Environmental Bisimulations for Program Equivalences

Eijiro Sumii
(Tohoku University)

In collaboration with:
Benjamin C. Pierce, Davide Sangiorgi,
Naoki Kobayashi, and Nobuyuki Sato

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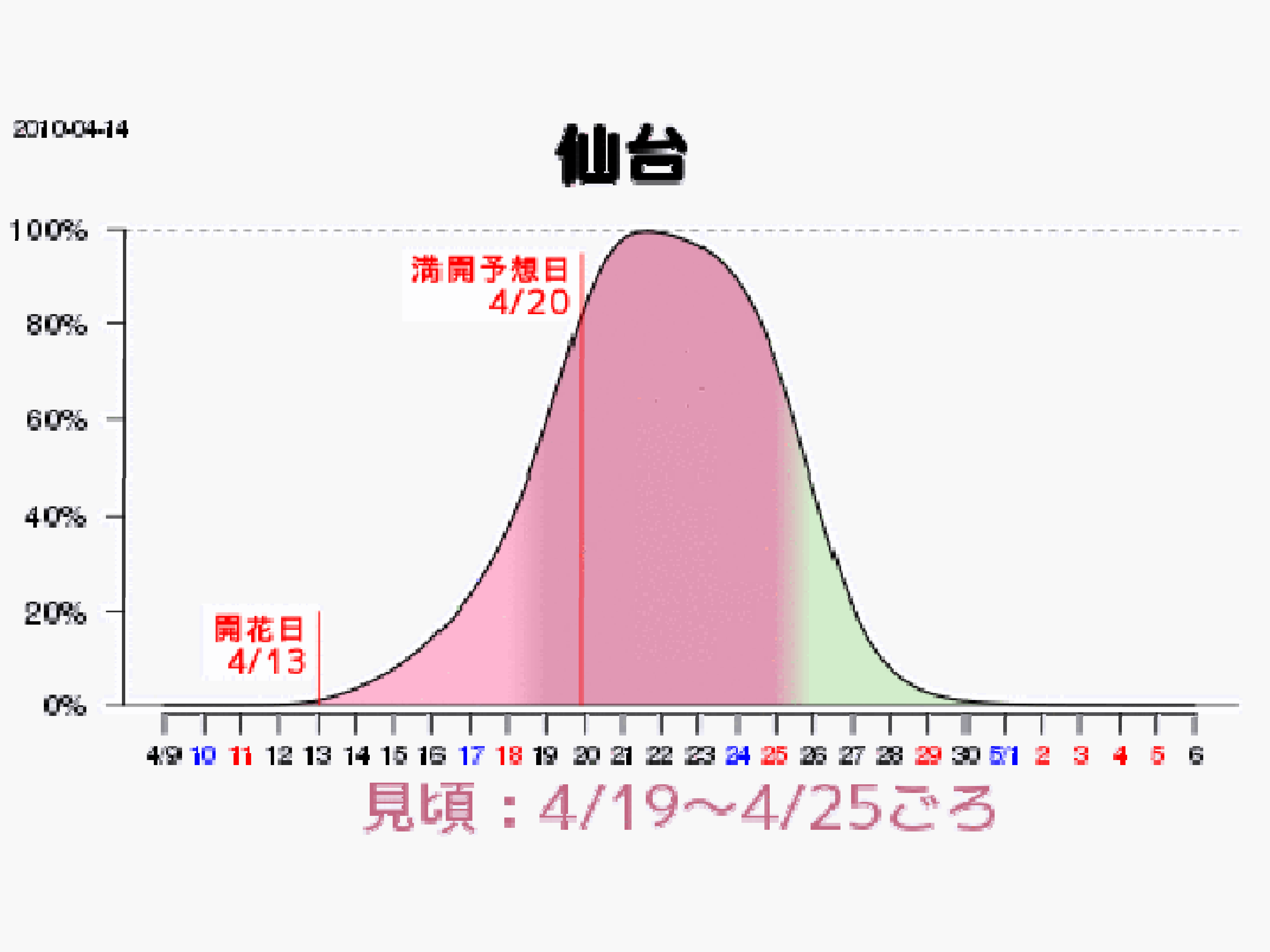
FLOPS 2010
Tenth International Symposium on Functional and Logic Programming
April 19-21, 2010
Sendai, Japan

Shortcuts: **Registration**, **Program**, **Venue**, **Excursion**, **More Excursions**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FLOPS 2010 : Excursion

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Excursion †

Half-day trip to Hiraizumi is planned on the afternoon of the second day (April 20, Tuesday).

