## CS 4110

Programming Languages \& Logics

Lecture 37
Concurrency and Victory Lap

5 December 2014

Announcements

- Foster Office Hours 11am-12pm today


## $\pi$-calculus Syntax

$$
x, y, z \in \mathcal{N}
$$

Names

## $\pi$-calculus Syntax

$$
\begin{array}{rll}
x, y, z & \in \mathcal{N} & \text { Names } \\
\pi & ::=\tau|\bar{x}\langle y\rangle| x(y) \mid[x=y] \pi & \\
\text { Prefixes }
\end{array}
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M, N \quad::=\mathbf{0}|\pi . P| M+M & & \text { Summations } \\
P, Q, R & ::=M\left|P_{1}\right| P_{2}|\nu x . P|!P & \\
\text { Processes }
\end{array}
$$

Reaction

$$
\overline{\tau . P+M \rightarrow P} \text { R-Tau }
$$

Reaction

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$$
\overline{\left(\bar{x}\langle y\rangle \cdot P_{1}+M_{1}\right)\left|\left(x(z) \cdot P_{2}+M_{2}\right) \rightarrow P_{1}\right| P_{2}\{y / z\}} \text { R-React }
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$$
\begin{gathered}
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\frac{P_{1} \rightarrow P_{1}^{\prime}}{P_{1}\left|P_{2} \rightarrow P_{1}^{\prime}\right| P_{2}} \text { R-Par }
\end{gathered}
$$

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\frac{P \rightarrow P^{\prime}}{\nu x . P \rightarrow \nu x . P^{\prime}} \text { R-Res }
\end{gathered}
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\end{gathered}
$$

$$
\frac{P \equiv P^{\prime} \quad P^{\prime} \rightarrow Q^{\prime} \quad Q^{\prime} \equiv Q}{P \rightarrow Q} \text { R-Struct }
$$

## Example: Encoding Booleans

Idea: encode a boolean value $b$ as a process that receives two channels $t$ and $f$ on the channel / where the boolean is "located" and then signals on the corresponding channel

$$
\operatorname{True}(I) \triangleq I(t, f) \cdot \bar{t}
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\operatorname{True}(I) & \triangleq I(t, f) \cdot \bar{t} \\
\operatorname{False}(I) & \triangleq I(t, f) \cdot \bar{f} \\
\operatorname{Cond}(P, Q)(/) & \triangleq \nu t, f \cdot(\bar{l}\langle t, f\rangle \cdot(t . P+f . Q))
\end{aligned}
$$

## Example: Encoding Naturals

Idea: encode a natural number value $n$ as a process that receives two channels $s$ and $z$ on the channel $c$ where the number is "located" and then signals on $s n$ times terminated by $z$

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$$
\begin{aligned}
\operatorname{Zero}(c) & \triangleq c(s, z) \cdot \bar{z} \\
\operatorname{succ}(n)(c) & \triangleq c(s, z) \cdot \bar{n}\langle s, z\rangle \cdot \bar{s}
\end{aligned}
$$

## Encoding Lists

Idea: encode a list I as a process that receives two channels $c$ and $n$ on the channel / where the list is "located" and then signals on $c$ with each value of the list, terminated by $n$

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$$
\begin{aligned}
\operatorname{Nil}(/) & \triangleq I(n, c) \cdot \bar{n} \\
\operatorname{Cons}(H, T)(/) & \triangleq \nu h, t \cdot(/(n, c) \cdot \bar{c}\langle h, t\rangle|H\langle h\rangle| T\langle t\rangle)
\end{aligned}
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\operatorname{Nil}(I) & \triangleq I(n, c) \cdot \bar{n} \\
\operatorname{Cons}(H, T)(I) & \triangleq \nu h, t \cdot(I(n, c) \cdot \bar{c}\langle h, t\rangle|H\langle h\rangle| T\langle t\rangle) \\
\operatorname{lsNil}(L)(r) & \triangleq \nu \mid, n, c \cdot(L\langle I\rangle \mid \bar{T}\langle n, c\rangle \cdot(n . \operatorname{True}\langle r\rangle+c(h, t) \cdot F a l s e\langle r\rangle))
\end{aligned}
$$

