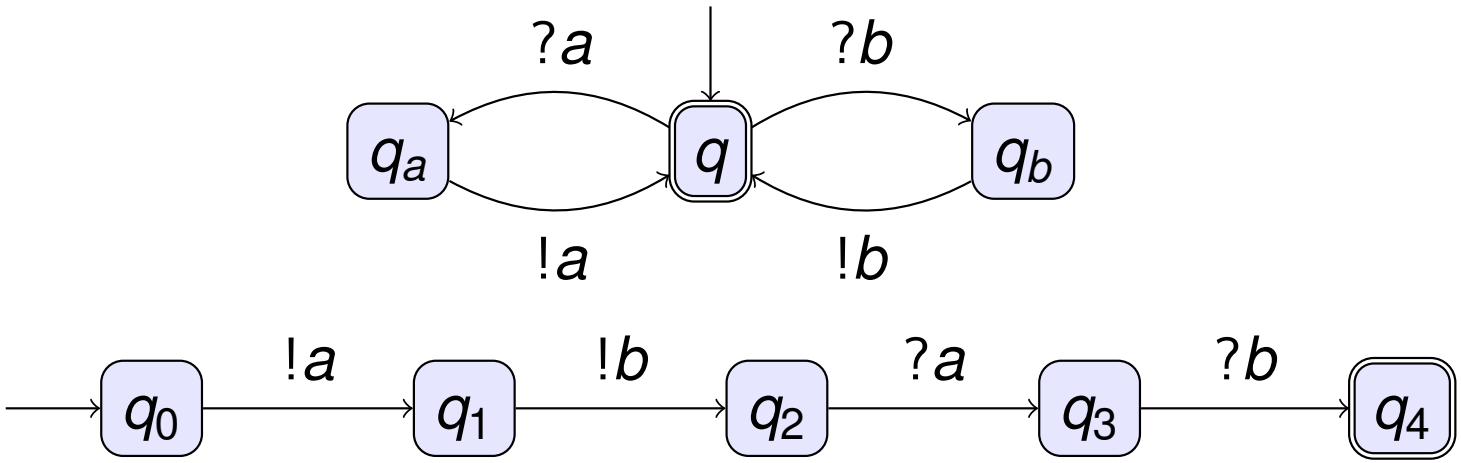
• Communicating automata
Heap-Hop

A Dialogue System



- Sending transitions: $!a$
- Receiving transitions: $?a$
- Two buffers: one in each direction
- Configuration: $\langle q, q', w, w' \rangle$

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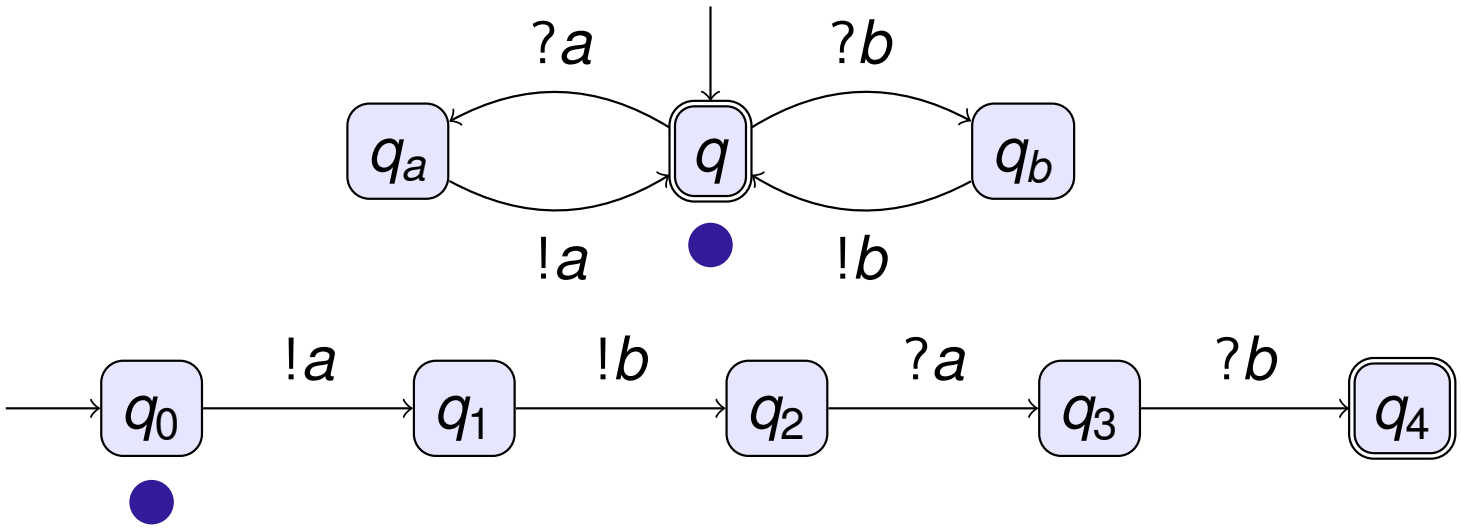

$$\langle q, q_0, \varepsilon, \varepsilon \rangle$$

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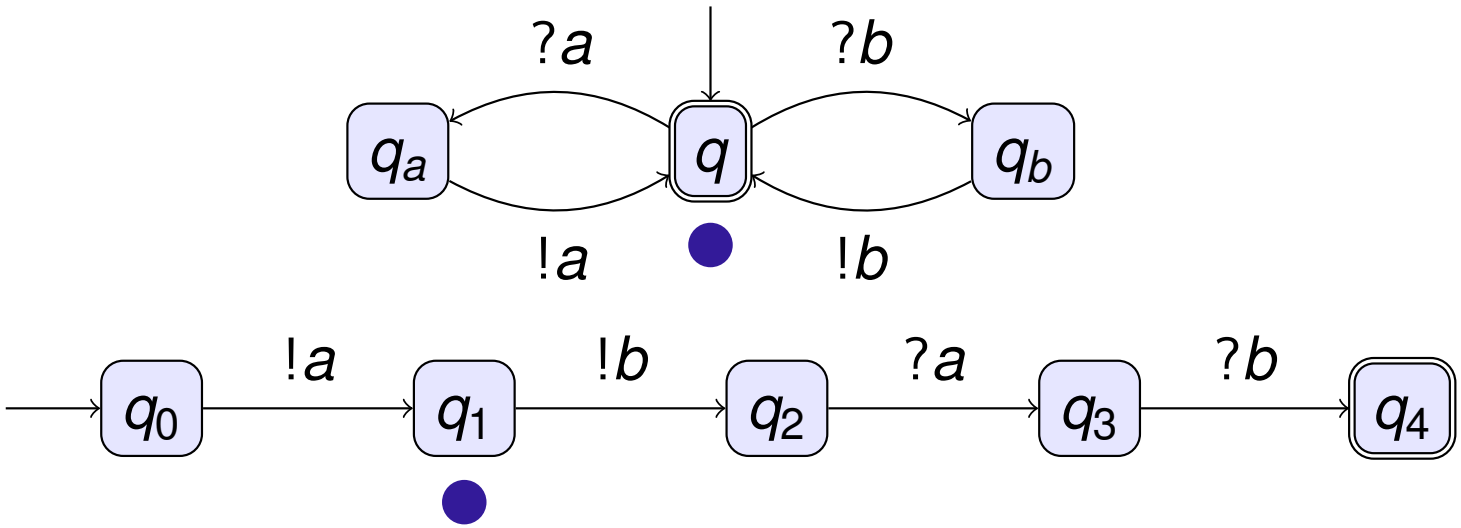

$$\langle q, q_1, a, \varepsilon \rangle$$

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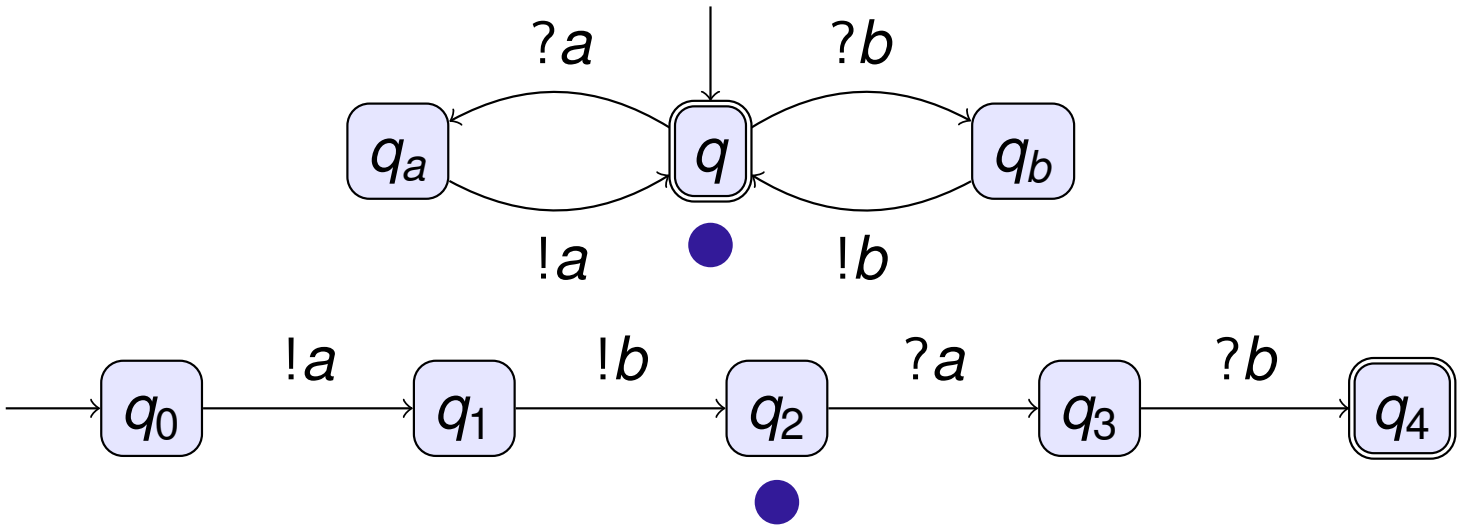

$$\langle q, q_2, ab, \varepsilon \rangle$$

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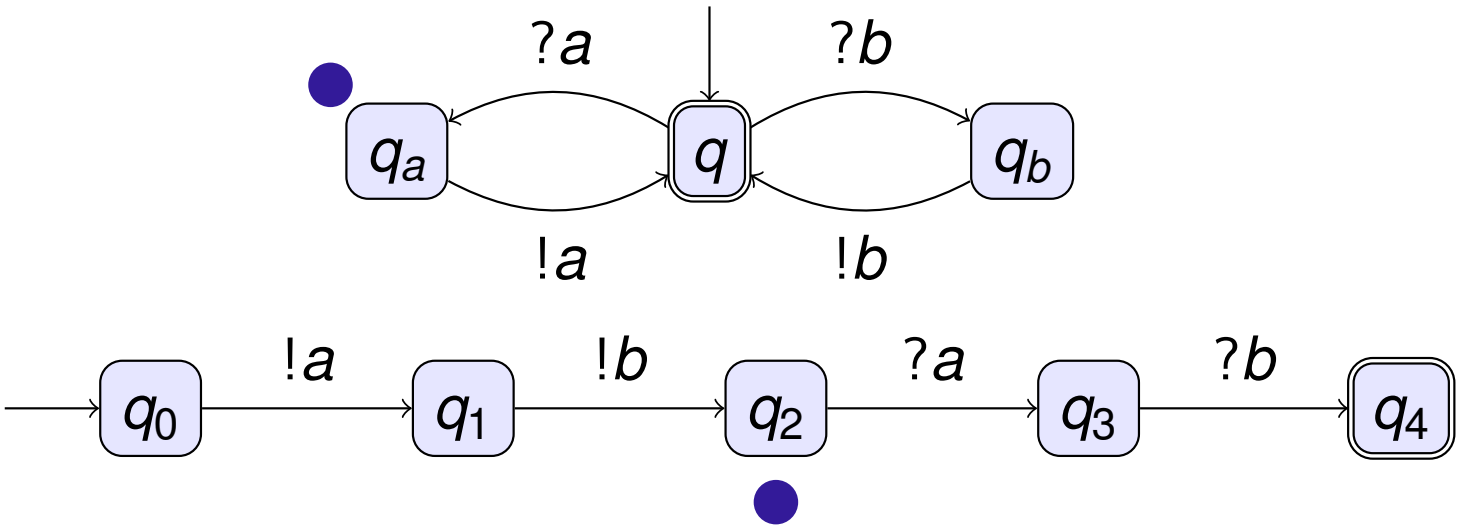