Environmental Bisimulations for Program Equivalences

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What are environmental bisimulations?

A theory for proving <u>equivalences</u> of programs in various languages (higher-order, in partciular)

- Devised for λ-calculus with encryption [Sumii-Pierce POPL04]
- Adapted for polymorphic λ-calculus [Sumii-Pierce POPL05], untyped λ-calculus with references [Koutavas-Wand POPL06] [Sangiorgi-Kobayashi-Sumii LICS07] and deallocation [Sumii ESOP09], etc.

This talk

Two instances of environmental bisimulations, for

I. Polymorphic λ-calculus with references [Sumii CSL09], and

II. Higher-order π-calculus (concurrent language with message passing) with encryption [Sato-Sumii APLAS09] (if time allows).

Part I: Environmental Bisimulations for Polymorphic λ-calculus with References

Executive Summary

Sound and <u>complete</u> "proof method"
for contextual equivalence
in a language with

- Higher-order functions,
- First-class references (like ML), <u>and</u>
- Abstract data types

Caveat: the method is not fully automatic!

- The equivalence is (of course) undecidable in general
- Still, it successfully proved all known examples

(Very) General Motivation

1. Equations are important in science
   - $1 + 2 = 3$, $x + y = y + x$, $E = mc^2$, ...
2. Computing is (should be) a science
3. Therefore, equations are important in (so-called) computer science

4. Computing is described by programs
5. Therefore, equivalence of programs is important!

Program Equivalence as Contextual Equivalence

- In general, equations should be preserved under any <u>context</u>
  - E.g., x + y = y + x implies (x + y) + z = (y + x) + z by considering the context [ ] + z
- ⇒ <u>Contextual equivalence</u>: Two programs "give the same result" under any context
  - Termination/divergence suffices for the "result"

Contextual Equivalence: Definition

Two programs P and Q are <u>contextually equivalent</u> if, for any context C,

$$C[P] \text{ terminates} \Leftrightarrow C[Q] \text{ terminates}$$

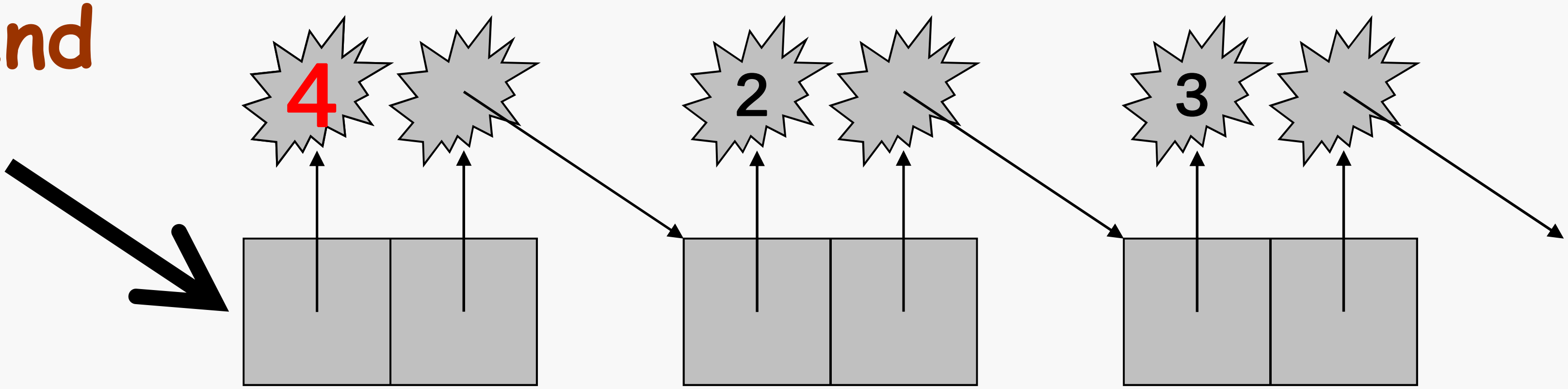
- C[P] (resp. C[Q]) means "filling in" the "hole" [ ] of C with P (resp. Q)

Example: Two Implementations of Mutable Integer Lists

```
(* pseudo-code in
  imaginary ML-like language *)
signature S
  type t (* abstract *)
  val nil : t
  val cons : int → t → t
  val setcar : t → int → unit
  (* car, cdr, setcdr, etc. *)
end
```

