Foundations of Global Computing

A Personal Perspective

Vladimiro Sassone

University of Sussex
**Global Ubiquitous Computing:**

Computation over a global network of mobile, bounded resources shared among mobile entities which move between highly dynamic, largely unknown, untrusted networks.

**Difficulties:**

- Extreme dynamic reconfigurability; lack of coordination and trust; limited capabilities; partial knowledge . . .

**Issues:**

- Protection and management of resources; privacy and confidentiality of data; . . .
A distributed timed-arc Petri net (DTAPN) is a Petri net together with
- a interval time constraint on transitions, either discrete or continuous;
- a clock synchronisation equivalence Σ on places.

Tokens age, and transitions are enabled accordingly.
Time elapses at the same speed on p and p′ if $p \Sigma p′$.

Globally Asynchronous, Locally Synchronous

Global Time: $\Sigma = P \times P$  Local Time: $\Sigma = \Delta_P$

A Separation Result: Reachability for safe LT nets is decidable, but undecidable for safe GT nets.

ICATPN 2001, FST&TCS 2001
A categorical machinery which allows the derivation of LTSs from reduction systems.

Bisimulation on such LTSs is a congruence, provided a general condition is met.

Coinduction Principle Desiderata:

- Operational Corresp.: $p \not\sim q$ iff $p \xrightarrow{\tau} q$
- Correctness: $p \approx q$ implies $p \approx q$
- Completeness: $p \approx q$ implies $p \approx q$

The intuition:

\[ a \xrightarrow{c} b \text{ iff } c[a] \not\sim b \]

Eg:

\[ a \xrightarrow{-[\bar{a}]} 0 \quad M \xrightarrow{(\lambda x. -)N} M[N/x] \quad KM \xrightarrow{-N} M \]
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Coinduction Principle Desiderata:

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- Correctness: \( p \approx q \) implies \( p \approx q \)
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The intuition:

\[
a \xrightarrow{c} b \text{ iff } c[a] \not\rightarrow b
\]

But: Must choose labels carefully not to mess up the bisimulation

Choose only ‘minimal’ redex-enabling contexts: GRPOs.

Relative pushouts in groupoidal categories:

EXPRESS 2002, FOSSACS 2003, NJC, TCS
Jeeg: concurrent OO with history-sensitive access control

- Java (no synchronized(), wait(), notify(), notifyAll()) for business code;
- Linear Time Temporal Logic for synchronisation code (method guards).

```java
public class MyClass {
    sync {
        m : φ;
        ...
    }
    ...// Standard Java class def
}
```

where \( m \) is a method identifier and \( φ \), the guard, is an LTL formula. When \( m \) is invoked, the thread is kept on hold unless \( φ \). When the condition is true, all waiting threads are awakened. \( m \) is implicitly synchronised.
Resources: Models, Types, Logics, Languages

- **Access Control**  
  (Concur 2002, ESOP 2004)

- **Access Authorisation**  
  (FST&TCS 2002, Info&Co)

- **Secrecy for Mobile Agents**  
  (ICALP 2003)

- **Trust Management**  
  (SEFM 2003)

- **Bounds Control**  
  (ASIAN 2003)
Mobile Ambients

Both administrative domains and computational environments

➤ Subjective movements

\[ n[ \text{in } m.P | Q ] | m[ R ] \rightarrow m[ n[ P | Q ] | R ] \]
\[ m[ n[ \text{out } m.P | Q ] | R ] \rightarrow n[ P | Q ] | m[ R ] \]

➤ Boundary dissolver

\[ \text{open } n.P | n[ Q ] \rightarrow P | Q. \]

➤ Process interaction

\[ n[ \langle M \rangle.P | (x).Q ] \rightarrow n[ P | Q\{x := M\} ], \]
Group Types for Mobility

Aim: Resource Access Control

- Detect and prevent unwanted access to resources.
- Focus on static approaches based on enforcing type disciplines.
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- Detect and prevent unwanted access to resources.
- Focus on static approaches based on enforcing type disciplines.

Groups: Sets of processes with common access rights.

Constraints like $k : \text{CanEnter}(n)$ are modelled as:

$n$ belongs to group $G$

$k$ may cross the border of ambients of group $G$.

For instance, the system:

$$k[\text{in} n | l[\text{out} k]] | n[_]$$

is well-typed under assumptions of the form:

$$k : \text{amb}[K, \text{cross}(N)]$$

$$l : \text{amb}[L, \text{cross}(K)]$$

$$n : \text{amb}[N, \ldots]$$
Indirect Border Crossing

**Trojan Horses:** The system

\[ \text{Odysseus} \left[ \text{in Horse} . \text{out Horse} . \text{Destroy} \right] \mid \text{Horse} \left[ \text{in Troy} \right] \mid \text{Troy} \left[ \text{Trojans} \right] \]

is well-typed under assumptions:

\[ \text{Odysseus} : \text{amb} \left[ \text{Achaean} , \text{cross}(\text{Toy}) \right] \]
\[ \text{Horse} : \text{amb} \left[ \text{Toy} , \text{cross}(\text{City}) \right] \]
\[ \text{Troy} : \text{amb} \left[ \text{City}, \_ \right] \]
Indirect Border Crossing