$$\langle q_a, q_2, b, \varepsilon \rangle$$

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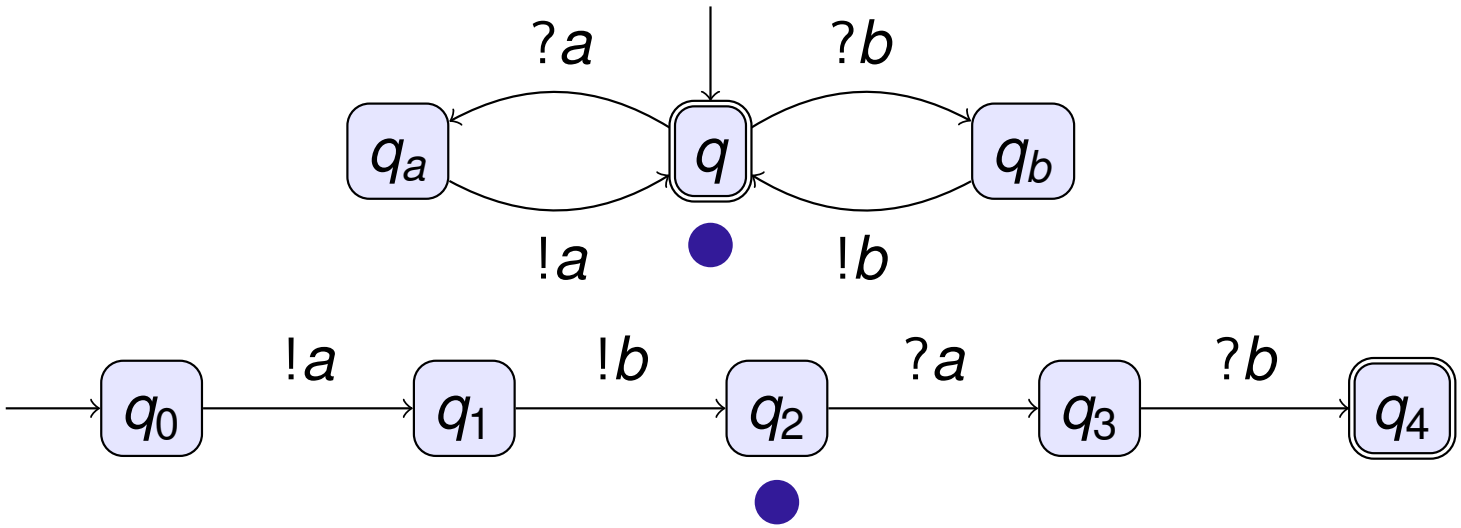

$\langle q, q_2, b, a \rangle$

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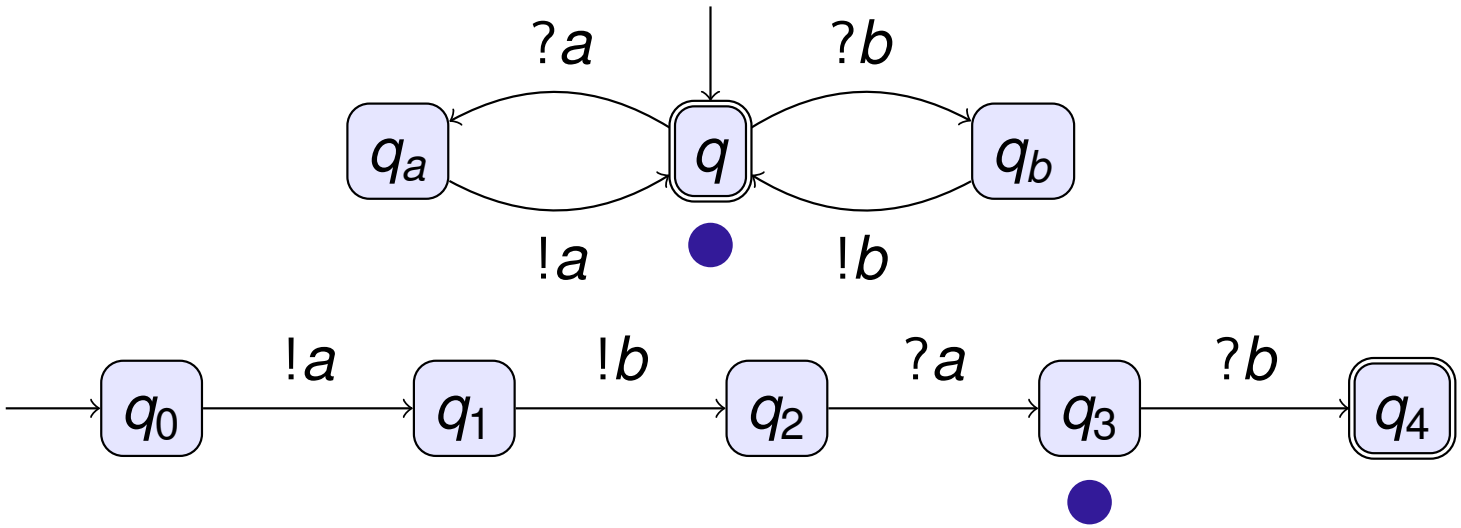

$$\langle q, q_3, b, \varepsilon \rangle$$

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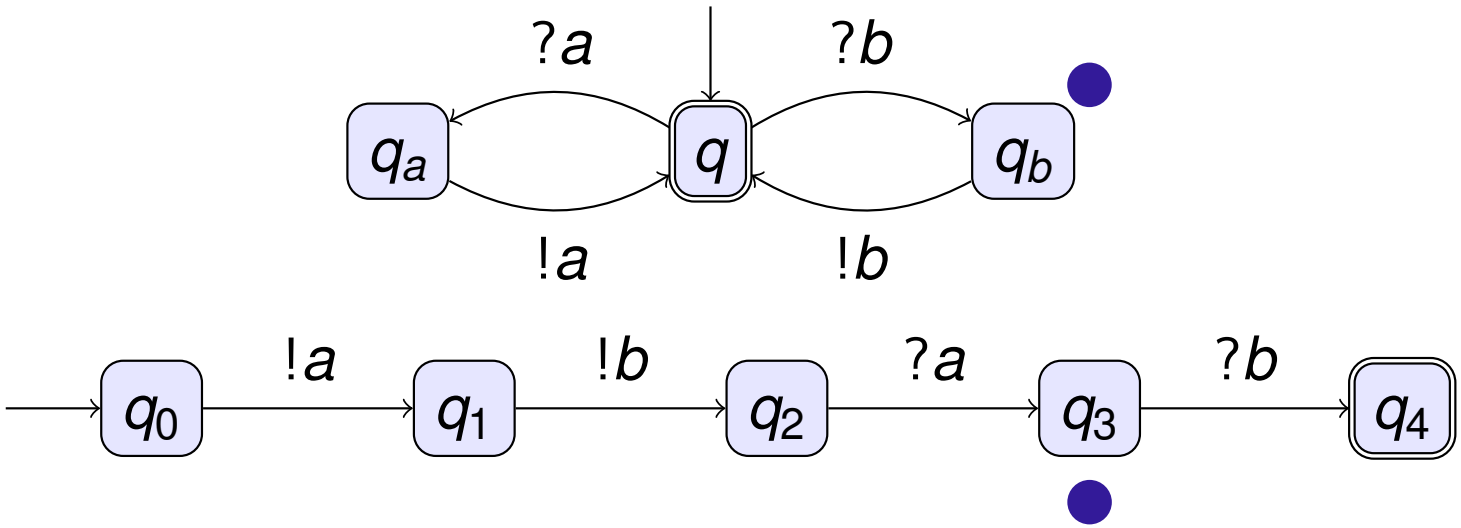

$$\langle q_b, q_3, \varepsilon, \varepsilon \rangle$$

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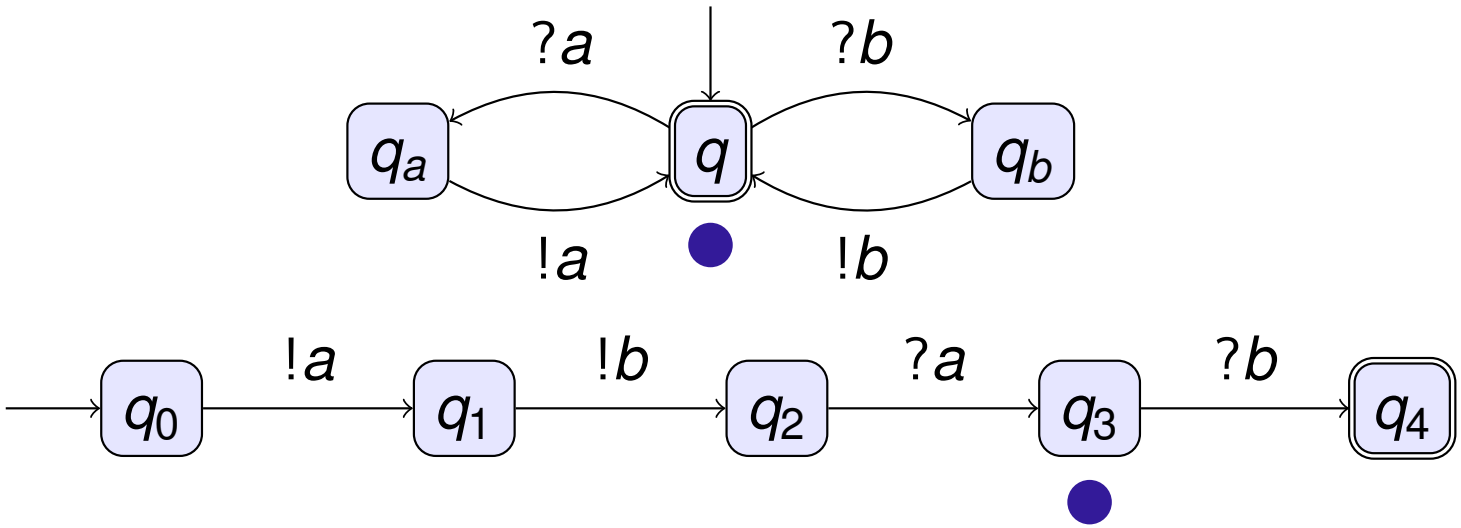

