Typing Copyless Message Passing

Viviana Bono   Chiara Messa   Luca Padovani

Dipartimento di Informatica, Università di Torino

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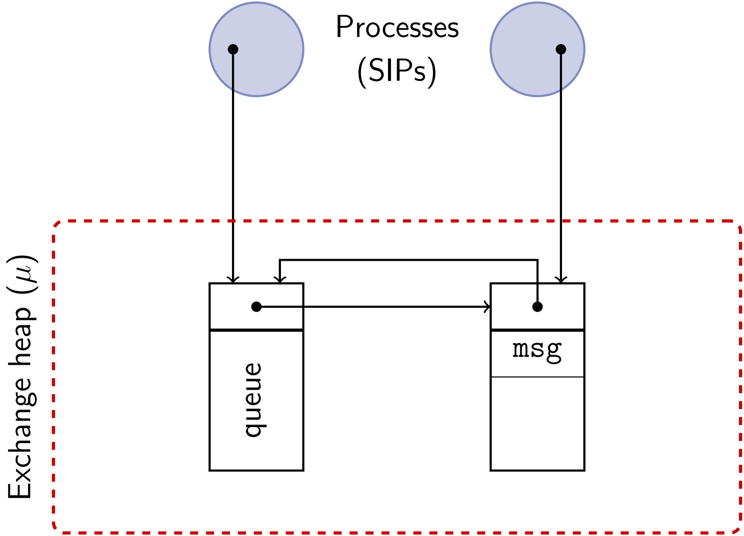
Singularity OS: architecture



Sing# examples

```
void CLIENT() {
  (e, f) = open();
  spawn { SERVER(f) }
  send(e, v1);
  send(e, v2);
  res = receive(e);
  close(e);
}
```

```
void SERVER(f) {
  a1 = receive(f);
  a2 = receive(f);
  ...
  send(f, OP(a1, a2));
  close(f);
}
```

Safety properties

1. no communication errors
2. no memory faults
3. no memory leaks
4. process isolation guaranteed by ownership

Contracts

```
contract OP_Service {
  initial state START { Arg! → WAIT_ARG_2 }
  state WAIT_ARG_2 { Arg! → WAIT_RES }
  state WAIT_RES { Res? → END }
  final state END { }
}
```

+ recursion
+ branching

Exposing structures

```
expose (a) {
  send(*a, b);
}
```

```
expose (b) {
  send(a, *b);
  *b = new T();
}
```

+ records with named fields (not in the paper)

Enforcing safety properties

1. no communication errors
2. no memory faults
3. no memory leaks
4. process isolation guaranteed by ownership

LINEAR TYPE SYSTEM!

- too restrictive in some cases
- too permissive in others

Linearity is too restrictive

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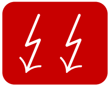

```
  *b = new T();
}
```

Linearity is too permissive

```
void foo()
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  (e, f) = open();
  send(e, f);
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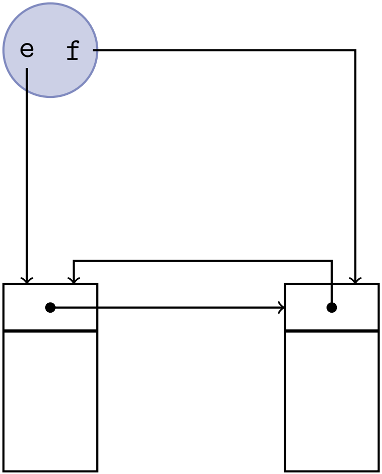

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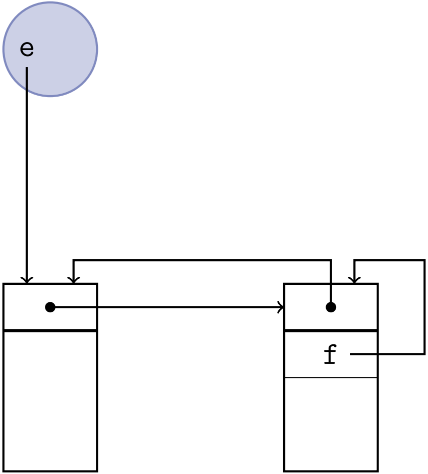

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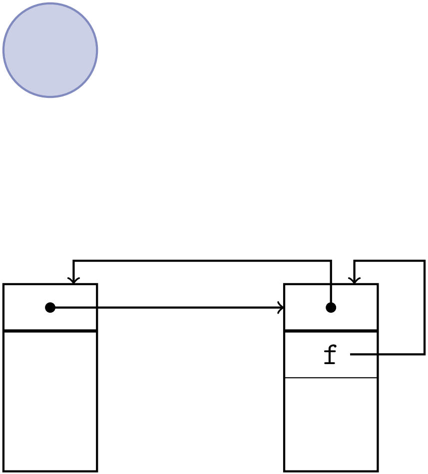

Modeling processes

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  send(e, v2);
  res = receive(e);
  close(e);
}
```