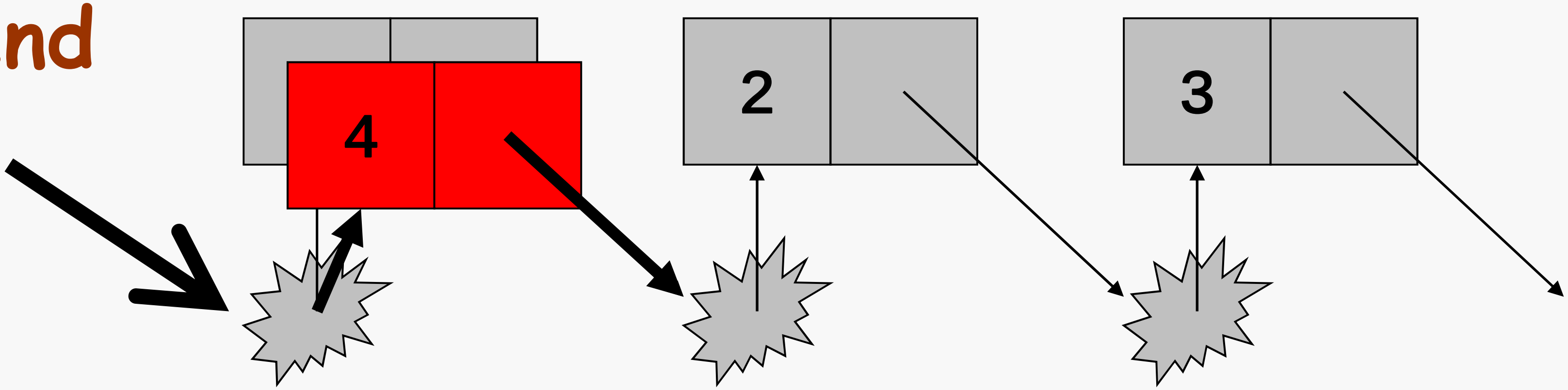
First Implementation

```
structure L
  type t =
    Nil | Cons of (int ref * t ref)
  let nil = Nil
  let cons a d = Cons(ref a, ref d)
  let setcar (Cons p) a = (fst(p) := a)
end
```



Second Implementation

```
structure L'
  type t = Nil | Cons of (int * t) ref
  let nil = Nil
  let cons a d = Cons(ref(a, d))
  let setcar (Cons r) a =
    r := (a, snd(!r))
end
```



The Problem

The implementations L and L' <u>should</u> be contextually equivalent under the interface S

How can we <u>prove</u> it?

- Direct proof is infeasible because of the universal quantification: "for any context *C*"
- Little previous work deals with <u>both</u> abstract data types and references (cf. [Ahmed-Dreyer-Rossberg POPL'09])
  - None is complete (to my knowledge)

Our Approach: Environmental Bisimulations

- Initially devised for λ-calculus with perfect encryption [Sumii-Pierce POPL'04]
- Successfully adapted for
  - Polymorphic λ-calculus [Sumii-Pierce POPL'05]
  - Untyped λ-calculus with references [Koutavas-Wand POPL'06] and deallocation [Sumii ESOP'09]
  - Higher-order π-calculus [Sangiorgi-Kobayashi-Sumii LICS'07]
  - Applied HOπ [Sato-Sumii APLAS'09] etc.

Our Target Language

Polymorphic λ-calculus with existential types and first-class references

M ::= ...standard λ-terms... |
pack (τ, M) as ∃α.σ |
open M as (α, x) in N |
ref M | !M | M := N | ℓ | M == N

locations

equality of locations

τ ::= ...standard polymorphic types...
| ∃α.τ | τ ref

Environmental Relations

An environmental relation X is a set of tuples of the form:

$$(\Delta, R, s \triangleright M, s' \triangleright M', \tau)$$

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  - M and M' (and τ) are omitted when terminated

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- R is the <u>environment</u>: a (typed) relation between values known to the context

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- Program M (resp. M') of type τ is running under store s (resp. s')
  - M and M' (and τ) are omitted when terminated
- R is the environment: a (typed) relation between values known to the context
- Δ maps an abstract type α to (the pair of) their concrete types σ and σ'

Environmental Bisimulations for Our Calculus

An environmental relation X is an <u>environmental bisimulation</u> if it is preserved by

- execution of the programs and
- operations from the context

Formalized by the following conditions...