$$\langle q, q_3, \varepsilon, b \rangle$$

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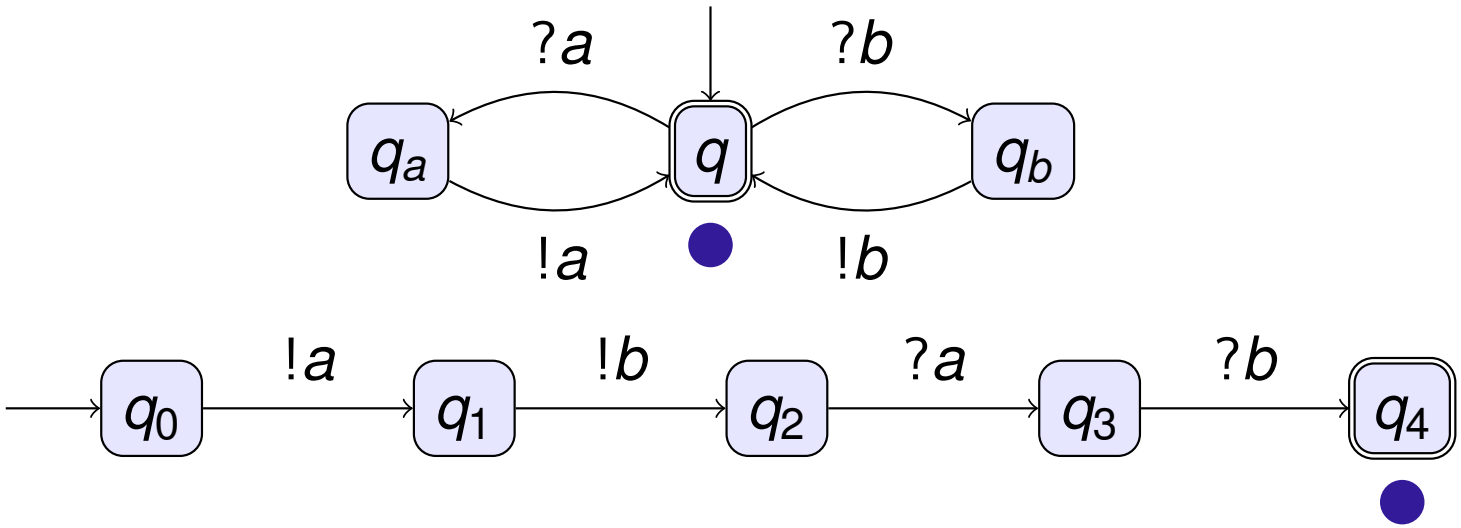
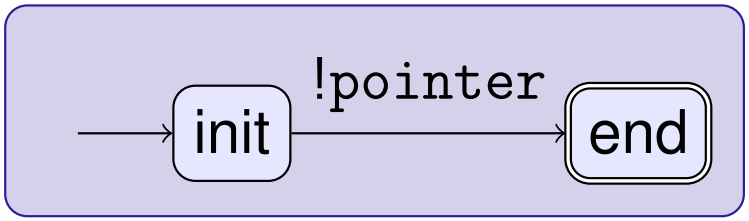


$$\langle q, q_4, \varepsilon, \varepsilon \rangle$$

Describe dual communicating finite state machines

$\mathfrak{C}$



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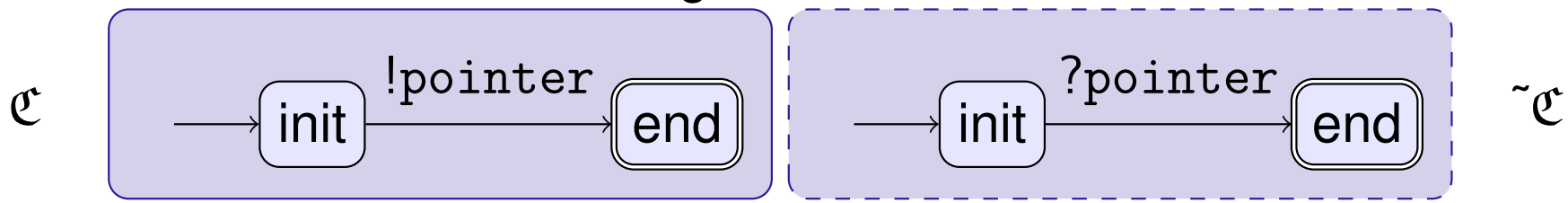

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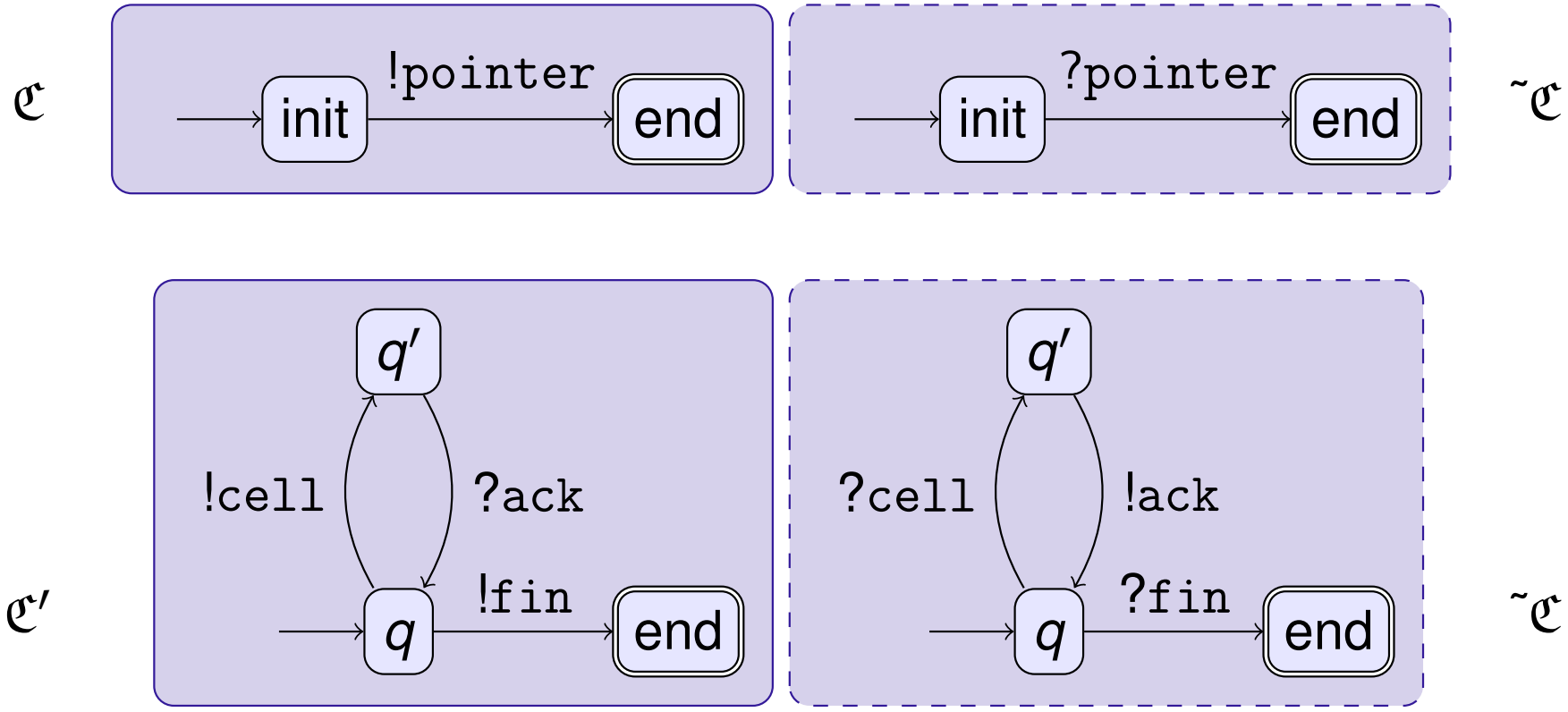
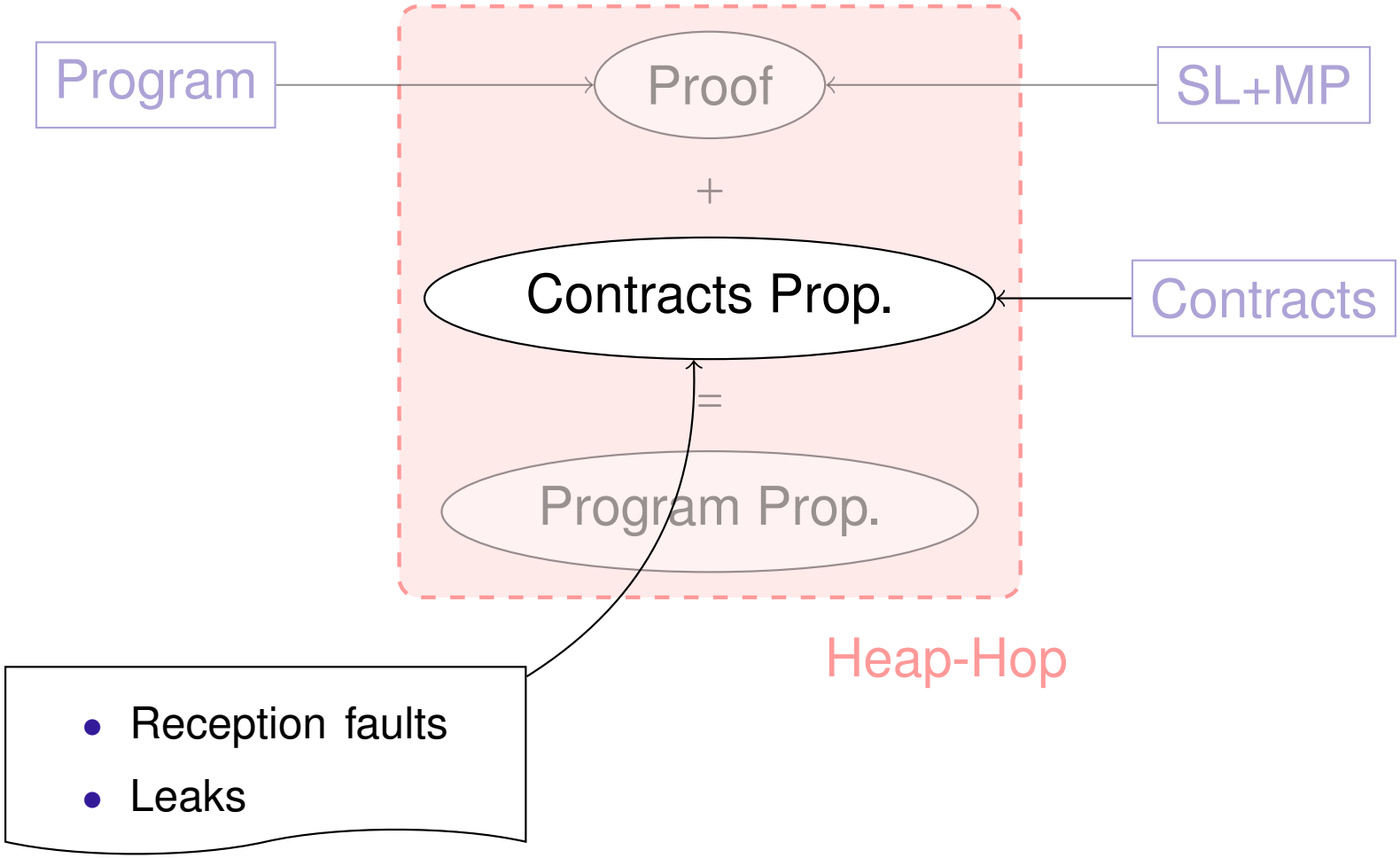


Contracts as Protocol Specifications

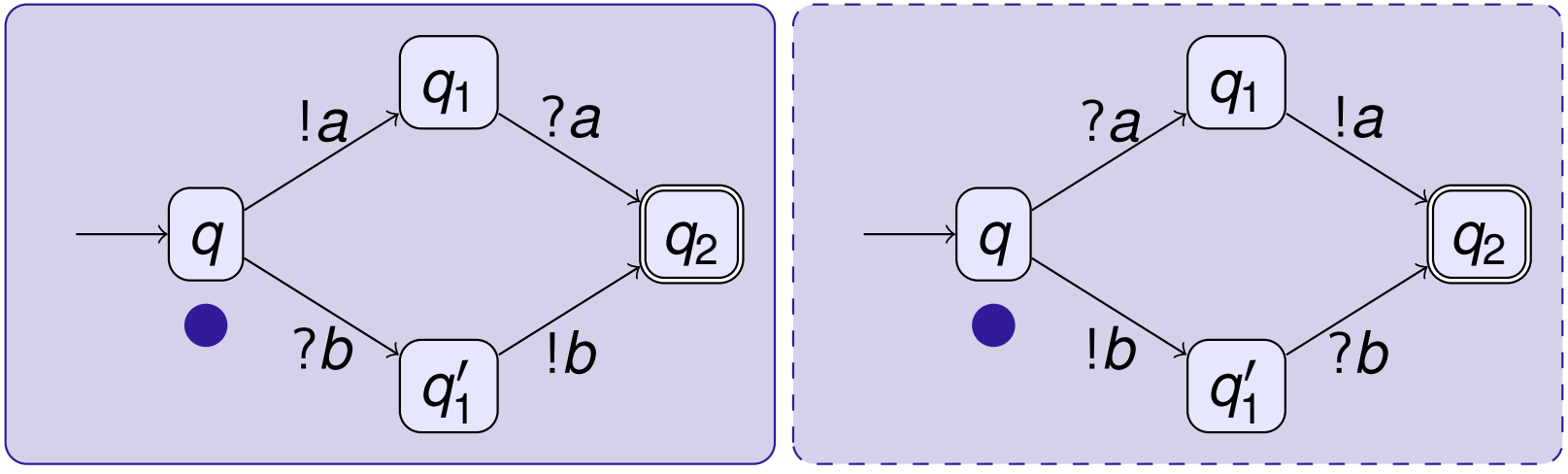
- `(e,f) = open(`$\mathfrak{C}$`)`: initialise endpoints in the initial state of the contract
- `send(a,e,x)`: becomes a $!a$ transition
- `y = receive(a,f)`: becomes a $?a$ transition
- `closed(e,f)` only when both endpoints are in the same **final** state.