Trojan Horses: The system

\[ \text{Odysseus} \in \text{Horse.out Horse.Destroy} \mid \text{Horse} \in \text{Troy} \mid \text{Troy} \in \text{Trojans} \]

is well-typed under assumptions:

\[ \text{Odysseus} : \text{amb[ Achaean, cross(Toy) ]} \]
\[ \text{Horse} : \text{amb[ Toy, cross(City) ]} \]
\[ \text{Troy} : \text{amb[ City, _ ]} \]

However, the system may evolve to

\[ \text{Troy} \in \text{Trojans} \mid \text{Horse[ _ ]} \mid \text{Odysseus[ Destroy ]} \]

where Odysseus got inside Troy's Walls taking by surprise the Trojans.
Types

Groups: \( G, H, \ldots \)

Sets of groups: \( \mathcal{P}, \mathcal{I}, \ldots \) \( \mathcal{U} \) The universal set of groups

Ambients types:
\[
A ::= \text{amb}[G, M]
\]
amb of group \( G \), with mobility type \( M \)

Process types:
\[
\Pi ::= \text{proc}[G, M]
\]
process that can be enclosed in an ambient of group \( G \), may drive to ambients whose groups are in \( M \)

Capability types:
\[
K ::= \text{cap}[G, M]
\]
capability that can appear in an ambient of group \( G \), may drive it to ambients whose groups are in \( M \)

Mobility types:
\[
M ::= \text{mob}[\mathcal{P}]
\]
mobility specs: where processes are allowed to reside
Access Control Properties

Mobility properties:

➤ If $\Gamma \vdash n[\text{in}m.P \mid Q] \mid m[R] : \Pi$, then

$$\Gamma \vdash m : \text{amb}[M, \_] \quad \text{and} \quad \Gamma \vdash n : \text{amb}\[\_, \text{mob}[P]\]$$

with $M \in P$.

➤ If $\Gamma \vdash m[\text{out} m.P \mid Q] \mid R : \Pi$, then

$$\Gamma \vdash m : \text{amb}[M, \text{mob}[P_m]] \quad \text{and} \quad \Gamma \vdash n : \text{amb}[N, \text{mob}[P_n]]$$

with $M \in P_n$ and $P_m \subseteq P_n$. 
Detecting Odysseus' intentions

Now, in order to assign a type to

\[ \text{Odysseus [in Horse.out Horse.Destory] \mid Horse [in Troy] \mid Troy [Trojans]} \]

we need assumptions of the form:

\[ \text{Odysseus : amb[\text{Achaean}, \text{mob[\{Ground, Toy, City\}]]}} \]
\[ \text{Horse : amb[\text{Toy}, \text{mob[\{Ground, City\}]]}} \]
\[ \text{Troy : amb[\text{City, \_}]} \]

representing that Odysseus is an Achaean intentioned to move into a City!
Detecting Odysseus’ intentions

Now, in order to assign a type to

\[ \text{Odysseus}[ \text{in Horse}.\text{out Horse.} \text{Destroy}] | \text{Horse}[ \text{in Troy}] | \text{Troy}[ \text{Trojans}] \]

we need assumptions of the form:

\[ \text{Odysseus : amb}[\text{Achaean}, \text{mob}[\text{Ground, Toy, City}]] \]

\[ \text{Horse : amb}[\text{Toy}, \text{mob}[\text{Ground, City}]] \]

\[ \text{Troy : amb}[\text{City, _}] \]

representing that Odysseus is an Achaean intended to move into a City!

On the other hand, under assumptions of the form

\[ \text{Odysseus : amb}[\text{Achaean}, \text{mob}[\text{Ground, Toy}]] \]

the Trojans should not fear any attack from Odysseus.
Dependent Mobility Types: ($P$ and $C$ are sets of names, not groups.)

\[ A ::= \text{amb}[\text{hasFathers}(P), \text{hasChildren}(C)] \]
Dependent Types for Access Control

Dependent Mobility Types: \((P \text{ and } C \text{ are sets of names, not groups.})\)

\[ A ::= \text{amb}[\text{hasFathers}(P), \text{hasChildren}(C)] \]

Dependent types allow personalised services and dynamic access control.

\[ \text{HorseServer} \triangleq !x(\nu \text{Horse} : \text{amb}[\_ , \text{hasChildren}\{x\}] )\text{Horse}[\text{out Troy.in Troy.0}] \]
Dependent Types for Access Control

**Dependent Mobility Types:** \( (P \text{ and } C \text{ are sets of names, not groups.}) \)

\[
A ::= \text{amb}[\text{hasFathers}(P), \text{hasChildren}(C)]
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**Dependent types** allow personalised services and dynamic access control.

\[
\text{HorseServer} \triangleq !x!(v\text{Horse} : \text{amb}[\_, \text{hasChildren}\{x\}])\text{Horse}[\text{out Troy}.\text{in Troy.0}]
\]

➤ Names have several possible types, depending on the actual communications occurred.

