CS 4110

Programming Languages & Logics

Lecture 37
Concurrency and Victory Lap

5 December 2014

Announcements

- Foster Office Hours 11am-12pm today

π-calculus Syntax

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π-calculus Syntax

$$x, y, z \quad \in \quad \mathcal{N} \qquad\qquad \textit{Names}$$

π-calculus Syntax

$$
\begin{array}{rcll}
x, y, z & \in & \mathcal{N} & \textit{Names} \\
\pi & ::= & \tau \mid \bar{x}\langle y\rangle \mid x(y) \mid [x = y]\,\pi & \textit{Prefixes}
\end{array}
$$

π-calculus Syntax

x, y, z	$\in$	$\mathcal{N}$	*Names*
π	$::=$	$\tau \mid \bar{x}\langle y \rangle \mid x(y) \mid [x = y]\,\pi$	*Prefixes*
M, N	$::=$	$\mathbf{0} \mid \pi.P \mid M + M$	*Summations*

π-calculus Syntax

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\begin{array}{rcll}
x, y, z & \in & \mathcal{N} & \textit{Names} \\
\pi & ::= & \tau \mid \bar{x}\langle y\rangle \mid x(y) \mid [x = y]\,\pi & \textit{Prefixes} \\
M, N & ::= & \mathbf{0} \mid \pi.P \mid M + M & \textit{Summations} \\
P, Q, R & ::= & M \mid P_1 \mid P_2 \mid \nu x.\ P \mid !P & \textit{Processes}
\end{array}
$$

Reaction

$$\frac{}{\tau.P + M \to P}\ \text{R-Tau}$$

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$$\frac{}{(\overline{x}\langle y\rangle.P_1 + M_1) \mid (x(z).P_2 + M_2) \to P_1 \mid P_2\{y/z\}} \text{ R-React}$$

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$$\frac{P \to P'}{\nu x.\ P \to \nu x.\ P'} \text{ R-Res}$$

$$\frac{P \equiv P' \qquad P' \to Q' \qquad Q' \equiv Q}{P \to Q} \text{ R-Struct}$$

Example: Encoding Booleans

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

$$True(l) \triangleq l(t, f).\overline{t}$$

Example: Encoding Booleans

Idea: encode a boolean value *b* as a process that receives two channels *t* and *f* on the channel *l* where the boolean is “located” and then signals on the corresponding channel

$$\begin{aligned} True(l) &\triangleq l(t, f).\overline{t} \\ False(l) &\triangleq l(t, f).\overline{f} \end{aligned}$$

Example: Encoding Booleans

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

$$
\begin{aligned}
True(l) &\triangleq l(t, f).\overline{t} \\
False(l) &\triangleq l(t, f).\overline{f} \\
Cond(P, Q)(l) &\triangleq \nu t, f.\ (\overline{l}\langle t, f\rangle.(t.P + f.Q))
\end{aligned}
$$

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*

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

$$Zero(c) \triangleq c(s, z).\bar{z}$$

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*

$$
\begin{aligned}
\mathit{Zero}(c) &\triangleq c(s,z).\overline{z} \\
\mathit{Succ}(n)(c) &\triangleq c(s,z).\overline{n}\langle s,z\rangle.\,\overline{s}
\end{aligned}
$$

Encoding Lists

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

Encoding Lists

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

$$Nil(l) \triangleq l(n, c).\bar{n}$$

Encoding Lists

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

$$
\begin{aligned}
Nil(l) &\triangleq l(n, c).\bar{n} \\
Cons(H, T)(l) &\triangleq \nu h, t.\ (l(n, c).\bar{c}\langle h, t\rangle \mid H\langle h\rangle \mid T\langle t\rangle)
\end{aligned}
$$

Encoding Lists

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$$
\begin{aligned}
Nil(l) &\triangleq l(n, c).\overline{n} \\
Cons(H, T)(l) &\triangleq \nu h, t.\ (l(n, c).\overline{c}\langle h, t\rangle \mid H\langle h\rangle \mid T\langle t\rangle) \\
IsNil(L)(r) &\triangleq \nu l, n, c.\ (L\langle l\rangle \mid \overline{l}\langle n, c\rangle.(n.True\langle r\rangle + c(h, t).False\langle r\rangle))
\end{aligned}
$$

Pattern Matching

We can encode pattern matching on lists

$$\begin{array}{l} \text{case } l \text{ of} \\ \quad \mathit{Nil}? \Rightarrow P \\ \quad \mathit{Cons}?(h, t) \Rightarrow Q \end{array}$$