Program
Proof
SL+MP
+
Contracts Prop.
Contracts
=
Program Prop.
Heap-Hop
Reception faults
Leaks

Definition — Reception fault

$\langle q_1, q_2, a \cdot w_1, w_2 \rangle$ is a **reception fault** if

- $q_1 \xrightarrow{?b} q$ for some b and q and
- $\forall b, q.\, q_1 \xrightarrow{?b} q$ implies $b \neq a$



$\langle q, q, \varepsilon, \varepsilon \rangle$

Definition — Reception fault

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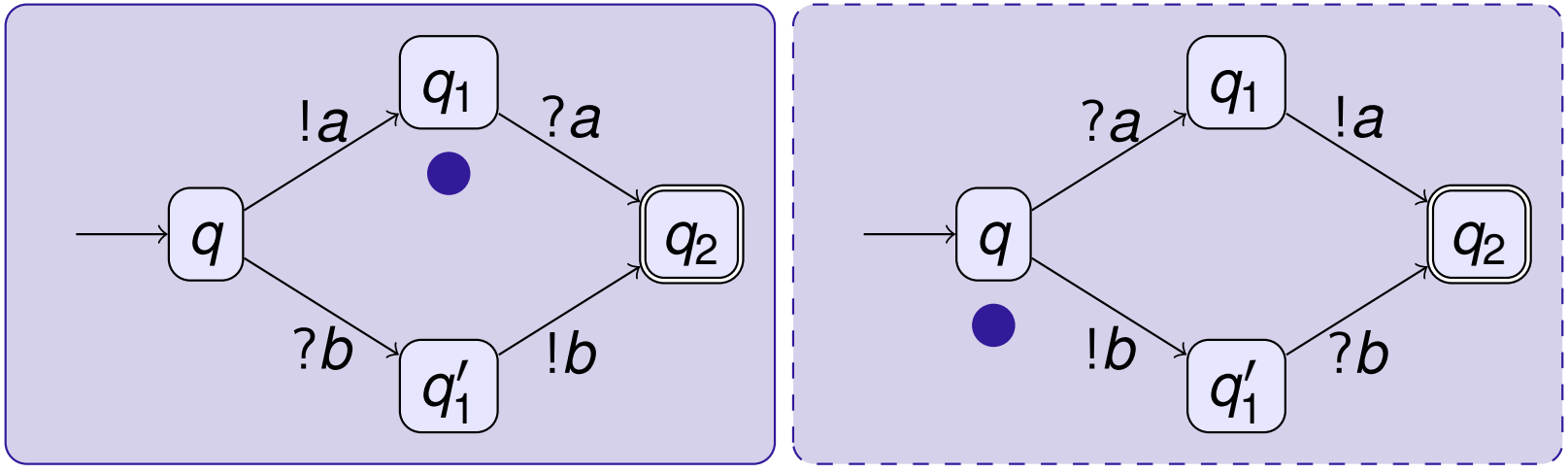

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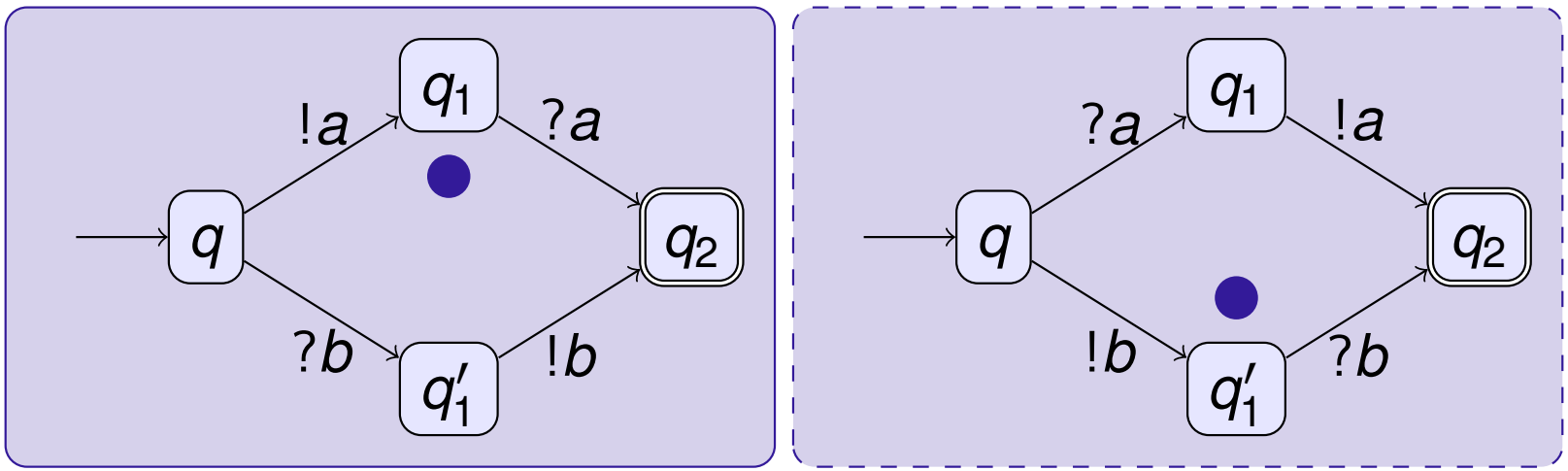

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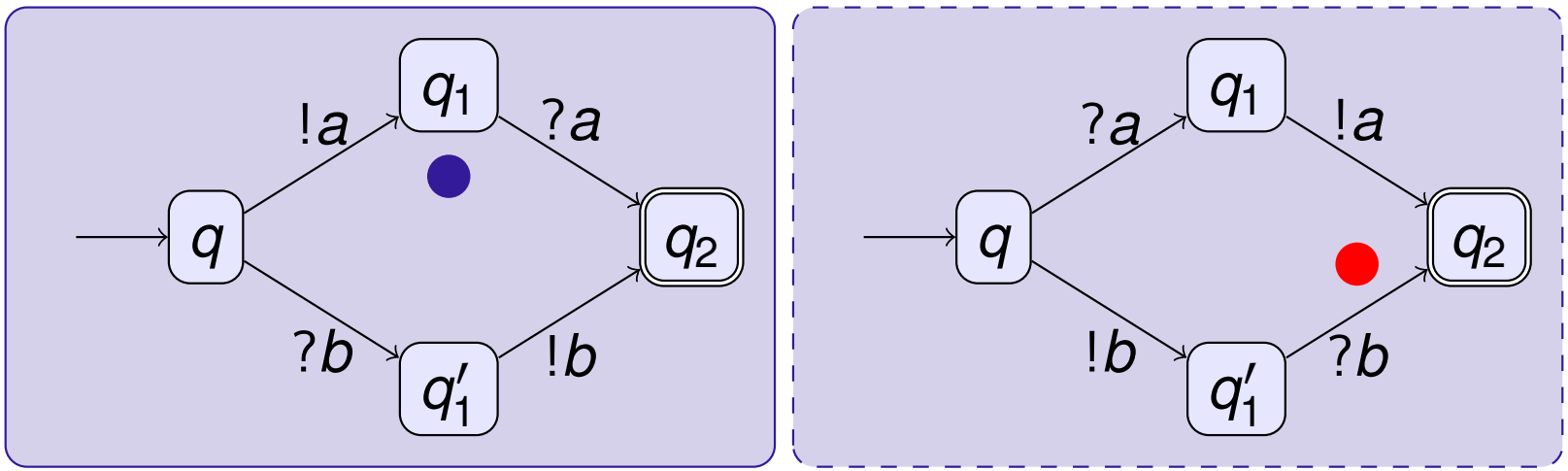

$$\langle q_1, q_1', a, b \rangle \xrightarrow{?b}_2 \textbf{error}$$

Reception Errors

Definition — Reception fault

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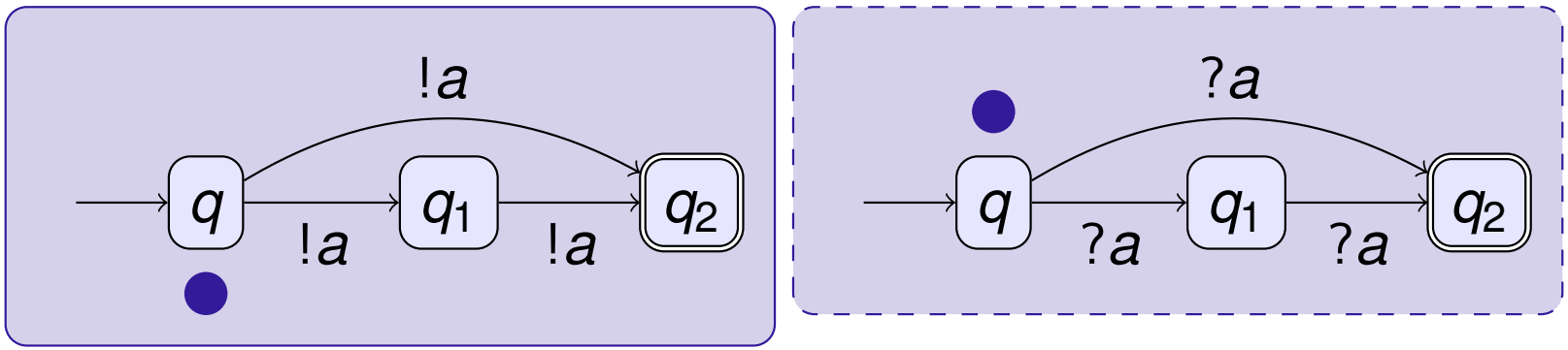
- A contract is **reception fault-free** if it cannot reach a reception fault.

Definition — Leak

$\langle q_f, q_f, w_1, w_2 \rangle$ is a **leak** if $w_1 \cdot w_2 \neq \varepsilon$ and q_f is final.