➤ The set of names exchanged over a channel must be tracked. Luckily, The set of possible types for a name has a **maximum** and a **minimum** element.
Names ≈ Cryptokeys: Carrying messages inside private ambients preserves message integrity and privacy. Or, does it?

$$(vn)(a[n[\text{out}\ a.\text{in}\ b.\langle M\rangle}]|b[\text{open}\ n.(x)P])$$
Secrecy in Mobile Ambients

Names ≈ Cryptokeys: Carrying messages inside private ambients preserves message integrity and privacy. Or, does it?

\[(vn)( a[ n[ out a.in b.\langle M \rangle ] ] | b[ open n.(x)P ] )\]

It actually offers no guarantees for software agents, as \(n\) must be revealed along the move, and servers may peek inside.

How to provide stronger protection?
Secrecy in Mobile Ambients

Names ≈ Cryptokeys: Carrying messages inside private ambients preserves message integrity and privacy. Or, does it?

\[(vn)(a[n[ out a.in b.(M) ] ] | b[ open n.(x)P ] )\]

It actually offers no guarantees for software agents, as \(n\) must be revealed along the move, and servers may peek inside.

How to provide stronger protection?

A new crypto-primitive: subjective access control using co-capabilities + data encryption to preserve secrecy of data while agents move autonomously

\[n[ seal k.P | Q ] \rightarrow n\{ P | Q \}_k\]

Effects:

➤ blocks message exchanges and encrypts their contents;

➤ the sealed ambient cannot communicate, but it may move.
The mechanism to resume to a fully operational state is associated to movements and co-capabilities containing keys

\[ n\{ \text{in } m.P \mid Q \}_k \mid m\{ \text{in } \{x\}_k.R \mid R' \} \longrightarrow m\{ n[ P \mid Q ] \mid R \{ x := n \} \mid R' \} \]
Sealed Ambients

The mechanism to resume to a fully operational state is associated to movements and co-capabilities containing keys

\[
\begin{align*}
  & n \{ \text{in } m.P \mid Q \} \mid_k m \{ \overline{\text{in } x} \}_k R \mid R' \\
\end{align*}
\]
The mechanism to resume to a fully operational state is associated to movements and co-capabilities containing keys.

\[
\begin{align*}
    n\{ \text{in } m.P \mid Q \}_k & \quad m\{ \text{in } \{x\}_k R \mid R' \} \\
    & \quad \longrightarrow \\
    & \quad m\{ n[P \mid Q] \mid R x := n \mid R' \}
\end{align*}
\]

Example:

\[
(\forall k)a[ \ n[ \text{seal } k.\text{out } a.\text{in } b.<M>^\wedge ] ] \mid b[ \text{in } \{x\}_k (y)^x . P ]
\]
Sealed Ambients

The mechanism to resume to a fully operational state is associated to movements and co-capabilities containing keys

\[
\begin{align*}
n \{ \text{in} \ m.\mathcal{P} \mid \mathcal{Q} \} \mid m \{ \overline{\text{in}} \ \{ x \} \text{seal} \mid R \mid R' \} & \rightarrow m \{ n \{ \mathcal{P} \mid \mathcal{Q} \} \mid R \{ x := n \} \mid R' \} \\
\end{align*}
\]

Example:

\[
\begin{align*}
(vk)a[ n \{ \text{seal} \ k.\text{out} \ a.\text{in} \ b.\langle \mathcal{M} \rangle \} ] & \mid b[ \overline{\text{in}} \ \{ x \} k.\mathcal{P} ] \\
\rightarrow (vk)a[ n \{ \text{out} \ a.\text{in} \ b.\langle \mathcal{M} \rangle \} ] & \mid b[ \overline{\text{in}} \ \{ x \} k.\mathcal{P} ]
\end{align*}
\]
The mechanism to resume to a fully operational state is associated to movements and co-capabilities containing keys

\[ n \{ \text{in} \ m.P \mid Q \}^k_k \mid m \{ \overline{\text{in}} \{x\}^k_k.R \mid R' \} \rightarrow m \{ n[ P \mid Q ] \mid R \{ x := n \} \mid R' \} \]

Example:

\[
(vk)a[ n[ \text{seal} \ k.\text{out} \ a.\text{in} \ b.\langle M \rangle^k_k ] ] \mid b[ \overline{\text{in}} \{x\}^k_k.(y)^x.P ]
\]

\[
\rightarrow (vk)a[ n[ \text{out} \ a.\text{in} \ b.\langle M \rangle^k_k ] ] \mid b[ \overline{\text{in}} \{x\}^k_k.(y)^x.P ]
\]

\[
\rightarrow (vk)a[ ] \mid n[ \text{in} \ b.\langle M \rangle^k_k ] \mid b[ \overline{\text{in}} \{x\}^k_k.(y)^x.P ]
\]
The mechanism to resume to a fully operational state is associated to movements and co-capabilities containing keys

\[ n \{ \text{in } m.P \mid Q \} \quad m \{ \text{in } \{ x \} \}_{k} \cdot R \mid R' \} \quad \rightarrow \quad m \{ n[ P \mid Q ] \mid R \{ x := n \} \mid R' \} \]