Environmental Bisimulations: Condition for Reduction

- If $(\Delta, R, s \triangleright M, s' \triangleright M', \tau) \in X$ and $s \triangleright M$ converges to $t \triangleright V$, then $s' \triangleright M'$ also converges to some $t' \triangleright V'$ with $(\Delta, R \cup \{(V, V', \tau)\}, t, t') \in X$

(Symmetric condition omitted)

Strictly speaking, this is a "big-step" version of environmental bisimulations

Environmental Bisimulations: Condition for Opening

- If $(\Delta, R, s, s') \in X$ and $(\text{pack } (\tau, V) \text{ as } \exists\alpha.\sigma,$ $\text{pack } (\tau', V') \text{ as } \exists\alpha.\sigma, \exists\alpha.\sigma) \in R$, then $(\Delta \cup \{(\alpha, \tau, \tau')\}, R \cup \{(V, V', \sigma)\}, s, s') \in X$

Environmental Bisimulations: Condition for Dereference

- If $(\Delta, R, s, s') \in X$ and $(\ell, \ell', \sigma\ \mathrm{ref}) \in R$, then $(\Delta, R \cup \{(s(\ell), s'(\ell'), \sigma)\}, s, s') \in X$

Environmental Bisimulations: Condition for Update

- If $(\Delta, R, s, s') \in X$ and $(\ell, \ell', \sigma \text{ ref}) \in R$, then $(\Delta, R, s\{\ell \mapsto W\}, s'\{\ell' \mapsto W'\}) \in X$ for any W and W' <u>synthesized</u> from R
  - Formally,

$$W = C[V_1, \ldots, V_n]$$
$$W' = C[V'_1, \ldots, V'_n]$$

for some $(V_1, V'_1, \tau_1), \ldots, (V_n, V'_n, \tau_n) \in R$ and some well-typed C

Environmental Bisimulations: Condition for Application

- If $(\Delta, R, s, s') \in X$ and $(\lambda x.M, \lambda x.M', \sigma \to \tau) \in R$, then $(\Delta, R, s \triangleright [W/x]M, s' \triangleright [W'/x]M', \tau) \in X$ for any W and W' synthesized from R

Other Conditions

- Similar conditions for allocation, location equality, projection, etc.
- No condition for values of abstract types

$$\text{If } (\Delta, R, s, s') \in X$$
$$\text{and } (V, V', \alpha) \in R,$$
$$\text{then } \ldots ?$$

Abstract

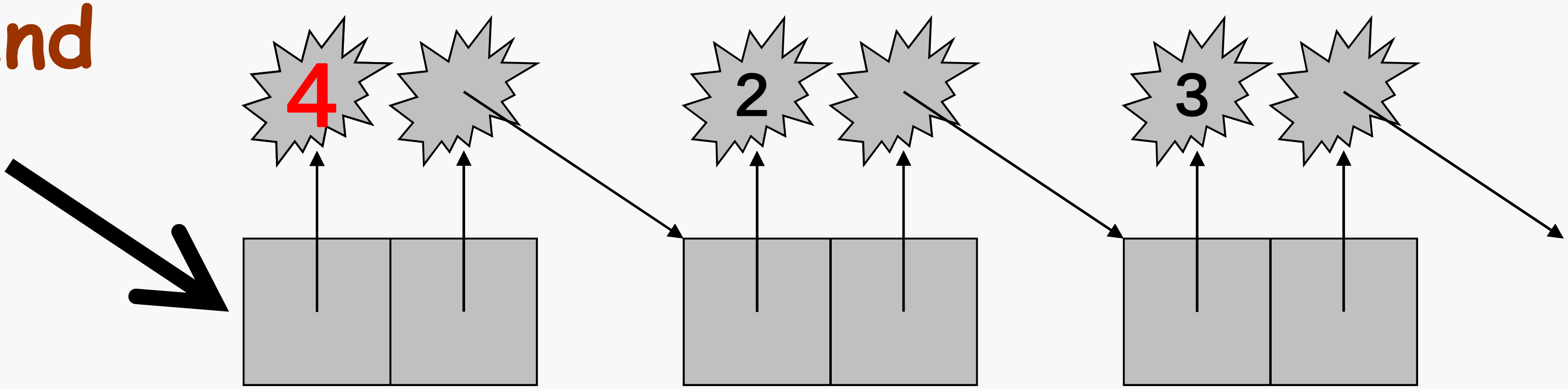
  - Context cannot operate on them

Mutable Integer Lists Interface (Reminder)

```
(* pseudo-code in
  imaginary ML-like language *)
signature S
  type t (* abstract *)
  val nil : t
  val cons : int -> t -> t
  val setcar : t -> int -> unit
  (* setcdr, car, cdr, etc. *)
end
```