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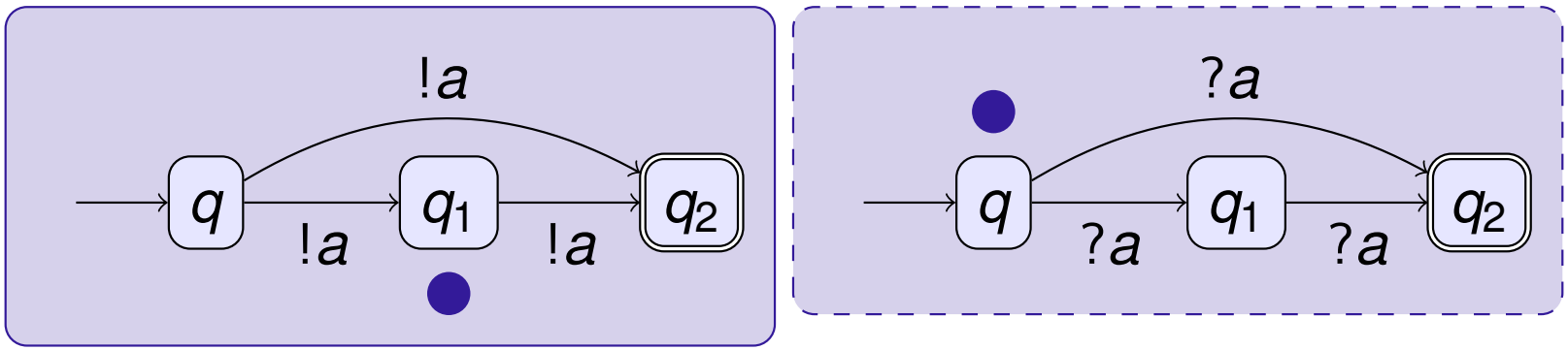

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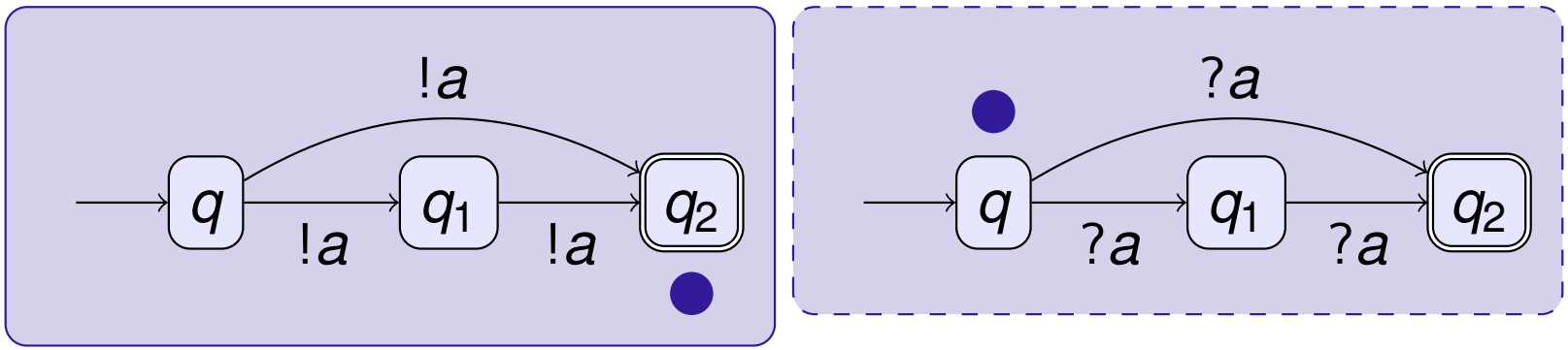

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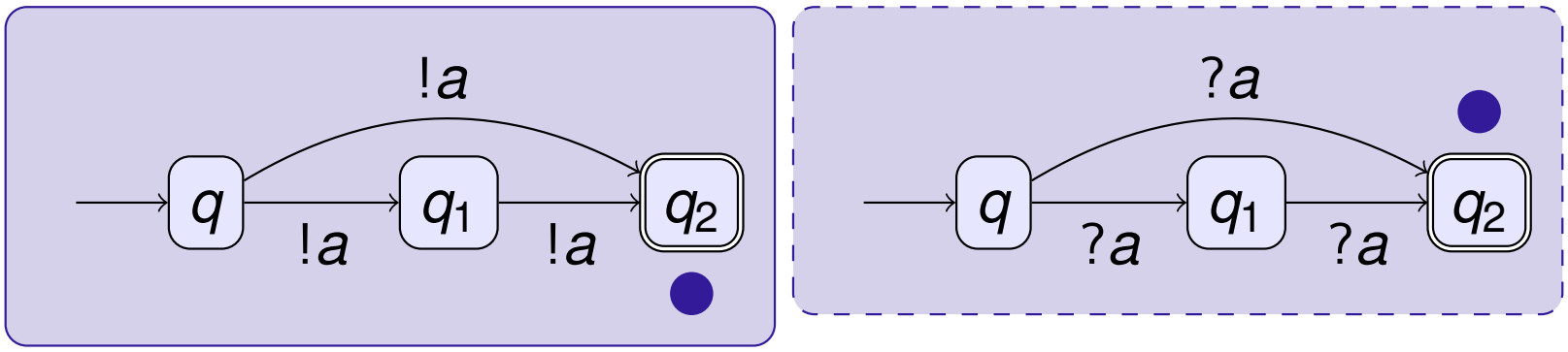

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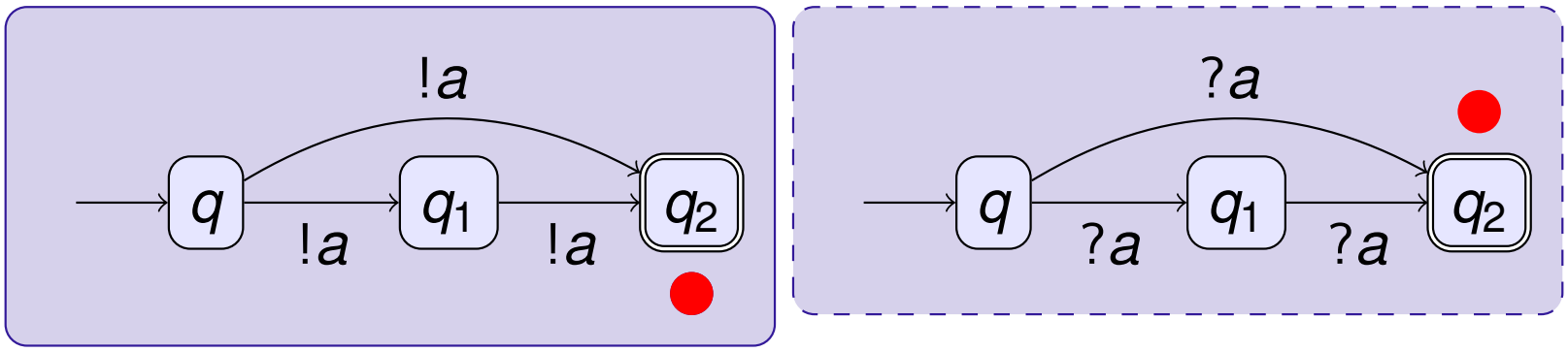

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Definition — **Leak**

$\langle q_f, q_f, w_1, w_2 \rangle$ is a **leak** if $w_1 \cdot w_2 \neq \varepsilon$ and q_f is final.

- A contract is **leak free** if it cannot reach a leak.
- A contract is **safe** if it is reception fault free and leak free.

Contract Verification

- ⊖ Safety of communicating systems is undecidable in general

  Channel's buffer ≈ *Turing machine's tape*

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Theorem

Safety is undecidable for contracts.

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Theorem

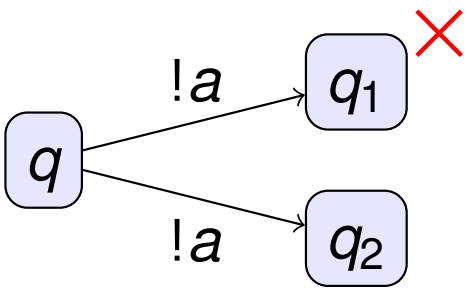
Safety is undecidable for contracts.

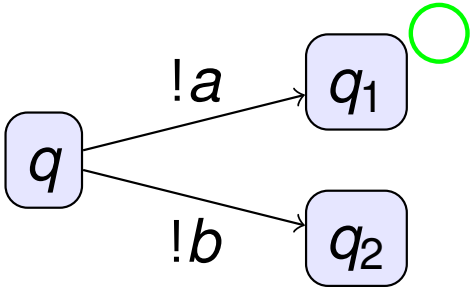
- We give **sufficient conditions** for safety.

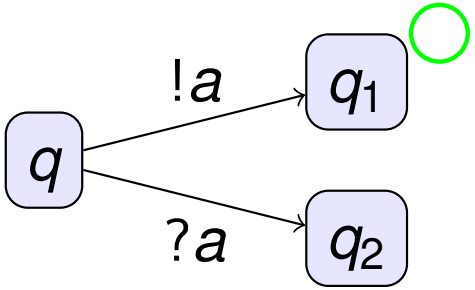
Sufficient Conditions for Reception Safety

Definition — Deterministic contract

Two distinct edges in a contract must be labelled by different messages.





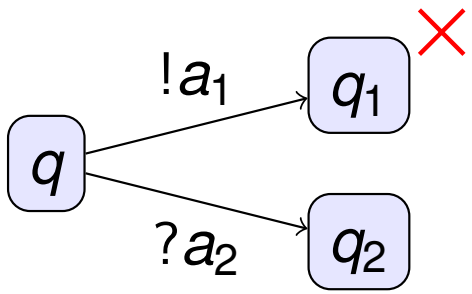


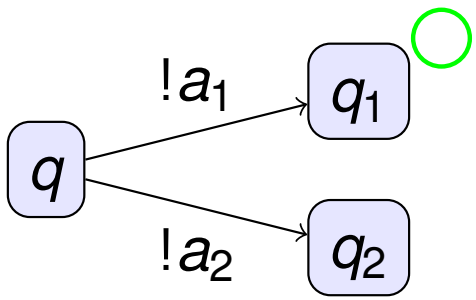
Sufficient Conditions for Reception Safety

Definition — Deterministic contract

Definition — Positional contracts

All outgoing edges from a same state in a contract must be either all sends or all receives.





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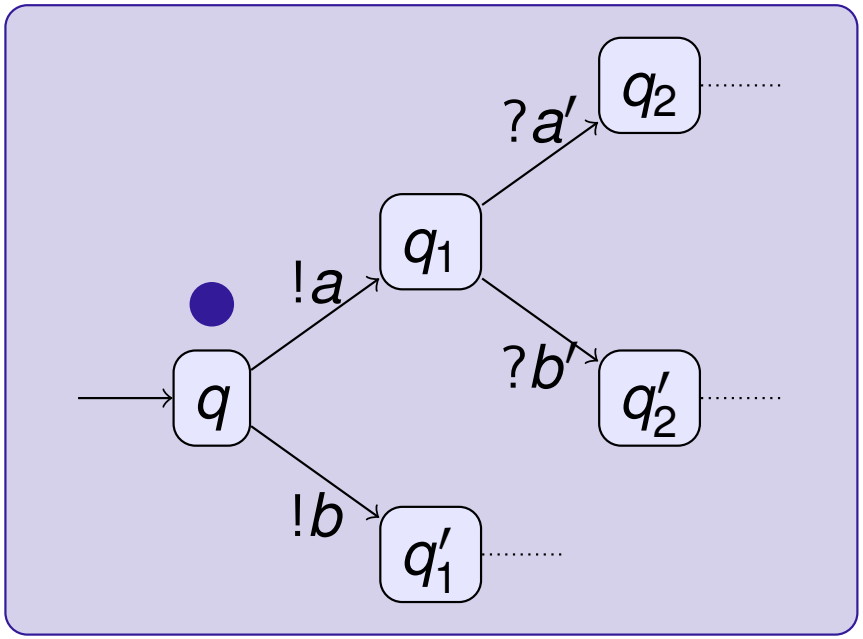
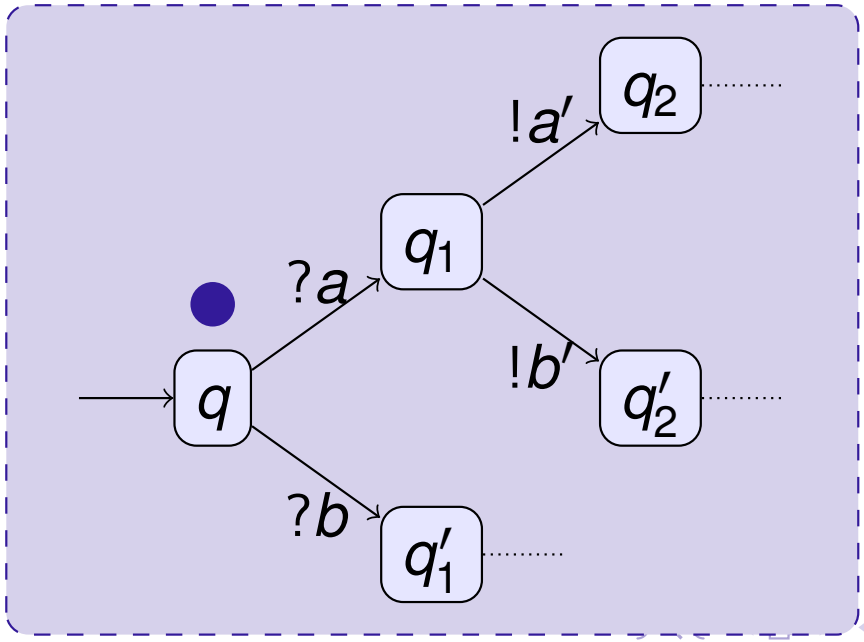
Theorem — [Stengel & Bultan'09] • [V., Lozes & Calcagno '09]