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

Pattern Matching

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$$\begin{array}{l} \text{case } l \text{ of} \\ \quad \mathit{Nil}? \Rightarrow P \\ \quad \mathit{Cons}?(h, t) \Rightarrow Q \end{array}$$

Idea: send fresh channels *n* and *c* to *l* and test which it signals on:

$$\nu n, c.\, \overline{l}\langle n, c\rangle\; n.P + c(h, t).Q$$

Destructive Operations

$$
\begin{aligned}
\mathit{Copy}\langle l, m\rangle \quad \triangleq \quad & \text{case } l \text{ of} \\
& \mathit{Nil}? \Rightarrow \mathit{Nil}\langle m\rangle \\
& \mathit{Cons}?(h, t) \Rightarrow \nu t'.\ (m(n, c).\bar{c}\langle h, t'\rangle \mid \mathit{Copy}\langle t, t'\rangle)
\end{aligned}
$$

Destructive Operations

$$
\begin{aligned}
\mathit{Copy}\langle l, m\rangle \;&\triangleq\; \text{case } l \text{ of} \\
&\quad \mathit{Nil}? \Rightarrow \mathit{Nil}\langle m\rangle \\
&\quad \mathit{Cons}?(h, t) \Rightarrow \nu t'.\,(m(n, c).\bar{c}\langle h, t'\rangle \mid \mathit{Copy}\langle t, t'\rangle)
\end{aligned}
$$

$$
\begin{aligned}
\mathit{Join}\langle k, l, m\rangle \;&\triangleq\; \text{case } k \text{ of} \\
&\quad \mathit{Nil}? \Rightarrow \mathit{Copy}\langle l, m\rangle \\
&\quad \mathit{Cons}?(h, t) \Rightarrow \nu t'.\,(m(n, c).\bar{c}\langle h, t'\rangle \mid \mathit{Join}\langle t, l, t'\rangle)
\end{aligned}
$$

Encoding Persistent Datatypes

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

$$
\begin{array}{rcl}
\mathit{Nil}(l) & \triangleq & !l(n,c).\overline{n} \\
\mathit{Cons}(H,T)(l) & \triangleq & \nu h,t.\ (!l(n,c).\overline{c}\langle h,t\rangle \mid H\langle h\rangle \mid T\langle t\rangle)
\end{array}
$$

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

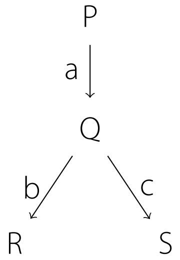
Encoding λ-calculus

$$
\begin{aligned}
[\![x]\!](u) &\triangleq \bar{x}\langle u\rangle \\
[\![\lambda x.\, e]\!](u) &\triangleq u(x, y).[\![e]\!](y) \\
[\![e_1\ e_2]\!](u) &\triangleq \nu y.\ ([\![e_1]\!](y) \mid \nu x.\ (\bar{y}\langle x, u\rangle \mid\ !x(w).[\![e_2]\!](w)))
\end{aligned}
$$

Bisimulation

When are two processes equal?

Perhaps the most important contributions of research on π calculus has been the development of the notion of *bisimulation*



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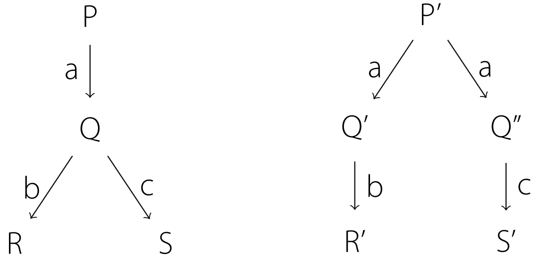

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Date	Topic	Notes	Reading	Assignments
22 August	Introduction	PDF	Winskel 1	
24 August	Small-step semantics	PDF	Winskel 2	HW1 out
27 August	Inductive definitions and proofs	PDF		
29 August	Large-step semantics	PDF		
31 August	IMP	PDF		HW2 out
3 September	No class (Labor Day)			
5 September	IMP properties	PDF		
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Mathematical Preliminaries & Operational Semantics

Date	Topic	Notes	Reading	Assignments
22 August	[illegible]			
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λ-calculus

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Mathematical Preliminaries & Operational Semantics

Denotational & Axiomatic Semantics

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Preliminary Exam I

Fall Break

Type Systems & Program Analyses

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29 August	Large-step semantics	PDF		