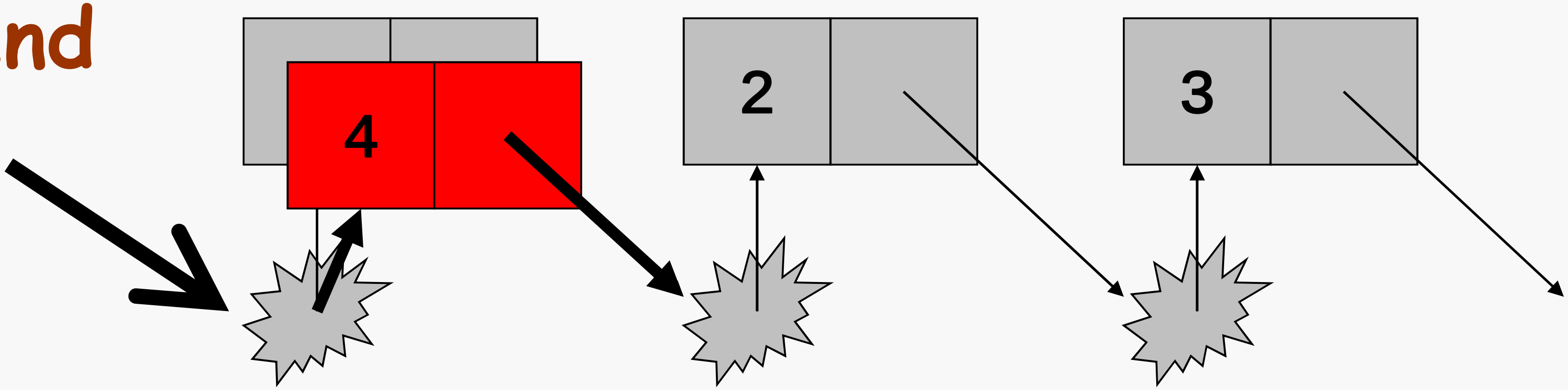
First Implementation (Reminder)

```
structure L
  type t =
    Nil | Cons of (int ref * t ref)
  let nil = Nil
  let cons a d = Cons(ref a, ref d)
  let setcar (Cons p) a = (fst(p) := a)
end
```



Second Implementation (Reminder)

```
structure L'
  type t = Nil | Cons of (int * t) ref
  let nil = Nil
  let cons a d = Cons(ref(a, d))
  let setcar (Cons r) a =
    r := (a, snd(!r))
end
```



Environmental Bisimulaton for The Mutable Integer Lists

$X = \{ (\Delta, R, s, s') \mid$

$\Delta = \{ (S.t, L.t, L'.t) \}$,

$R = \{ (L, L', S)$,

$(L.nil, L'.nil, S.t)$,

$(L.cons, L'.cons, int \rightarrow S.t \rightarrow S.t)$,

$(L.setcar, L'.setcar, S.t \rightarrow int \rightarrow unit)$,

$(L.Cons(\ell_i, m_i), L'.Cons(\ell'_i), S.t)$

$(L.Nil, L'.Nil, S.t) \mid i = 1, 2, 3, \ldots, n \}$,

$s(\ell_i) = fst(s'(\ell'_i))$ and

$(s(m_i), snd(s'(\ell'_i)), S.t) \in R$, for each $i \}$

More complicated example (1/3)

(* Adapted from [Ahmed-Dreyer-Rossberg POPL'09], credited to Thamsborg *)

$$\texttt{pack (int ref, (ref 1, } \lambda x.V_x\texttt{)) as } \sigma$$

vs. $\texttt{pack (int ref, (ref 1, } \lambda x.V'\texttt{)) as } \sigma$

where

$V_x = \lambda f.\ (x{:=}0;\ f();\ x{:=}1;\ f();\ !x)$

$V' = \lambda f.\ (f();\ f();\ 1)$

$\sigma = \exists\alpha.\ \alpha \times (\alpha\to(1\to1)\to\mathrm{int})$

- f is supplied by the context
- What are the reducts of V f and V' f?

More complicated example (2/3)

$X = X_0 \cup X_1$

$X_0 = \{ (\Delta, R, t\{\ell \mapsto 0\} \triangleright N, t' \triangleright N', \text{int}) \mid$
N and N' are made of contexts in T_0, with holes filled with elements of R $\}$

$X_1 = \{ (\Delta, R, t\{\ell \mapsto 1\} \triangleright N, t' \triangleright N', \text{int}) \mid$
N and N' are made of contexts in T_1, with holes filled with elements of R $\}$

More complicated example (3/3)