*Deterministic positional contracts are **reception fault free**.*





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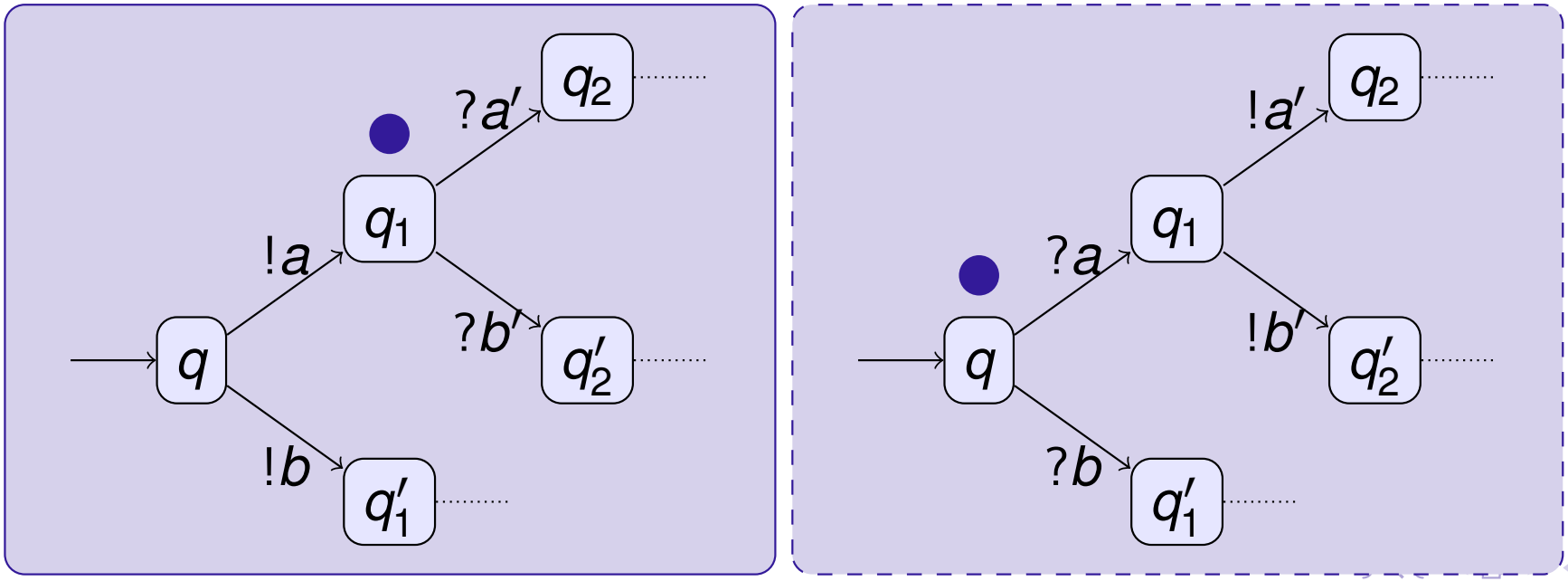

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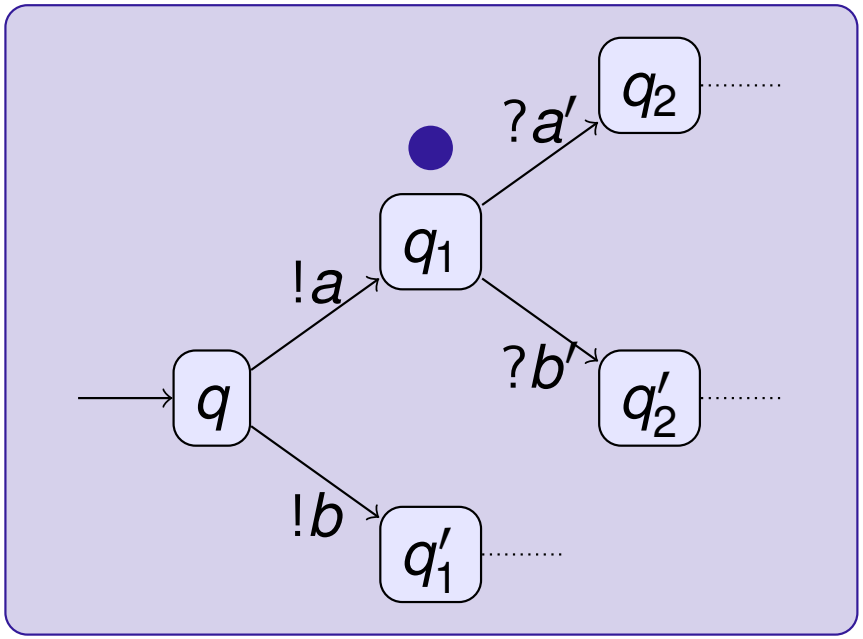

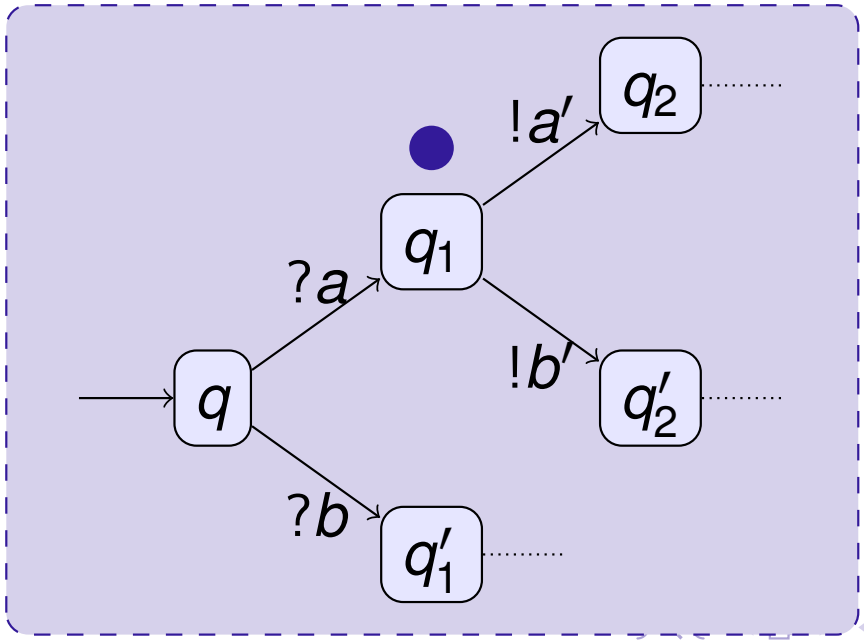

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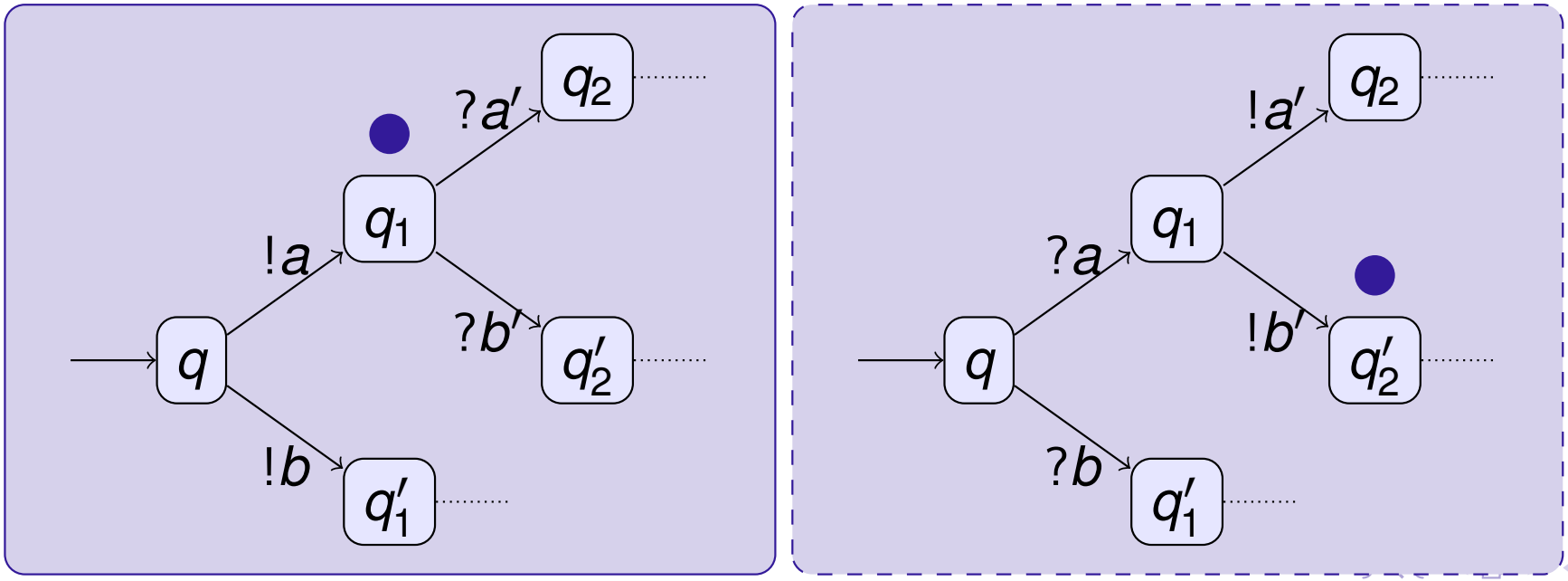

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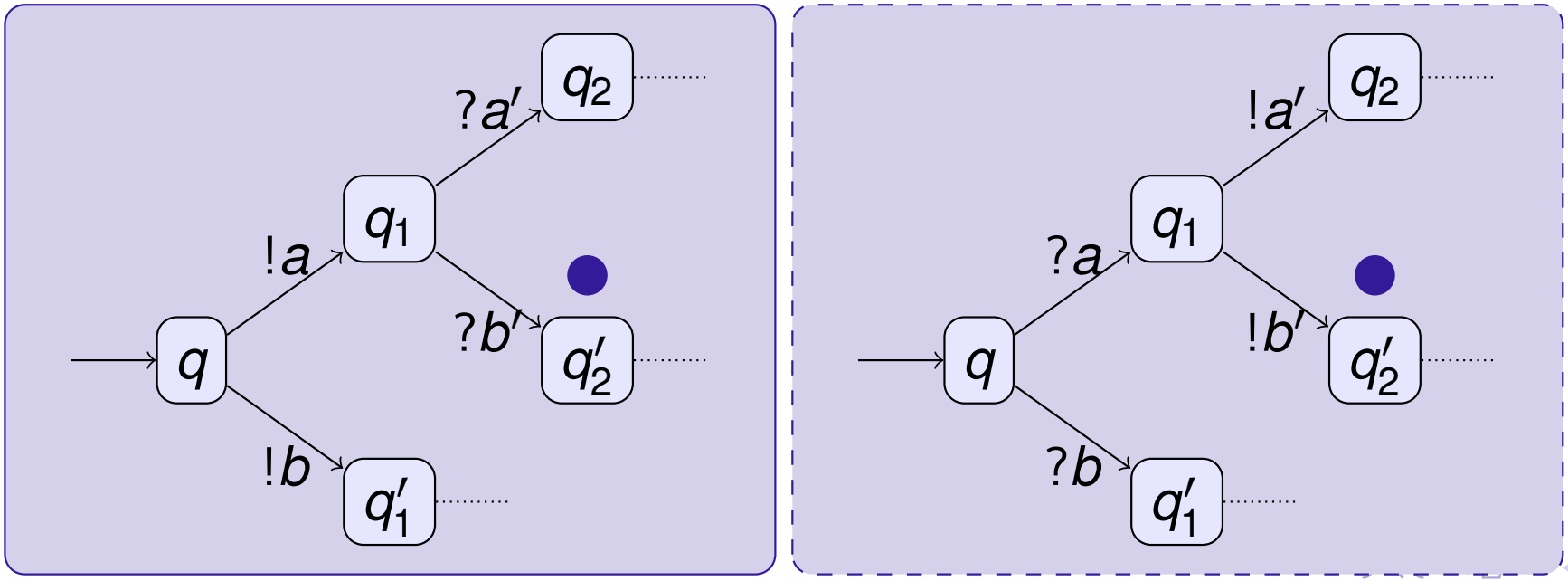
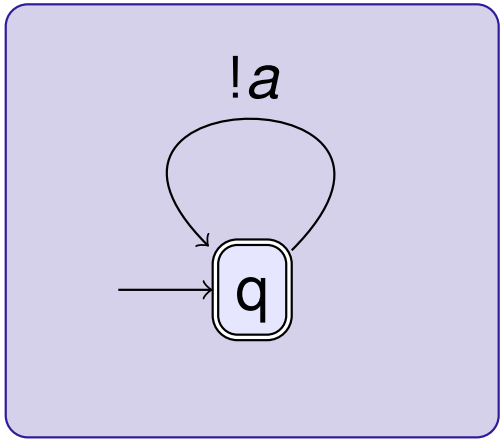