## Pattern Matching

We can encode pattern matching on lists

$$
\begin{aligned}
& \text { case I of } \\
& \quad \text { Nil? } \Rightarrow P \\
& \quad \text { Cons? }(h, t) \Rightarrow Q
\end{aligned}
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Idea: send fresh channels $n$ and $c$ to / and test which it signals on:

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Idea: send fresh channels $n$ and c to / and test which it signals on:

$$
\nu n, c . \bar{I}\langle n, c\rangle n \cdot P+c(h, t) \cdot Q
$$

## Destructive Operations

$$
\begin{aligned}
\text { Copy }\langle\langle, m\rangle \triangleq & \text { case I of } \\
& \text { Nil? } \Rightarrow \text { Nil }\langle m\rangle \\
& \text { Cons? }(h, t) \Rightarrow \nu t^{\prime} .\left(m(n, c) \cdot \bar{c}\left\langle h, t^{\prime}\right\rangle \mid \operatorname{Copy}\left\langle t, t^{\prime}\right\rangle\right)
\end{aligned}
$$

## Destructive Operations

$$
\begin{aligned}
\text { Copy }\langle l, m\rangle \triangleq & \text { case I of } \\
& \text { Nil? } \Rightarrow \text { Nil }\langle m\rangle \\
& \text { Cons? }(h, t) \Rightarrow \nu t^{\prime} .\left(m(n, c) . \bar{c}\left\langle h, t^{\prime}\right\rangle \mid \operatorname{Copy}\left\langle t, t^{\prime}\right\rangle\right)
\end{aligned}
$$

Join $\langle k, I, m\rangle \triangleq$ case $k$ of
Nil? $\Rightarrow$ Copy $\langle 1, m\rangle$
Cons? $(h, t) \Rightarrow \nu t^{\prime} .\left(m(n, c) . \bar{c}\left\langle h, t^{\prime}\right\rangle \mid J \operatorname{Join}\left\langle t, I, t^{\prime}\right\rangle\right)$

## Encoding Persistent Datatypes

We can put a ! in front of processes to turn them into servers create arbitrary numbers of the original process

$$
\begin{aligned}
\operatorname{Nil}(I) & \triangleq!((n, c) \cdot \bar{n} \\
\operatorname{Cons}(H, T)(I) & \triangleq \nu h, t \cdot(!!(n, c) \cdot \bar{c}\langle h, t\rangle|H\langle h\rangle| T\langle t\rangle)
\end{aligned}
$$

This causes the list to still exist after sending or receiving a message

## Encoding $\lambda$-calculus

$$
\begin{aligned}
\llbracket x \rrbracket(u) & \triangleq \bar{x}(u\rangle \\
\llbracket \lambda x \cdot e \rrbracket(u) & \triangleq u(x, y) \cdot \llbracket \llbracket \rrbracket(y) \\
\llbracket e_{1} e_{2} \rrbracket(u) & \triangleq \nu y \cdot\left(\llbracket e_{e} \rrbracket(y) \mid \nu x \cdot\left(\bar{y}(x, u\rangle \mid!x(w) \cdot \llbracket e_{2} \rrbracket(w)\right)\right)
\end{aligned}
$$

## Bisimulation

When are two processes equal?
Perhaps the most important contributions of research on $\pi$ calculus has been the development of the notion of bisimulation


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When are two processes equal?
Perhaps the most important contributions of research on $\pi$ calculus has been the development of the notion of bisimulation