Denotational & Axiomatic Semantics

Date	Topic	Notes	Reading	Assignments
31 August	IMP	PDF		HW2 out
3 September	No class (Labor Day)			
5 September	IMP properties	PDF		
7 September	Denotational semantics	PDF		HW3 out
10 September	Denotational semantics	PDF		
12 September	Axiomatic semantics	PDF		
14 September	Hoare logic	PDF		HW4 out

λ-calculus

Date	Topic	Notes	Reading	Assignments
17 September	λ-calculus	PDF		
19 September	More λ-calculus	PDF		
21 September	λ-calculus encodings	PDF		HW5 out
24 September	Recursion	PDF		
26 September	Definitional translation	PDF		
28 September	Review	PDF		

Preliminary Exam I

Date	Topic	Notes	Reading	Assignments
1 October	Preliminary Exam I			
3 October	Continuations	PDF		
5 October	More continuations	PDF		HW6 out

Fall Break

Date	Topic	Notes	Reading	Assignments
8 October	No class (Fall Break)			
10 October	Types	PDF		

Type Systems & Program Analyses

Date	Topic	Notes	Reading	Assignments
12 October	More types	PDF		HW7 out
15 October	Record types	PDF		
17 October	Subtyping	PDF		
19 October	Polymorphism	PDF		HW8 out
25 October	More polymorphism	PDF		
27 October	Type inference	PDF		
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		

Preliminary Exam II

Date	Topic	Notes	Reading	Assignments
12 November	Preliminary Exam II			
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	No class (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 9:05-9:55
Gates G01

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Mathematical Preliminaries & Operational Semantics

Date	Topic	Notes	Reading	Assignments
22 August	[illegible]			
24 August	Small-step semantics	PDF	Winskel 2	HW1 out
27 August	Inductive [illegible]	PDF		
29 August	Large-step semantics	PDF		

Denotational & Axiomatic Semantics

Date	Topic	Notes	Reading	Assignments
31 August	IMP	PDF		HW2 out
3 September	No class (Labor Day)			
5 September	IMP properties	PDF		
7 September	[illegible]	[illegible]		[illegible] out
10 September	Denotational semantics	PDF		
12 September	Axiomatic semantics	PDF		
14 September	Hoare logic	PDF		HW4 out

λ-calculus

Date	Topic	Notes	Reading	Assignments
17 September	λ-calculus	PDF		
19 September	More λ-calculus	PDF		
21 September	λ-calculus encodings	PDF		HW5 out
24 September	Recursion	PDF		
26 September	Definitional translation	PDF		
28 September	Review	PDF		

Preliminary Exam I

Date	Topic	Notes	Reading	Assignments
1 October	Preliminary [illegible]			
3 October	Continuations	PDF		
5 October	More continuations	PDF		HW6 out

Fall Break

Date	Topic	Notes	Reading	Assignments
8 October	No class (Fall Break)			
10 October	Types	PDF		

Type Systems & Program Analyses

Date	Topic	Notes	Reading	Assignments
12 October	More types	PDF		HW7 out
15 October	Record types	PDF		
17 October	Subtyping	PDF		
19 October	Polymorphism	PDF		HW8 out
25 October	More polym[illegible]			
27 October	Type inference	PDF		
29 October	Propositio[illegible]			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		

Preliminary Exam II

Date	Topic	Notes	Reading	Assignments
12 November	Prelimin[illegible]			

Advanced Topics

Date	Topic	Notes	Reading	Assignments
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			
26 November	No class (Thanksgiving)			
29 November	More Coq	PDF		
1 December	Current trends in PL research	PDF		
3 December	Review	PDF		
13 December	Final Exam			

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Mathematical Preliminaries & Operational Semantics

Date	Topic	Notes	Reading	Assignments
22 August				
24 August	Small-step semantics	PDF	Winskel 2	HW1 out
27 August	Inductive definitions and proofs	PDF		
29 August	Large-step semantics	PDF		

Denotational & Axiomatic Semantics

Date	Topic	Notes	Reading	Assignments
31 August	IMP	PDF		HW2 out
3 September	No class (Labor Day)			
5 September	IMP properties	PDF		
7 September	[illegible]			[illegible] out
10 September	Denotational semantics	PDF		
12 September	Axiomatic semantics	PDF		
14 September	Hoare logic	PDF		HW4 out

λ-calculus

Date	Topic	Notes	Reading	Assignments
17 September	λ-calculus	PDF		
19 September	More λ-calculus	PDF		
21 September	λ-calculus encodings	PDF		HW5 out
24 September	Recursion	PDF		
26 September	Definitional translation	PDF		
28 September	Review	PDF		