Another Source of Leaks



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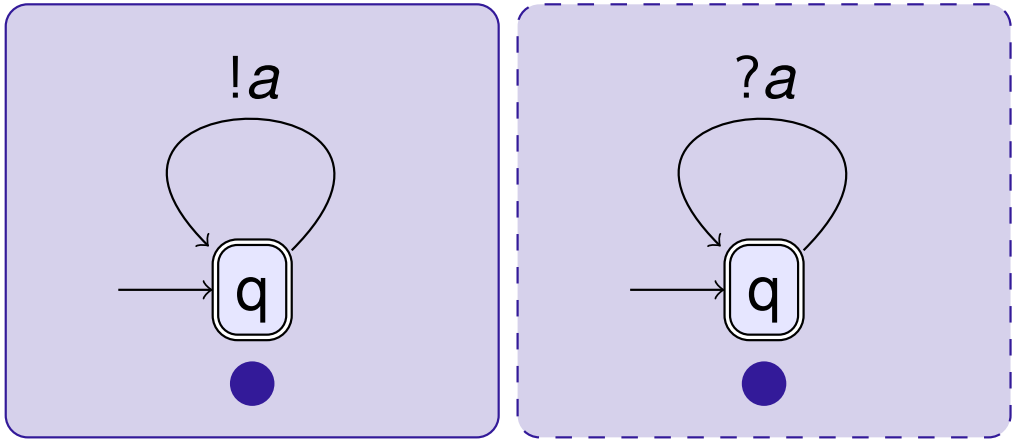

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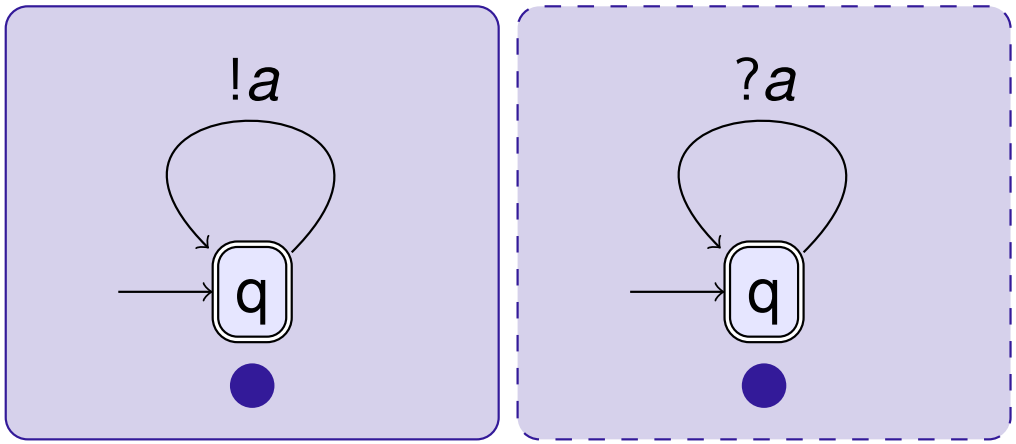

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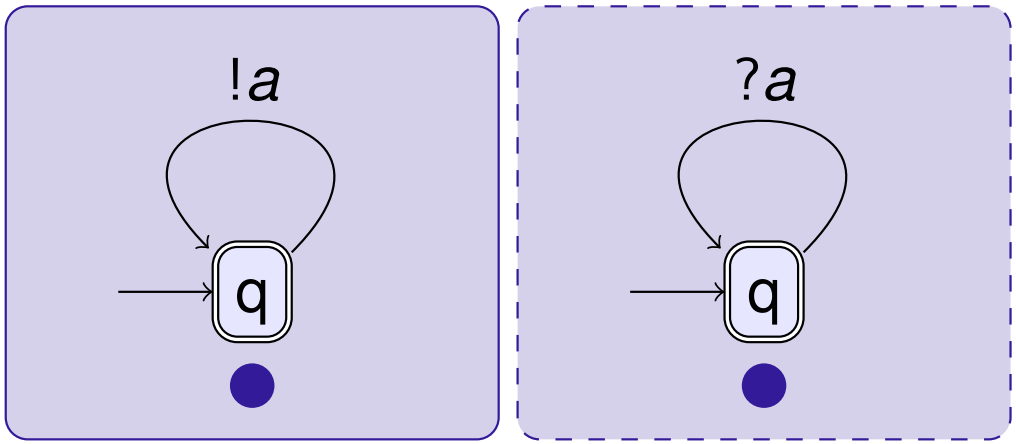

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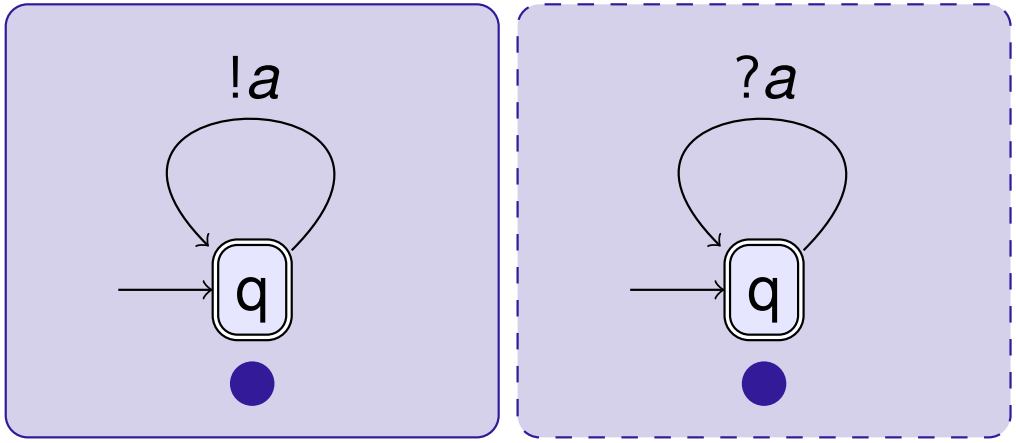

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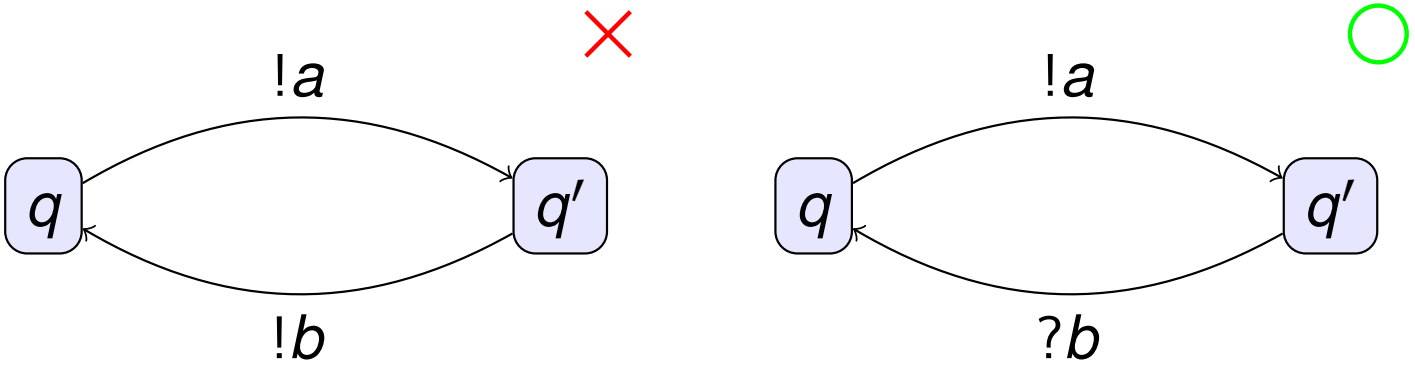
Definition — **Synchronising state**

A state s is synchronising if every cycle that goes through it contains at least one send and one receive.



Synchronising Contracts

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Definition — **Synchronising contract**

A contract is synchronising if all its final states are.

Synchronising Contracts

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Definition — Synchronising contract

A contract is synchronising if all its final states are.

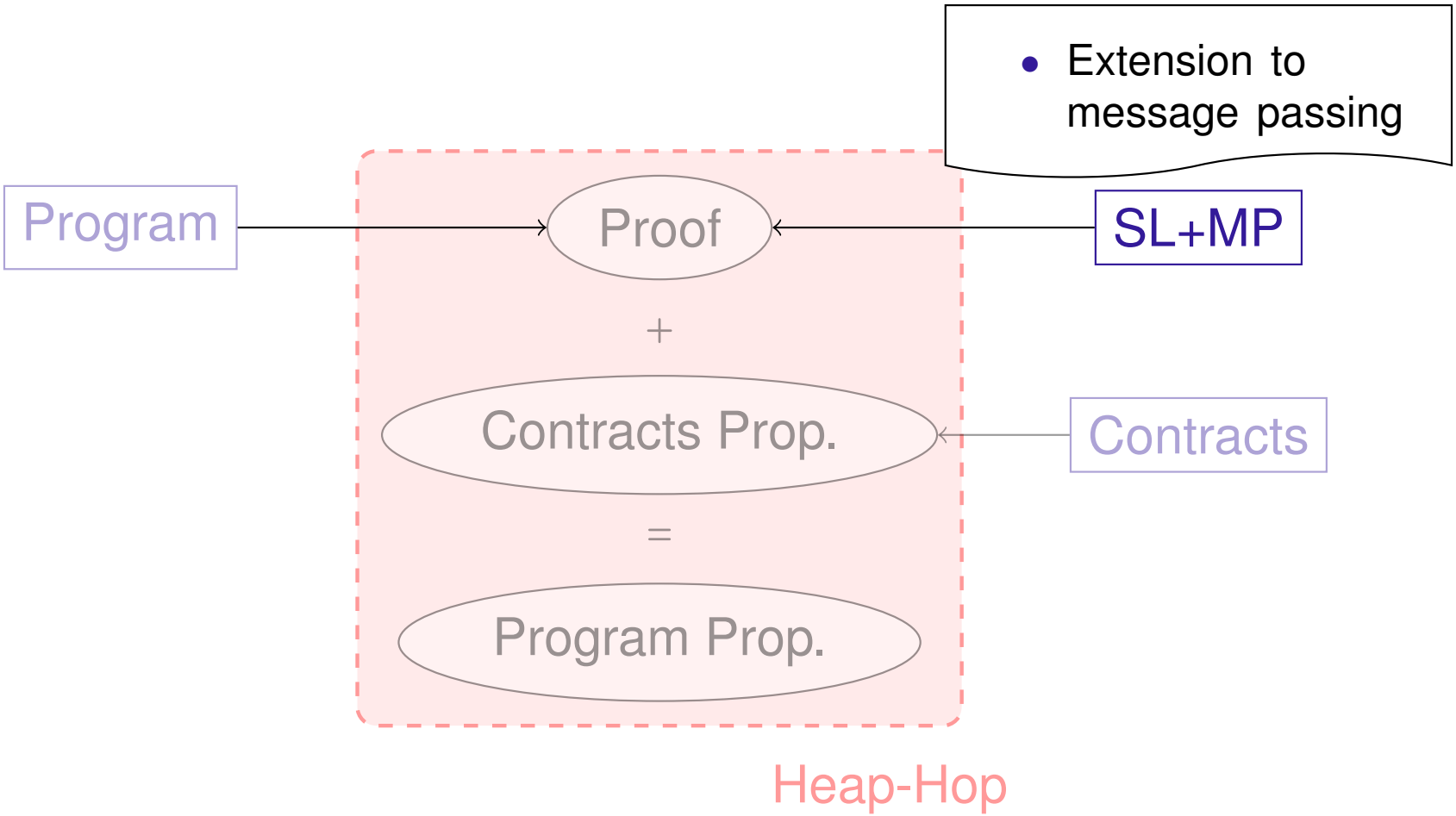
Theorem — [V., Lozes & Calcagno '09]

*Deterministic, positional and synchronising contracts are **safe** (fault and leak free).*

Definition — **Singularity contract**

Singularity contracts are deterministic and **all** their states are synchronising.