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Gates G01

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| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Date | Topic | Notes | Reading | Assignments | 12 October | More types | PDF | HW7 out |
| 22 August | Introduction | PDF | Winskel 1 |  | 15 October | Record types | PDF |  |
| 24 August | Small-step semantics | PDF | Winskel 2 | HW1 out | 17 October | Subtyping | PDF |  |
| 27 August | Inductive definitions and proofs | PDF |  |  | 19 October | Polymorphism | PDF | HWB out |
| 29 August | Large-step semantics | PDF |  |  | 25 October | More polymorphism | PDF |  |
| 31 August | IMP | PDF |  | HW2 out | 27 October | Type inference | PDF |  |
| 3 September | No class (Labor Day) |  |  |  | 29 October | Propositions-as-types | PDF | HW9 out |
| 5 September | IMP properties | PDF |  |  | 1 November | Existential types | PDF |  |
| 7 September | Denotational semantics | PDF |  | HW3 out | 3 November | Objects | PDF |  |
| 10 September | Denotational semantics | PDF |  |  | 5 November | Featherweight Java | PDF | HW10 out |
| 12 September | Axiomatic semantics | PDF |  |  | 8 November | Featherweight Java types | PDF |  |
| 14 September | Hoare logic | PDF |  | HW4 out | 10 November | Review | PDF |  |
| 17 September | $\lambda$-calculus | PDF |  |  | 12 November | Prelliminary Exam Ill |  |  |
| 19 September | More $\lambda$-calculus | PDF |  |  | 15 November | Abstract interpretation | PDF |  |
| 21 September | $\lambda$-calculus encodings | PDF |  | HWS out | 17 November | Concurrency | PDF |  |
| 24 September | Recursion | PDF |  |  | 19 November | More concurrency | PDF | HW11 out |
| 26 September | Definitional translation | PDF |  |  | 22 November | Language-based security | PDF |  |
| 28 September | Review | PDF |  |  | 24 November | Coq | PDF |  |
| 1 October | Preliminary Exam I |  |  |  | 26 November | Noclass (Thanksgiving) |  |  |
| 3 October | Continuations | PDF |  |  | 29 November | More Coq | PDF |  |
| 5 October | More continuations | PDF |  | HW6 out | 1 December | Current trends in PL research | PDF |  |
| 8 October | No class (Fall Break) |  |  |  | 3 December | Review | PDF |  |
| 10 October | Types | PDF |  |  | 13 December | Final Exam |  |  |

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| 12 October | More types | PDF | HW7 out |
| :---: | :---: | :---: | :---: |
| 15 October | Record types | PDF |  |
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| 19 October | Polymorphism | PDF | HWB out |
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| 3 November | Objects | PDF |  |
| 5 November | Featherweight Java | PDF | HW10 out |
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| 19 November | More concurrency | PDF | HWIt out |
| 22 November | Language-based security | PDF |  |
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| Date | Tople | Note | Asignments |
| :---: | :---: | :---: | :---: |
| 22Augus: | Mathematical Preliminaries \& |  |  |
| $\left\lvert\, \begin{aligned} & 24 \text { August } \\ & 27 \text { August } \end{aligned}\right.$ | Operational Semantics |  | HWh out |
| 29August | Lamestepsamantia | PDE |  |
| 31 August |  | PDF | HW2 out |
| 3 Septamber | Noclast (Labo Disy) |  |  |
| Denotational \& Axiomatic Semantics |  |  |  |
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| 125 eptember | frioratic semanitics | POF |  |
| 145eptember | Hoare logic | POF | HWY out |
| 17 September | $\lambda$-calculus | PDF |  |
| 19 September | More $\lambda$-calculus | PDF |  |
| 21 September | $\lambda$-calculus encodings | PDF | HWS out |
| 24 September | Recursion | PDF |  |
| 26 September | Definitional translation | PDF |  |
| 285 eptember | Review | PDF |  |
| 1 October | Preliminary Exam 1 |  |  |
| 3 October | Continuations | PDF |  |
| 5 October | More continuationis | PDF | HW6 out |
| 8 October | Noclass (Fall Break) |  |  |
| 10 October | Types | PDF |  |