Example:

\[(v k) a[ n \{ \text{seal } k.\text{out } a.\text{in } b.\langle M \rangle \hat{\rangle} \} ] \mid b[ \text{in } \{ x \}_{k} .(y)^{x}.P ] \]

\[\rightarrow (v k) a[ n \{ \text{out } a.\text{in } b.\langle M \rangle \hat{\rangle} \}_{k} ] \mid b[ \text{in } \{ x \}_{k} .(y)^{x}.P ] \]

\[\rightarrow (v k) a[ ] \mid n \{ \text{in } b.\langle M \rangle \hat{\rangle} \}_{k} \mid b[ \text{in } \{ x \}_{k} .(y)^{x}.P ] \]

\[\rightarrow (v k) a[ ] \mid b[ n[ \langle M \rangle \hat{\rangle} ] \mid (y)^{n}.P \{ x := n \} ] \]
Sealed Ambients

The mechanism to resume to a fully operational state is associated to movements and co-capabilities containing keys

\[
\begin{align*}
&\quad n\{ \text{in } m.P \mid Q \}\}_{k} \ | \ m\{ \text{in} \{x\}_{k}.R \mid R' \} 
\rightarrow\ 
\quad m\{ n[P \mid Q] \mid R_{x := n} \mid R' \}
\end{align*}
\]

Example:

\[
\begin{align*}
&(vk)a[\ n[\text{seal } k.\text{out } a.\text{in } b.\langle M \rangle]\ ] \ | \ b[\text{in } \{x\}_{k}.(y)^{x}.P] \\
\rightarrow\ 
&(vk)a[\ n[\text{out } a.\text{in } b.\langle M \rangle]\ ] \ | \ b[\text{in } \{x\}_{k}.(y)^{x}.P] \\
\rightarrow\ 
&(vk)a[\ ] \ | \ n[\text{in } b.\langle M \rangle]\ ] \ | \ b[\text{in } \{x\}_{k}.(y)^{x}.P] \\
\rightarrow\ 
&(vk)a[\ ] \ | \ b[\ n[\langle M \rangle]\ ] \ | \ (y)^{n}.P\{x := n\}]
\end{align*}
\]
Intuitively:

A process preserves the secrecy of a piece of data $M$ if it does not publish $M$, or anything that would permit the computation of $M$. 
Secrecy and Adversaries

Intuitively:

A process preserves the secrecy of a piece of data $M$ if it does not publish $M$, or anything that would permit the computation of $M$.

**S-Adversary:** A context $A(-)$ which initially knows names and capabilities in $S$.

**Revealing Names:** $P$ may reveal $n$ to $S$ if there exists an $S$-adversary $A(-)$ and a name $c \in S$ such that:

$$A(P) \Rightarrow C(c[\langle n\rangle^\hat{\cdot} | Q]) \quad (c \text{ free})$$
Intuitively:

A process preserves the secrecy of a piece of data $M$ if it does not publish $M$, or anything that would permit the computation of $M$.

**S-Adversary:** A context $A(\_)$ which initially knows names and capabilities in $S$.

**Revealing Names:** $P$ may reveal $n$ to $S$ if there exists an $S$-adversary $A(\_)$ and a name $c \in S$ such that:

$$A(P) \implies C(c[\langle n \rangle | Q]) \quad (c \text{ free})$$

**Typing System:** Secrecy is captured by a type system $\vdash$ which may classify processes as untrusted $\Gamma \vdash P : Un$, and data as public $a : Public$ if it can be exchanged with untrusted process.

**Secrecy Theorem:** Well-typed processes do not reveal their secrets publicly. Formally, if $\Gamma \vdash P : Un$ and $\Gamma \not\vdash s : Public$, then $P$ preserves the secrecy of $s$ from all public channels, i.e. from $\{a | \Gamma \vdash a : Public\}$. (Payload $s$ won’t be entrusted to a public $a$.)
That's all good, but ...
That’s all good, but ...

... one cannot type the Internet

The gap between theory and practice matters in practice.

All this only works as long as you trust the certified types, or are willing to typecheck migrating code yourself (bytecode verification, PCC, ...), ...
That’s all good, but ... 

...one cannot type the Internet

The gap between theory and practice matters in practice.

All this only works as long as you trust the certified types, or are willing to typecheck migrating code yourself (bytecode verification, PCC,...), ...

➢ **Verification** (relates to type checking/inference)

➢ **Certificates** (groups as certified roles)

➢ **Trust**: In UbiComp, security must work be coupled with trust management.