$\mathsf{open}(\mathtt{e},\mathtt{f}).(\mathtt{SERVER} \mid$
$\quad \mathtt{e}!\mathtt{v1}.$
$\quad \mathtt{e}!\mathtt{v2}.$
$\quad \mathtt{e}?(\mathtt{res}).$
$\quad \mathsf{free}(\mathtt{e}).$
$\quad \mathbf{0}$
$)$

- channel = peer endpoints
- explicit channel closure

Modeling exposures

```
expose (a) {
  send(*a, b);
}
```

$\mathsf{expose}(\mathtt{a}, x).$
$x!\mathtt{b}.$
$\mathsf{unexpose}(\mathtt{a}, x).\ \ \ldots$

```
expose (b) {
  send(a, *b);
  *b = new T();
}
```

$\mathsf{expose}(\mathtt{b}, x).$
$\mathtt{a}!x.$
$\mathsf{cell}(c).$
$\mathsf{unexpose}(\mathtt{b}, c).\ \ \ldots$

- expose/unexpose $\sim$ dereferentiation/assignment
- with type effects

Modeling contracts

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```

Client/Import	Service/Export
!Arg.!Arg.?Res.end	?Arg.?Arg.!Res.end

Types and endpoint types

t	$::=$		**Type**
		$*t$	(cell type)
	$\mid$	$*\bullet$	(exposed cell type)
	$\mid$	T	(endpoint type)

T	$::=$		**Endpoint Type**
		end	(termination)
	$\mid$	X	(variable)
	$\mid$	$!t.T$	(output)
	$\mid$	$?t.T$	(input)
	$\mid$	rec $X.T$	(recursive type)

Typing message passing

(T-Open)

$$\frac{\Delta, a : T, b : \overline{T} \vdash P}{\Delta \vdash \mathsf{open}(a, b).P}$$

(T-Send)

$$\frac{\Delta, u : T \vdash P}{\Delta, u : !t.T, v : t \vdash u!v.P}$$

(T-Receive)

$$\frac{\Delta, u : T, x : t \vdash P}{\Delta, u : ?t.T \vdash u?(x).P}$$

Typing exposures

(T-Expose)
$$\frac{\Delta, u : *\bullet, x : t \vdash P}{\Delta, u : *t \vdash \mathsf{expose}(u, x).P}$$

(T-Unexpose)
$$\frac{\Delta, u : *t \vdash P}{\Delta, u : *\bullet, v : t \vdash \mathsf{unexpose}(u, v).P}$$

Typing exposures: example

$\text{expose}(\mathtt{a}, x).$

$x!\mathtt{b}.$

$\text{unexpose}(\mathtt{a}, x).$

$\ldots$

Typing exposures: example

$$\{\mathtt{a} : *(!s.T), \mathtt{b} : s\} \vdash \text{expose}(\mathtt{a}, x).$$

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$$\text{unexpose}(\mathtt{a}, x).$$

$$\ldots$$

Typing exposures: example

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$$\{\mathtt{a} : *T\} \vdash \ldots$$

Typable leak

```
void foo()
{
  (e, f) = open();
  send(e, f);
  close(e);
}
```

open(e, f).
e!f.
free(e).
0

$T = !\overline{T}.\mathsf{end}$ $\qquad\qquad$ $\overline{T} = \mathsf{rec}\ X.?X.\mathsf{end}$