Preliminary Exam I

Date	Topic	Notes	Reading	Assignments
1 October	Preliminary [illegible]			
3 October	Continuations	PDF		
5 October	More continuations	PDF		HW6 out

Fall Break

Date	Topic	Notes	Reading	Assignments
8 October	No class (Fall Break)			
10 October	Types	PDF		

Type Systems & Program Analyses

Date	Topic	Notes	Reading	Assignments
12 October	More types	PDF		HW7 out
15 October	Record types	PDF		
17 October	Subtyping	PDF		
19 October	Polymorphism	PDF		HW8 out
25 October	More polym[illegible]			
27 October	Type inference	PDF		
29 October	Propositi[illegible]			HW9 out
1 November	Existential types	PDF		
3 November	Objects	PDF		
5 November	Featherweight Java	PDF		HW10 out
8 November	Featherweight Java types	PDF		
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Preliminary Exam II

Date	Topic	Notes	Reading	Assignments
12 November	Prelimin[illegible]			

Advanced Topics

Date	Topic	Notes	Reading	Assignments
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			
26 November	No class (Thanksgiving)			
29 November	More Coq	PDF		
1 December	Current trends in PL research	PDF		
3 December	Review	PDF		

Final Exam

Date	Topic	Notes	Reading	Assignments
13 December	Final Exam			

CS 4110 (Fall 2014)

Programming Languages and Logics

MWF 9:05-9:55

Gates G01

Cornell University
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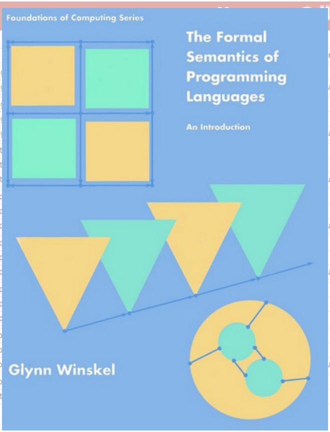

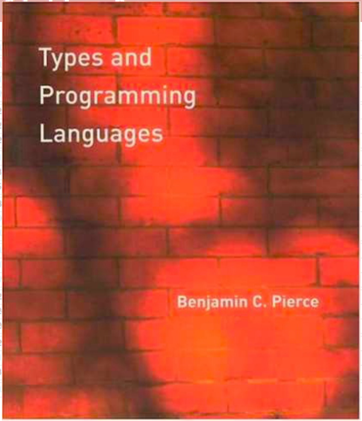

Final Topics

- Mathematical Preliminaries (inductive definitions)

Final Topics

- Mathematical Preliminaries (inductive definitions)
- Semantics (operational, axiomatic, denotational)

Final Topics

- Mathematical Preliminaries (inductive definitions)
- Semantics (operational, axiomatic, denotational)
- λ-calculus (basics, encodings, extensions)

Final Topics

- Mathematical Preliminaries (inductive definitions)
- Semantics (operational, axiomatic, denotational)
- λ-calculus (basics, encodings, extensions)
- Type systems (simple, extensions, properties)

Final Topics

- Mathematical Preliminaries (inductive definitions)
- Semantics (operational, axiomatic, denotational)
- λ-calculus (basics, encodings, extensions)
- Type systems (simple, extensions, properties)
- Advanced topics (TAL, concurrency)

Final Topics

- Mathematical Preliminaries (inductive definitions)
- Semantics (operational, axiomatic, denotational)
- λ-calculus (basics, encodings, extensions)
- Type systems (simple, extensions, properties)
- Advanced topics (TAL, concurrency)

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

Final Topics

- Mathematical Preliminaries (inductive definitions)
- Semantics (operational, axiomatic, denotational)
- λ-calculus (basics, encodings, extensions)
- Type systems (simple, extensions, properties)
- Advanced topics (TAL, concurrency)

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

Going further

- CS 6110 – Advanced Programming Languages

Going further

- CS 6110 – Advanced Programming Languages
- CS 611X – Certified Software Systems

Going further

- CS 6110 – Advanced Programming Languages
- CS 611X – Certified Software Systems
- CS 7190 – Seminar in Programming Languages

Going further

- CS 6110 – Advanced Programming Languages
- CS 611X – Certified Software Systems
- CS 7190 – Seminar in Programming Languages
- CS 4999 – Independent Research

Going further

- CS 6110 – Advanced Programming Languages
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- CS 7190 – Seminar in Programming Languages
- CS 4999 – Independent Research

Thank you, and stay in touch!