Which is hard, because of delegation and dynamic policies.
Trust Management

Focus on Trust Evolution and Delegation in Dynamic Networks

\[ a\{ A \}_\pi \]
Trust Management

Focus on Trust Evolution and Delegation in Dynamic Networks

principal $P \rightarrow a\{ A \}_\pi \rightarrow$ trust policy: expressions on lattice $(D, \leq)$

agent/behaviour
Trust Management

Focus on Trust Evolution and Delegation in Dynamic Networks

Principal $P \rightarrow a\{ A \}_\pi$ 

Trust policy: expressions on lattice $(D, \leq)$

Agent/behaviour $a\{ A \}_\pi \rightarrow a\{ A \}_\pi$

Trust Based Services:

$$a\{ b, \ell(v) \cdot A \}_\pi \mid b\{ \ell(x) \cdot \Sigma_i B_i \}_\pi \rightarrow a\{ A \}_\pi \mid b\{ B_{\pi(a)}\{ x := v \} \}_\pi$$

Trust Evolution:

$$a\{ \zeta \cdot A \mid B \}_\pi \rightarrow a\{ A \mid B \}_{\zeta(\pi)}$$
Trust Management

Focus on Trust Evolution and Delegation in Dynamic Networks

principal $\mathcal{P} \rightarrow a\{ A \}_\pi$ trust policy: expressions on lattice $(D, \leq)$

agent/behaviour

Trust Based Services:

$$a\{ b.\ell(v) \cdot A \}_\pi | b\{ \ell(x) \cdot \sum_i B_i \}_\pi \rightarrow a\{ A \}_\pi | b\{ B_{\pi(a)} \{ x := v \} \}_\pi$$

Trust Evolution:

$$a\{ \zeta \cdot A | B \}_\pi \rightarrow a\{ A | B \}_{\zeta(\pi)}$$

Policies and Expressions:

$$\pi ::= \begin{cases} \top & \text{delegation} \\ \lambda x : \mathcal{P}.\tau & \text{abstraction} \\ \operatorname{op}(\pi_1, \ldots, \pi_n) & \text{lattice op} \\ a \in \mathcal{P}, \; x : \mathcal{P} & \text{principal/vars} \end{cases} \quad \tau ::= \begin{cases} t \in D & \text{value/var} \\ \pi(p) & \text{policy value} \\ e \mapsto \tau;\tau & \text{choice} \end{cases}$$

$$e ::= \begin{cases} \tau \equiv \tau, \; p \equiv p & \text{comparisons} \\ e \; \text{bop} \; e & \text{boolean op} \end{cases}$$
Example:

\[
\begin{align*}
a : & \quad p \leftrightarrow \text{trusted} ; \\
& \quad q \leftrightarrow b^\downarrow(q) ; \\
& \quad z \leftrightarrow p^\downarrow(z) ; \\
\hline
b : & \quad p \leftrightarrow a^\downarrow(p) ; \\
& \quad q \leftrightarrow \text{untrusted} ; \\
& \quad z \leftrightarrow a^\downarrow(z) ;
\end{align*}
\]
Example:

\[
\begin{align*}
    a : & \quad p \leftrightarrow \text{trusted}; \\
    & \quad q \leftrightarrow \neg b^{-1}(q); \\
    & \quad z \leftrightarrow \neg p^{-1}(z);
\end{align*}
\hspace{1cm}
\begin{align*}
    b : & \quad p \leftrightarrow \neg a^{-1}(p); \\
    & \quad q \leftrightarrow \text{untrusted}; \\
    & \quad z \leftrightarrow \neg a^{-1}(z);
\end{align*}
\]

Delegation, formally: Global trust as a fixed point.

\[
\pi : (\mathcal{P} \to \mathcal{P} \to D) \to (\mathcal{P} \to D)
\]

\[
\Xi : (\mathcal{P} \to \mathcal{P} \to D) \to (\mathcal{P} \to \mathcal{P} \to D)
\]

Global Trust: \( \text{fix}(\Xi) : \mathcal{P} \to \mathcal{P} \to D. \) But, is this good enough?
Understanding Delegation

Example:

\[
\begin{align*}
  a: & \quad p &\leftrightarrow & \text{trusted}; \\
  & \quad q &\leftrightarrow & \text{\(\Gamma\)b\(\neg\)(q)}; \\
  & \quad z &\leftrightarrow & \text{\(\Gamma\)p\(\neg\)(z)};
  \\
  b: & \quad p &\leftrightarrow & \text{\(\Gamma\)a\(\neg\)(p)}; \\
  & \quad q &\leftrightarrow & \text{untrusted}; \\
  & \quad z &\leftrightarrow & \text{\(\Gamma\)a\(\neg\)(z)};
\end{align*}
\]

Delegation, formally: Global trust as a fixpoint.

\[
\begin{align*}
  \pi: (\mathcal{P} \to \mathcal{P} \to D) &\to (\mathcal{P} \to D) \\
  \Xi: (\mathcal{P} \to \mathcal{P} \to D) &\to (\mathcal{P} \to \mathcal{P} \to \mathcal{P} \to D)
\end{align*}
\]

Global Trust: \(\text{fix}(\Xi): \mathcal{P} \to \mathcal{P} \to D\). But, is this good enough?

\[
\begin{align*}
  p: & \text{trusted} & q: & \text{untrusted} & z: & ???
\end{align*}
\]

Cannot confuse don't trust with don't know: the value of \(\Gamma p\neg(z)\) could become available later.