- This is missing the positional condition!
- Does not guarantee reception fault freedom
- In fact, we proved that safety is still **undecidable** for deterministic or positional contracts.
- Positional Singularity contracts are **safe** and **bounded**.


• Extension to message passing
Program
Proof
SL+MP
+
Contracts Prop.
Contracts
=
Program Prop.
Heap-Hop

Separation Logic [Reynolds 02, O'Hearn 01, ...]

- Local reasoning for heap-manipulating programs
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- Numerous extensions, *e.g.* storable locks [Gotsman et al. 07]

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New Now with message passing! [APLAS'09]

Syntax of SL

$$
\begin{array}{rcll}
E & ::= & x \mid n \in \{0, 1, 2, \ldots\} \mid \cdots & \text{expressions} \\
\phi & ::= & E_1 = E_2 \mid E_1 \neq E_2 & \text{stack predicates} \\
 & & \mid \mathsf{emp} \mid E_1 \mapsto E_2 & \text{heap predicates} \\
 & & \mid \exists x.\, \phi \mid \phi_1 \wedge \phi_2 \mid \neg\phi \mid \phi_1 * \phi_2 & \text{formulas}
\end{array}
$$

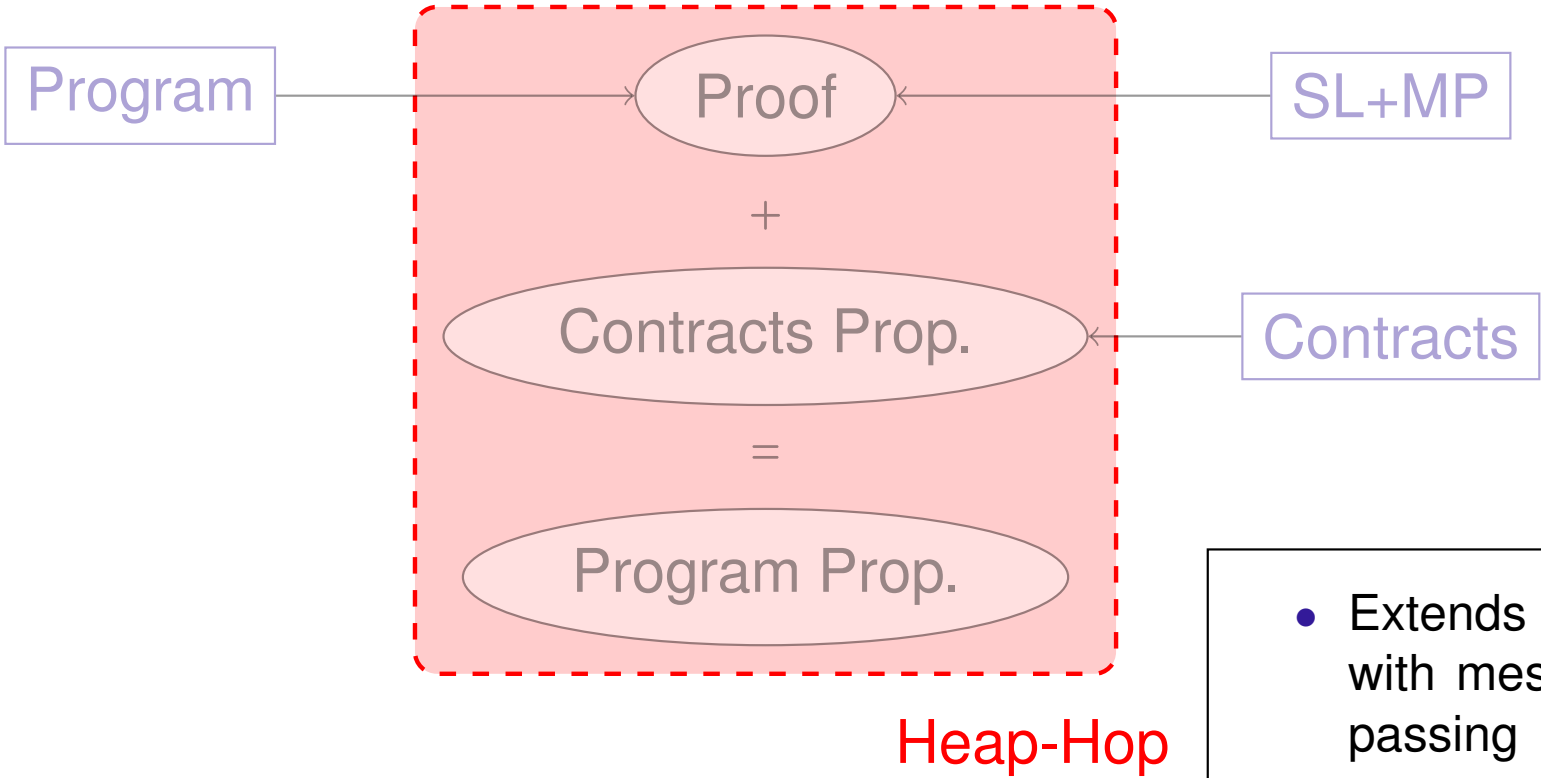
Assertions (extension)

Syntax (continued)

$$\phi \quad ::= \quad \ldots \mid E \mapsto (\mathfrak{C}\{q\}, E') \qquad \text{endpoint predicate}$$

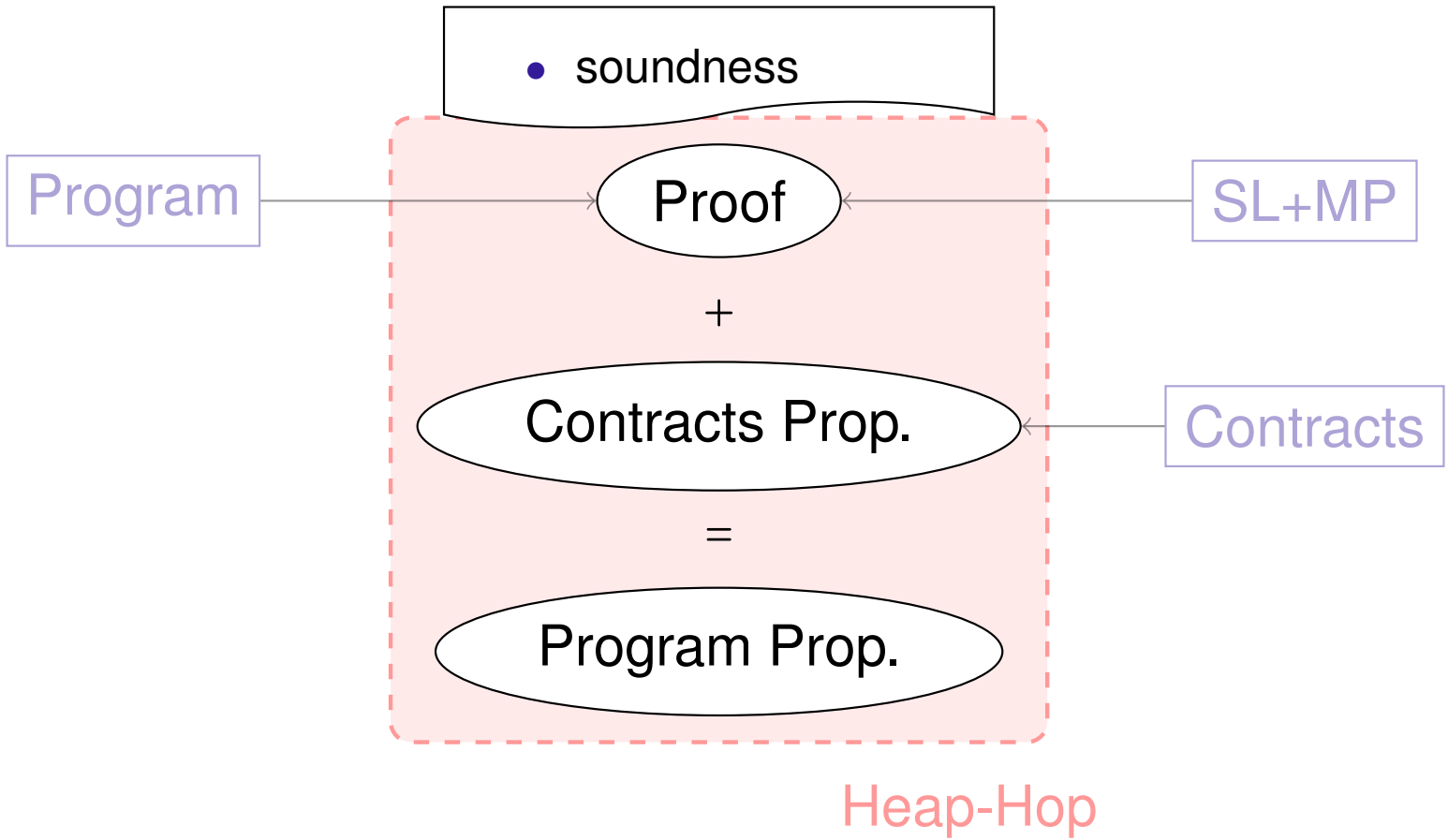
Intuitively $E \mapsto (\mathfrak{C}\{q\}, E')$ means:

- E is an allocated endpoint
- it is ruled by contract $\mathfrak{C}$
- it is currently in the control state q of $\mathfrak{C}$
- its peer is E'



- Extends Smallfoot with message passing
- Written in OCaml
- Open source

[V., Lozes & Calcagno TACAS'10]


soundness
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Validity and Leak Freedom

Definition — Program validity

$\{\phi\}\ p\ \{\psi\}$ is valid if, for all $\sigma \vDash \phi$

- p has **no race or memory fault** starting from σ
- p has **no reception faults** starting from σ
- if $p, \sigma \rightarrow^* \sigma'$ then $\sigma' \vDash \psi$

Definition — Leak free programs

p is **leak free** if for all σ

$p, \sigma \rightarrow^* \sigma'$ implies that the heap and buffers of σ' are empty

Properties of Proved Programs

Theorem — **Soundness**

If $\{\phi\}$ *p* $\{\psi\}$ *is provable with* ***reception fault free*** *contracts then* $\{\phi\}$ *p* $\{\psi\}$ *is* ***valid****.*

Theorem — **Leak freedom**

If $\{\phi\}$ *p* $\{\mathsf{emp}\}$ *is provable with* ***leak free*** *contracts then p is* ***leak free****.*

Conclusion

Contributions

Contracts

- Formalisation of contracts
- Automatic verification of contract properties

Program analysis

- First extension of separation logic to message passing
- Formalisation of heap-manipulating, message passing programs with contracts
- Contracts and proofs collaborate to prove freedom from reception errors and leaks
- Tool that integrates this analysis: **Heap-Hop**

Contracts

- Prove progress for programs
- Extend to the multiparty case
- Enrich contracts with counters, non determinism, ...

Automatic program verification

- Discover specs and message footprints
- Discover contracts
- Fully automated tool

Tracking Heaps that Hop with Heap-Hop

Jules Villard[1,3] Étienne Lozes[2,3] Cristiano Calcagno[4,5]

[1]Queen Mary, University of London

[2]RWTH Aachen, Germany

[3]LSV, ENS Cachan, CNRS

[4]Monoidics, Inc.

[5]Imperial College, London