- $(C;\ \ell{:=}1;\ D;\ !\ell)\ T_0\ (C;\ D;\ 1)$
- $(D;\ !\ell)\ T_1\ (D;\ 1)$
- If $E[zW]\ T_0\ E'[zW]$, then $E[C;\ \ell{:=}1;\ D;\ !\ell]\ T_0\ E'[C;\ D;\ 1]$ (for any evaluation contexts E and E')
- If $E[zW]\ T_0\ E'[zW]$, then $E[D;\ !\ell]\ T_1\ E'[D;\ 1]$
- If $E[zW]\ T_1\ E'[zW]$, then $E[C;\ \ell{:=}1;\ D;\ !\ell]\ T_0\ E'[C;\ D;\ 1]$
- If $E[zW]\ T_1\ E'[zW]$, then $E[D;\ !\ell]\ T_1\ E'[D;\ 1]$

Main Theorem: Soundness and Completeness

The largest environmental bisimulation $\sim$ coincides with (a generalized form of) contextual equivalence $\equiv$

Proof

- Soundness: Prove $\sim$ is preserved under any context (by induction on the context)
- Completeness: Prove $\equiv$ is an environmental bisimulation (by checking its conditions)

The Caveat

Our "proof method" is <u>not</u> automatic

- Contextual equivalence in our language is undecidable
- Therefore, so is environmental bisimilarity

...but it proved <u>all</u> known examples!

Up-To Techniques

Variants of environmental bisimulations with weaker (yet sound) conditions

- Up-to reduction (and renaming)
- Up-to context (and environment)
- Up-to allocation

Details in my CSL'09 paper

Related Work

- Environmental bisimulations for other languages (already mentioned)
- Bisimulations for other languages
- Logical relations
- Game semantics

None has dealt with <u>both</u> abstract data types and references

  - Except [Ahmed-Dreyer-Rossberg POPL'09]

Conclusion of Part I

Summary:

Sound and complete "proof method" for contextual equivalence in polymorphic λ-calculus with existential types and references

Current and future work:

- Parametricity properties ("free theorems")
- Semantic model

Part II: Enviromental bisimulations for higher-order π-calculus with encryption

Nobuyuki Sato
Eijiro Sumii
(Tohoku University)

Agenda of Part II

- Informal overview of the work
- A little technical details
- A little more technical details
- Conclusion

Main Result

A bisimulation proof technique for <u>higher-order</u> process calculus with <u>cryptographic</u> primitives

- Can be used for proving security properties of concurrent systems that <u>send/receive programs</u> using <u>encryption/decryption</u>

Motivation

Higher-order cryptographic systems are now ubiquitous

- Web-based e-mail clients (e.g. Gmail)
- Software update systems (e.g. Windows Update)

Higher-order: transmitting programs themselves

$\Rightarrow$ **Security is even more important than in first-order systems**

- **Cryptography is essential**

Problem

The theory of higher-order cryptographic computation is underdeveloped

- Little work for the <u>combination</u> of higher-order processes and cryptographic primitives
  - Cf. Higher-order pi-calculus (no cryptography), spi-calculus (first-order), ...

A Challenge of Higher-Order Cryptographic Processes

- Consider the process $P = \overline{c}\langle Q \rangle$ where $Q = \overline{c}\langle encrypt(m,k) \rangle$
  - $\overline{c}\langle\ \rangle$ denotes output to the network c
  - Assume c is public and k is secret
- Does P leak m?
  1. Yes, because the attacker can receive Q from c and <u>extract</u> m
  2. No, if m is encrypted <u>before</u> Q is sent to c

Observations

- <u>Computation</u> (e.g. encryption) and <u>computed values</u> (e.g. ciphertext) must be distinguished
- The attacker should be able to <u>decompose</u> transmitted processes (but <u>not</u> computed values)

(Recall the previous example $P = \overline{c}\langle Q\rangle$ where $Q = \overline{c}\langle encrypt(m,k)\rangle$)

Solution

- Syntactically distinguish computation (e.g. encrypt(m,k)) and computed values (e.g. ^encrypt(m,k))
- Extend the calculus with a primitive to decompose transmitted processes:

  match P as x in Q

  (bind x to the decomposed abstract syntax tree of P and execute Q)
  - Computed values can not be decomposed

Examples

$\bar{c}\langle\ \bar{c}\langle encrypt(m,k)\rangle\ \rangle\ |$
$c(X).match\ X\ as\ y\ in\ R$

$\rightarrow\ match\ \bar{c}\langle encrypt(m,k)\rangle\ as\ y\ in\ R$

$\rightarrow\ [Out(Nam\ c, Enc(Nam\ m, Nam\ k))/y]R$

$\bar{c}\langle\ \bar{c}\langle \hat{}encrypt(m,k)\rangle\ \rangle\ |$
$c(X).match\ X\ as\ y\ in\ R$

$\rightarrow\ match\ \bar{c}\langle \hat{}encrypt(m,k)\rangle\ as\ y\ in\ R$

$\rightarrow\ [Out(Nam\ c, Val\ \hat{}encrypt(m,k))/y]R$

Next Challenge

How do we reason about higher-order cryptographic processes?