Need to account for uncertain knowledge of \(\Gamma p\neg(z) \in D\).
Trust Structures

\[(D, \leq, \sqsubseteq), \quad \text{where } \bigvee \text{ is } \sqsubseteq \text{-continuous}\]

\begin{itemize}
  \item Trust lattice
  \item Approximation cpo
\end{itemize}

**Thm.** \((D, \leq, \sqsubseteq)\) yields an adequate semantics \([[-]]: \text{Policies} \to \text{Env} \to (\mathcal{P} \to \mathcal{P} \to D)\). The trust structure is derived canonically from \((D, \leq)\). The fixpoint is computed with respect to \(\sqsubseteq\).

\[
[[\pi_{p_1}, \ldots, \pi_{p_n}]]_\sigma = \text{fix}_\sqsubseteq(\lambda m. \lambda p. ([\pi_p]_\sigma m))
\]

**Ongoing work:**

- Approximate the fixpoint in the presence of partial information.
- Use Kripke style semantics to capture trust evolution in time.
- Static safety guarantees: processes do not undermine their site policies.
Central Notion: Resource Usage

Focus: Capacity Bounds Awareness.

- Bounded Capacity Ambients
- Fine control of capacity.
- Space as a linear co-capability.

\[ a[ \text{ in } b \cdot P | Q ] | b[ \text{ move capability} ] | R ] \text{ move capability} \]

\[ \text{space co-capability} \]

Computation takes space, dynamically, and we'd like to model it.
Fundamentals: Space Conscious Movement

\[
\begin{align*}
  \text{a[ in}_b \text{.}\ P \mid Q] \mid b[ \quad \mid R]} & \quad \Rightarrow \quad \text{b[ a[ P \mid Q] \mid R]} \\
  \text{\neg [ b[ a[\ out}_b \text{.}\ P \mid Q] \mid R]} & \quad \Rightarrow \quad a[ P \mid Q] \mid b[ \quad \mid R]
\end{align*}
\]
Fundamentals: Space Conscious Movement

\[
\begin{align*}
& a[ \text{in} b . P \ | \ Q ] \ | \ b[ \text{out} R ] \quad \Downarrow \quad \neg \ | \ b[ \ | \ a[ P \ | \ Q ] \ | \ R ] \\
& \neg \ | \ b[ \ | \ a[ \text{out} b . P \ | \ Q ] \ | \ R ] \quad \Downarrow \quad a[ P \ | \ Q ] \ | \ b[ \ | \ R ]
\end{align*}
\]

Example: Travelling needs but consumes no space.

\[
\begin{align*}
& a[ \text{in} b . \text{in} c . \text{out} c . \text{out} b . 0 ] \ | \ b[ \ | \ c[ \ | \ ] ] \\
& \quad \Downarrow \ | \ b[ \ | \ c[ a[ \text{out} c . \text{out} b . 0 ] ] ] \\
& \quad \Downarrow \Downarrow \ a[ 0 ] \ | \ b[ \ | \ c[ \ | \ ] ]
\end{align*}
\]
A Calculus of Bounded Capacities: Sizes

Fundamentals: Space Conscious Movement

But the size of travellers matters!

\[ a^k \begin{array}{l} \text{in } b \cdot P \mid Q \end{array} \mid b[\ldots] \mid R \]

\[ b[a^k \begin{array}{l} \text{out } b \cdot P \mid Q \end{array} \mid R] \]

\[ k \text{ times} \]

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\[ \begin{array}{l} a^k P \mid Q \end{array} \mid b[\ldots] \mid R \]

\[ k \text{ times} \]
But the size of travellers matters!

What is the $a^k$? A type annotation measuring the size of $P$.

Notation. We use $a^k$ as a shorthand for $\ldots$.
A Calculus of Bounded Capacities: Spawning

Fundamentals: Space Conscious Process Activation

\[ \Delta^k P \mid -^k \downarrow \ P \]
Fundamentals: Space Conscious Process Activation

passive process: $^k P \rightarrow^k P \rightarrow P$

$P$ weighs $k$

Types ensure only 0-weighted processes are replicable: One must use spawning, so that replication needs space proportional to the process' weight.
Fundamentals: Space Conscious Process Activation

Example: Replication: $!^k \triangleq !^k\triangleright^k$

Types ensure only 0-weighted processes are replicable: One must use spawning, so that replication needs space proportional to the process’ weight.
A Calculus of Bounded Capacities: Transfer

Fundamentals: Space Acquisition and Release

$$\text{put}^\ast a.P \mid - \vdash a^k[\text{get}^\ast.Q \mid R] \Downarrow P \mid a^{k+1}[Q \mid - \mid R]$$

$$a^{k+1}[\text{put}.P \mid - \mid S] \mid b^h[\text{get} a.Q \mid R] \Downarrow a^k[P \mid S] \mid b^{h+1}[Q \mid - \mid R]$$
A Calculus of Bounded Capacities: Transfer

Fundamentals: Space Acquisition and Release

\[
\begin{align*}
\text{put} \tilde{a}.P & \downarrow a^k[ \text{get} \hat{Q} | R ] \quad \Rightarrow \quad P \mid a^{k+1}[Q \mid R] \\
& \downarrow a^{k+1}[\text{put}.P \mid S] \mid b^h[\text{get} a.Q | R] \quad \Rightarrow \quad a^k[P \mid S] \mid b^{h+1}[Q \mid R]
\end{align*}
\]