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\begin{aligned}
\{\} &\vdash \mathsf{open}(\mathtt{e}, \mathtt{f}).\\
\{\mathtt{e} : T, \mathtt{f} : \overline{T}\} &\vdash \mathtt{e}!\mathtt{f}.\\
&\quad\ \mathsf{free}(\mathtt{e}).\\
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Understanding the problem

"Improper" recursion?

$$T = !\overline{T}.\mathsf{end} \qquad \overline{T} = \mathsf{rec}\ X.?X.\mathsf{end}$$

No, the following endpoint types are safe

$$S = \mathsf{rec}\ X.!X.\mathsf{end} \qquad \overline{S} = ?S.\mathsf{end}$$

It's a matter of "ownership"

Understanding the problem

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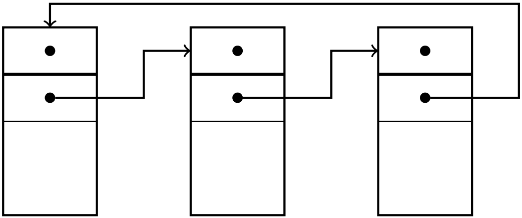

Type weight

In summary

- "receive state" = "has type $?T.S$"
- only endpoints in "receive state" can have a non-empty queue

Solution

- $\|T\|$ = "depth of the queue of an endpoint with type T"
- only endpoint types with finite weight are admitted

$$T = !\overline{T}.\mathsf{end} \qquad \overline{T} = \mathsf{rec}\ X.?X.\mathsf{end}$$
$$\|T\| = 0 \qquad \|\overline{T}\| = \infty$$

$$S = \mathsf{rec}\ X.!X.\mathsf{end} \qquad \overline{S} = ?S.\mathsf{end}$$
$$\|S\| = 0 \qquad \|\overline{S}\| = 1$$

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On weights and reachability

Proposition

If $a : T, b : S$ *and* $b \in \mathrm{reach}(a, \mu)$, *then* $\|S\| < \|T\|$.

Finite weight $\neq$ bounded queue

$$T = \mathsf{rec}\ X.?\mathtt{int}.X \qquad\qquad \|T\| = 1$$

Finite weight $\neq$ acyclic heap

$$*(?*\bullet.\mathsf{end})$$

Well-behaved processes

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

1. $\mathrm{fn}(Q) \subseteq \mathrm{dom}(\mu)$
2. $\mathrm{dom}(\mu) \subseteq \mathrm{reach}(\mathrm{fn}(Q), \mu)$
3. $Q \equiv P_1 \mid P_2$ implies $\mathrm{reach}(\mathrm{fn}(P_1), \mu) \cap \mathrm{reach}(\mathrm{fn}(P_2), \mu) = \emptyset$
4. $Q \equiv P_1 \mid P_2$ and $(\mu; P_1) \not\rightarrow$ where P_1 does not have unguarded parallel compositions imply either
   - $P_1 = \mathbf{0}$, or
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Results

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 [BMP@ESOP2011]

Formalization of Sing#

- contracts ⇒ endpoint types (= session types)
- `expose` ⇒ opaque references $*\bullet$ (= simple behavioral types)

Sing# restrictions

- Sing# too forbids sending endpoints in "receive state"...
- ...for implementative reasons
- Sing# is leak-free, incidentally? ☺

A new extension: polymorphic endpoint types

Modeling parametric contracts

$$!\langle\alpha\rangle(\alpha).?(\alpha).\mathsf{end}$$

But...

$$\vdash \mathsf{open}(\mathtt{e},\mathtt{f}).\mathtt{e}!\mathtt{f}.\mathsf{free}(\mathtt{e}).\mathbf{0}$$

$$\mathtt{e} : !\langle\alpha\rangle(\alpha).\mathsf{end} \qquad \mathtt{f} : ?\langle\alpha\rangle(\alpha).\mathsf{end}$$

Idea: bounded polymorphism

- $!\langle\alpha \leqslant T\rangle(\alpha).\mathsf{end}$ (T has ∞ weight)
- $T \leqslant S$ implies $\|T\| \leq \|S\|$

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