- Traditional techniques (bisimulations, in particular) do not apply
  - Most of them are first-order
  - Normal bisimulations [Sangiorgi 92] are unsound for process decomposition
    - Because they only transmit "triggers" (i.e. pointers to processes)

Solution

Adopt environmental bisimulations

- Devised for λ-calculus with encryption [Sumii-Pierce 04]
- Adapted for various languages [Sumii-Pierce, Koutavas-Wand, ...]
  - Including higher-order pi-calculus [Sangiorgi-Kobayashi-Sumii 07]

Idea of Environmental Bisimulations

- Traditional (i.e. non-environmental) bisimulation $P \sim P'$ means:

  P and P' behave the same
  under any observer process

- Environmental bisimulation $P \sim_E P'$ means:

  P and P' behave the same
  under any observer process
  <u>that uses any elements (V,V') of E</u>

  - E is a binary relation on values that represents the observer's <u>knowledge</u> (called an <u>environment</u>)

Agenda of Part II

- Informal overview of the work
- A little technical details
- A little more technical details
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Our Environmental Bisimulations (1/3)

Binary relation X on processes,
indexed by environments E,
is an environmental simulation
if $P \; X_E \; P'$ implies:

1. If P reduces to Q, then
   P' reduces to some Q'
   such that $Q \; X_E \; Q'$
2. If P outputs V and becomes Q, then
   P' outputs some V' and becomes some Q'
   such that $Q \; X_{E \cup \{(V, V')\}} \; Q'$

(cont.)

Our Environmental Bisimulations (2/3)

X is an environmental simulation
if $P \; X_E \; P'$ implies:

3. For any V and V' composed from E,
if P inputs V and becomes Q, then
P' inputs V' and becomes some Q'
such that $Q \; X_E \; Q'$
   - "Composed from" means
   for some context C and $(V_1,V_1'),\ldots,(V_n,V_n') \in E$,
   $V = C[V_1,\ldots,V_n]$ and $V' = C[V_1',\ldots,V_n']$
4. $P|Q \; X_E \; P'|Q'$ for any $(Q,Q') \in E$

(cont.)

Our Environmental Bisimulations (3/3)

X is an environmental simulation
    if $P \; X_E \; P'$ implies:

5. $P \; X_{E \cup \{(V,V')\}} \; P'$ if V and V' can be computed from E (by decomposition or first-order computation)

   E.g. suppose:

   $E = \{(k,k'),\ (\hat{}encrypt(V,k),\ \hat{}encrypt(V',k'))\}$

   Then (V,V') can be computed from E by the first-order context:

   $$C = decrypt([]_2,[]_1)$$

6. E preserves equality

Main Theorem

The largest environmental bisimulation (with appropriate E) coincides with reduction-closed barbed equivalence

- It exists because the generating function is monotone [Tarski 55]

- The $\subseteq$ direction is proved via a context closure property of environmental bisimulations
- The $\supseteq$ direction is proved by coinduction

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Our Calculus: Syntax of Terms

M ::=	terms
V	values
x	variables
$M(M_1,...,M_n)$	computations
V ::=	values
a	names
f	function symbols
$\hat{}f(V_1,...,V_n)$	computed values
$`P$	transmitted processes
$`M$	transmitted terms

Syntax of Processes

P ::=	processes
0	inaction
$\underline{M}(x).P$	input
$\overline{M}\langle N\rangle.P$	output
$P\|Q$	parallel composition
$!P$	replication
$\nu x.P$	restriction
run(M)	execution
if M=N then P else Q	conditional
match M as x in P	decomposition

Labeled Transition Semantics

- Parameterized by semantics of terms
  - Defined by (strongly normalizing and confluent) term rewriting system
- Key rules:

  $\overline{c}\langle M\rangle.P \xrightarrow{\overline{c}\langle V\rangle} P$

  if M rewrites to V ("call-by-value")

  $\mathrm{run}(`P) \xrightarrow{\tau} P$ (important!)