Example: A Memory Module

\[
\begin{align*}
\text{memMod} & \triangleq \text{mem}[256MB \mid \text{!put} \mid \text{!get} \text{free}] \\
\text{malloc} & \triangleq \text{m}[\text{!get} \text{mem}.\text{free}[\text{out m.get m.put}] \mid \text{!put}]
\end{align*}
\]
A Calculus of Bounded Capacities: Transfer

Fundamentals: Space Acquisition and Release

\[
\begin{align*}
\text{put} \; a \cdot P | \quad & \quad a^k[ \text{get} \cdot Q | R ] \quad \Downarrow \\
\hspace{1cm} a^{k+1}[ \quad & \quad P | a^{k+1}[ Q | R ]
\end{align*}
\]

\[
\begin{align*}
\hspace{1cm} a^{k+1}[ \quad & \quad \text{put} \cdot P | S ] \quad \Downarrow \\
b^h[ \quad & \quad \text{get} \cdot a \cdot Q | R ] \quad \Downarrow \\
\hspace{1cm} a^k[ \quad & \quad P | S ] \quad \Downarrow \\
b^{h+1}[ Q | R ]
\end{align*}
\]

Example: A Memory Module

\[
\begin{align*}
\text{memMod} & \triangleq \text{mem} \left[ 2^{256MB} \right] \text{!put} \text{!get free} \\
\text{malloc} & \triangleq \text{m} \left[ \text{!get} \text{mem} \cdot \text{free} \left[ \text{out} \text{m} \cdot \text{get} \text{m} \cdot \text{put} \right] \right] \text{!put}
\end{align*}
\]

\[
\begin{align*}
\text{memMod} \text{ malloc} & \downarrow 2^{256MB} \text{ mem} \left[ \text{!put} \text{!get free} \right] \text{ m} \left[ 2^{256MB} \right] \quad \Downarrow 2 \times 2^{256MB} \\
\text{mem} \left[ \text{!put} \text{!get free} \right] \text{ malloc} \text{ free}^{256MB} \left[ \quad \text{put} \right] & \downarrow 2^{256MB} \text{ memMod} \text{ malloc} \quad \Downarrow ...
\end{align*}
\]
A System of Capacity Types

Capacity Types: $\phi, \ldots$ are pairs of nats $[n, N]$, with $n \leq N$.

Effect Types $E, \ldots$ are pairs of nats $(d, i)$, representing $\mathtt{decs}$ and $\mathtt{incs}$.

Exchange Types: $\chi ::= \mathtt{Shh} \mid \mathtt{Amb}\langle \sigma, \chi \rangle \mid \mathtt{Cap}\langle E, \chi \rangle$

Process and Ambient and Capability Types:

$$a : \mathtt{Amb}\langle \phi, \chi \rangle \quad a \text{ has no less than } \phi_m \text{ and no more than } \phi_M \text{ spaces}$$

$$P : \mathtt{Proc}\langle k, E, \chi \rangle \quad P \text{ weighs } k \text{ and produces the effect } E \text{ on ambients}$$

$$C : \mathtt{Cap}\langle E, \chi \rangle \quad C \text{ transforms processes adding } E \text{ to their effects}$$
A System of Capacity Types

Capacity Types: $\phi, \ldots$ are pairs of nats $[n, N]$, with $n \leq N$.

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Process and Ambient and Capability Types:

- $a : \text{Amb}(\phi, \chi)$ $a$ has no less than $\phi_m$ and no more than $\phi_M$ spaces
- $P : \text{Proc}(k, \mathcal{E}, \chi)$ $P$ weighs $k$ and produces the effect $\mathcal{E}$ on ambients
- $C : \text{Cap}(\mathcal{E}, \chi)$ $C$ transforms processes adding $\mathcal{E}$ to their effects

Thm: Subject Reduction: Well-typed processes preserve space.

If $\Gamma \vdash P : \text{Proc}(k, \mathcal{E}, \chi)$ and $P \xrightarrow{} Q$ then $\Gamma \vdash Q : \text{Proc}(k, \mathcal{E}', \chi)$ for some $\mathcal{E}' \prec \mathcal{E}$.
Future Work

➤ What: Third-Party Resources: Models, Languages and Techniques

➤ Resource-Aware Computation: resource bounds negotiation & enforcement
➤ Resource Usage: calculi & logics for quantitative analysis
➤ Resource Safety: languages for security & trust policies; general resource logics
➤ Resource Trust: history-based: theory and infrastructures


➤ Who: Communities involved:
  ➤ EU FET Global Computing
  ➤ UKCRC Great Challenges: Science for Global Ubiquitous Computing
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Future Work

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➤ **How:** Integrated approach: Behavioural, Execution, Abstract Models.
Future Work

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The intuition:

\[ a \xrightarrow{\mathcal{C}} b \text{ iff } \mathcal{C}[a] \Downarrow b \]