| 12 October | More types | PDF | HW7 out |
| :---: | :---: | :---: | :---: |
| 15 October | Record types | PDF |  |
| 17 October | Subtyping | PDF |  |
| 19 October | Polymorphism | PDF | HWB out |
| 25 October | More polymorphism | PDF |  |
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| 29 October | Propositions-as-types | PDF | HW9 out |
| 1 November | Existential types | PDF |  |
| 3 November | Objects | PDF |  |
| 5 November | Featherweight Java | PDF | HW10 out |
| 8 November | Featherweight Java types | PDF |  |
| 10 November | Review | PDF |  |
| 12 November | Preliminary Exam ll |  |  |
| 15 November | Abstract interpretation | PDF |  |
| 17 November | Concurrency | PDF |  |
| 19 November | More concurrency | PDF | HW11 out |
| 22 November | Language-based security | PDF |  |
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| 22Augus: | Mathematical Preliminaries \& |  |  |
| 24 August | Operational Semantics |  | HWI out |
| 27 August |  |  |  |
| 29August | Lurgeatepsemantia | PDE |  |
| 31 August | MP | PDF | HW2 out |
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| Denotational \& Axiomatic Semantics |  |  |  |
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| 125 eptember | Axioratic semanitics | POF |  |
| 145eptember | Hoare logic | POF | HWH out |
| 175eptamber | X-glculus | PDF |  |
| 195 eptember | Mared-alculus | PDF |  |
| 21 September | $\lambda \text {-calculus }$ |  | HWS out |
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| 1 October | Preliminary Exam I |  |  |
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| 10 October | Types | PDF |  |


| 12 October | More types | PDF | HW7 out |
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| 15 October | Record types | PDF |  |
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| 29 October | Propositions-as-types | PDF | HW9 out |
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| 175 eptember | X-alculus | PDF |  |
| 195 eptember | Mared-alculus | PDF |  |
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| 5420 unt | Operational Semantics |  | HW out |
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| 5 November | Featherweight java | PDF | HW10 out |
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| Denotational \& Axiomatic Semantics |
| $\lambda$-calculus |
| Preliminary Exam I |
| Fall Break |


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| 12 November | Preliminary Exam Il |  |  |
| 15 November | Abstract interpretation | PDF |  |
| 17 November | Concurrency | PDF |  |
| 19 November | More concurrency | PDF | HW11 out |
| 22 November | Language-based security | PDF |  |
| 24 November | Coq | PDF |  |
| 26 November | Noclass (Thanksgiving) |  |  |
| 29 November | More Coq | PDF |  |
| 1 December | Current trends in PL research | PDF |  |
| 3 December | Review | PDF |  |
| 13 December | Final Exam |  |  |

## CS 4110 (Fall 2014)

Programming Languages and Logics
MWF 905-9.5s
Gates G01

## Home Syllabus Schedule Resources

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| Operational Semantics |
| Denotational \& Axiomatic Semantics |
| $\lambda$-calculus |
| Preliminary Exam I |
| Fall Break |


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Programming Languages and Logics

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| Advanced Topics |
| Final Exam |

## CS 4110 (Fall 2014)

Programming Languages and Logics
MWF 9005-9:5s
Gates G01
Cornell University
Department of
Computer Science


## Final Topics

- Mathematical Preliminaries (inductive definitions)


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Expect to solve probems just like the ones we've seen throughout the course...

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Expect to solve probems just like the ones we've seen throughout the course...
...and to apply the skills you've acquired to new problems too!

## Final Logistics

- Date: Friday, December 12th
- Time: 9-11:30am
- Where: Gates G01
- Practice: Available today
- Review: Next week?


## Going further

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- CS 6110 - Advanced Programming Languages


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- CS 6110 - Advanced Programming Languages
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Thank you, and stay in touch!