  $\mathrm{match}\ `P\ \mathrm{as}\ x\ \mathrm{in}\ Q \xrightarrow{\tau} [M/x]Q$

  where M is decomposed AST of P

Examples (Revisited)

$\overline{c}\langle$ ` $\overline{c}\langle$encrypt(m,k)$\rangle$ $\rangle$ |
c(X).match X as y in R

$\rightarrow$ match ` $\overline{c}\langle$encrypt(m,k)$\rangle$ as y in R

$\rightarrow$ [Out(Nam c,Enc(Nam m,Nam k))/y]R

$\overline{c}\langle$ ` $\overline{c}\langle$^encrypt(m,k)$\rangle$ $\rangle$ |
c(X).match X as y in R

$\rightarrow$ match ` $\overline{c}\langle$^encrypt(m,k)$\rangle$ as y in R

$\rightarrow$ [Out(Nam c,Val ^encrypt(m,k))/y]R

Bisimulation Example

$P = \bar{c}\langle$ ` $\bar{c}\langle$^encrypt(3,k)$\rangle$ $\rangle$ and
$P' = \bar{c}\langle$ ` $\bar{c}\langle$^encrypt(7,k)$\rangle$ $\rangle$
are bisimilar

Proof outline: Take X as follows (so $P\ X_E\ P'$)

X = { (E, C[^encrypt(3,k)], C[^encrypt(7,k)]) |
k not free in C }

E = { (D[^encrypt(3,k)], D[^encrypt(7,k)]) |
k not free in D }

and prove it to be an env. bisim.
(by case analysis on C and D)

Non-Bisimulation Example

$P = \overline{c}\langle\ \text{`}\ \overline{c}\langle \mathrm{encrypt}(3,k)\rangle\ \rangle$ and
$P' = \overline{c}\langle\ \text{`}\ \overline{c}\langle \mathrm{encrypt}(7,k)\rangle\ \rangle$ are
not bisimilar

Proof outline:

If $P\ X_E\ P'$ for some env. bisim. X and E, then by output we get $0\ X_{E'}\ 0$ with $(\text{`}\ \overline{c}\langle \mathrm{encrypt}(3,k)\rangle, \text{`}\ \overline{c}\langle \mathrm{encrypt}(7,k)\rangle) \in E'$.

Since $(3,7)$ can be computed from E' by decomposition, we get $0\ X_{E''}\ 0$ with $(3,7) \in E''$, which violates integer equality.

Simplification by Up-To Context Technique

Problem:

Many environmental bisimulations include <u>all</u> processes/values of the forms $C[V_1, \ldots, V_n]$ and $C[V_1', \ldots, V_n']$ for some $(V_1, V_1'), \ldots, (V_n, V_n')$

Solution:

A "smaller" version of environmental bisimulations, where processes/values of the forms $C[V_1, \ldots, V_n]$ and $C[V_1', \ldots, V_n']$ can be omitted if $(V_1, V_1'), \ldots, (V_n, V_n')$ are included

Example of Environmental Bisimulation Up-To Context

Consider again:

$$P = \overline{c}\langle \ \grave{}\ \ \overline{c}\langle \hat{}\,\mathrm{encrypt}(3,k)\rangle \ \ \rangle$$

$$P' = \overline{c}\langle \ \grave{}\ \ \overline{c}\langle \hat{}\,\mathrm{encrypt}(7,k)\rangle \ \ \rangle$$

Then

$$Y = \{ \ (E,\ P,\ P') \ \}$$

is an environmental bisimulation up-to context, where:

$$E = \{(c,c),\ (\hat{}\,\mathrm{encrypt}(3,k),\ \hat{}\,\mathrm{encrypt}(7,k))\}$$

In our APLAS'09 paper

- Formal definitions of the calculus and our environmental bisimulations (and the up-to context technique)
- Soundness and completeness proofs (i.e. proof of coincidence with reduction-closed barbed equivalence)
- More sophisticated examples
  - Software distribution system
  - Online e-mail client

Agenda of Part II

- Informal overview of the work
- A little technical details
- A little more technical details
- Conclusion

Conclusions of Part II

- Higher-order cryptographic processes are non-trivial
  - Previous theories do not apply (higher-order pi-calculus, spi-calculus, …)
- Environmental bisimulations "scale" well to such sophisticated calculi
  - Including the present one

- Future work: automation, extension, simplification, …

Sources of Discussion/Controversy

- Relationship to denotational semantics (especially, games)
  - Denotational semantics is "syntax-free"
  - Env. bisim. is "semantics-free"
    - <u>Very</u> robust, but (arguably) ugly, lacking good mathematical structure

    $\Rightarrow$ More structured <u>and</u> robust framework?
- (Semi-)automation/mechanization
  - What does "completeness" mean when the problem is undecidable?