For instance:

\[ a \xrightarrow{\mid a} 0 \quad M \xrightarrow{(\lambda x.-)N} M\{N/x\} \quad KM \xrightarrow{\neg N} M \]

Yep, but not quite:

➤ Too many labels not desirable:

➤ Useless combinatorial explosion: \( \lambda x.xx \xrightarrow{MN} MMN \)

➤ Messes up the bisimulation (too coarse): \( l \xrightarrow{\mathcal{D}} \mathcal{D}[r] \) for all rules \( l \Downarrow r \).
The intuition:

\[ a \xrightarrow{C} b \text{ iff } C[a] \not\Delta b \]

For instance:

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Choose only ‘minimal’ redex-enabling contexts

➤ Case analysis of basic situations: Sewell. Abstract approach: Leifer-Milner
Lawvere theory on $\Sigma$

- the natural numbers for objects
- a morphism $t: m \rightarrow n$, for $t$ a $n$-tuple of $m$-holed terms.
- Composition is substitution of terms into holes.

E.G. for $\Sigma$ the signature for arithmetics:

- term $(-1 \times x) + -2$ is an arrow $2 \rightarrow 1$ (two holes yielding one term)
- $\langle 3, 2 \times y \rangle$ is an arrow $0 \rightarrow 2$ (a pair of terms with no holes).
- Their composition is the term $(3 \times x) + (2 \times y)$, an arrow of type $0 \rightarrow 1$. 
Lawvere theory on $\Sigma$

- the natural numbers for objects
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- Composition is substitution of terms into holes.

A generalisation from term rewriting systems to categories.

- A category $\mathbb{C}$ with distinguished object $0$.
- A set of reaction rules $\mathcal{R} \subseteq \bigcup_{C \in \mathbb{C}} \mathbb{C}(0, C) \times \mathbb{C}(0, C)$.
- A set $\mathbb{D}$ of arrows of $\mathbb{C}$ called the reactive contexts.
  Assume that $d_0 . d_1 \in \mathbb{D}$ implies $d_0$ and $d_1 \in \mathbb{D}$.

The reaction relation is defined as

\[
\begin{align*}
  a \rightarrow b & \quad \text{iff} \quad a = d . l, \ b = d . r, \ d \in \mathbb{D} \ \text{and} \ \langle l, r \rangle \in \mathcal{R}.
\end{align*}
\]
Suppose that $\mathcal{C}$ is a (bi)category and consider a redex square

\[
\begin{array}{c}
\bullet \\
\downarrow^a \\
\bullet \\
\uparrow^l \\
\bullet \\
\downarrow^c \\
\bullet \\
\uparrow^d \\
\bullet
\end{array}
\]
Suppose that $\mathcal{C}$ is a (bi)category and consider a redex square

\[
\begin{array}{ccc}
\bullet & \xrightarrow{c} & \bullet \\
\downarrow{a} & & \uparrow{p} & \downarrow{d} \\
\bullet & \leftarrow{d} & \xleftarrow{l} & \bullet
\end{array}
\]

a relative pushout (RPO) is a tuple $\langle c, d, p \rangle$ which satisfies the universal property that:
Suppose that \( \mathcal{C} \) is a (bi)category and consider a redex square

\[
\begin{array}{ccc}
  c & \downarrow p & d \\
  \downarrow c' & \downarrow m & \downarrow d'' \\
  a & \uparrow p' & l \\
  \downarrow p & \downarrow d' \end{array}
\]

- a relative pushout (RPO) is a tuple \( \langle c, d, p \rangle \) which satisfies the universal property that:
  - for any other such \( \langle c', d', p' \rangle \) there exists a unique mediating morphism \( m \).
The LTS derived from the reactive system has:

- **Nodes:** $a : O \rightarrow N$

- **Transitions:** $a \xrightarrow{f} dr$ iff for $\langle l, r \rangle \in R$ and $d \in D$, $\langle f, d, id \rangle$ is a relative pushout of the square
The LTS derived from the reactive system has:

- **Nodes:** $a : O \rightarrow N$

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**Thm.** If all redex squares like the above have (G)RPOs then the bisimulation on the derived LTS is a congruence.

[Leifer-Milner 00, Sassone-Sobocinski 02]
Applying (G)RPOs

➤ Milner (2001) worked out RPOs for a graphical formalism called bigraphs.

➤ Sassone and Sobocinski (2002) introduced GRPOs to handle calculi with non-trivial structural congruences.

➤ Jensen and Milner (2003) derived (essentially) the usual π labelled bisimulation on asynchronous π using RPOs.

➤ Sassone and Sobocinski (2003) worked out an easy encoding of Milner’s pre-category approach into the G-world.

➤ Jensen and Milner (2004) found (G)RPOs for ambient-calculus and for weak bisimulations.

➤ Sassone and Sobocinski (2004) derived GRPOs for generic graph structures and graph rewrite systems.

So far, the price of the initial 2-categorical investment seems worth paying. . .

Future Work

➤ Extend to more complicated process calculi with complex structural congruences (e.g. replication); Apply to specific graph rewriting systems.
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