Compilation and Program Analysis (#10) : Parallelism

Ludovic Henrio

Master 1, ENS de Lyon et Dpt Info, Lyon1

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1. Generalities on Parallelism
2. Two case studies from the literature: Message passing and futures
3. Adding parallelism to Mini-while
4. Parallel programming languages in practice
5. MiniC with future: the lab session

Why parallelism?

1. To go faster
   Massive amount of computation, sometimes massively parallel, sometimes with complex parallelisation patterns
2. To handle large amount of data: big data-bases, consistency problems, synchronisation is crucial
3. To handle problems that are by nature parallel, from system interruption to online applications with several users/distributed data or decisions

Different forms of parallelism

Shared memory

principle: processes can write and read data in common memory spaces example: threads in most languages generally you need a form of locking to be able to write things correctly or something similar (can be basic mutex or more complex locking like Java serialize)

Message passing

principle: communication between thread by sending/receiving messages several communication patterns exist synchronous/asynchronous/different send and receive primitives, etc.

High-level programming models

Can mix shared data and message passing or simply provide a high-level view on one of them, generally provides richer and safer way to compose computations

Example: parallel skeletons like map-reduce, actors, ...

Parallel, concurrent, or distributed?

Objectives of this course

- Study and write semantics for parallel programs.
- Study one particular construct, futures, that we will implement in the practical session
- Focus on mini-while and futures (in the second half of the course).
- “Next” course we will see more general things on semantics for parallelism and more advanced features on futures.

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2. Two case studies from the literature: Message passing and futures
   - Operational semantics of CCS
   - Futures and Semantics
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2 Two case studies from the literature: Message passing and futures

- Operational semantics of CCS
- Futures and Semantics

CCS syntax

- Channel names: a, b, c , . . .
- Co-names: $\bar{a}, \bar{b}, \bar{c}, \ldots$ (complementary « $\bar{\bar{a}}$ = a »)
- Silent action (unobservable): τ
- Actions: $\mu ::= a \mid \bar{a} \mid \tau$
- Processes:

$$
\begin{array}{rcll}
P, Q & ::= & 0 & \text{inaction} \\
& \mid & \mu.P & \text{prefix} \\
& \mid & P \mid Q & \text{parallel} \\
& \mid & P + Q & \text{(external) choice} \\
& \mid & (\nu a)P & \text{restriction} \\
& \mid & \mathrm{rec}_K P & \text{process } P \text{ with definition } K = P \\
& \mid & K & \text{(defined) process name}
\end{array}
$$

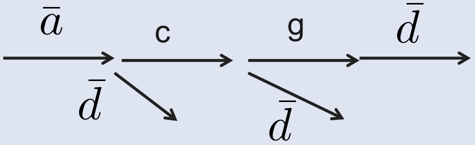
Intuitive Semantics from an "action" point of view

- a.P offers action a and then becomes P
- a.P+b.Q may offer either a and become P or b and become q
- $(\nu a)P$ may offer any action of P, except a
- P | Q may offer an action of P or of Q, but also if P offers a and Q offers a, they may synchronise (into a **τ** action)

We will use a labelled transition semantics for CCS processes.

A Micro-example

$$(\bar{a}.c.g)|\bar{d}$$



A tiny example

$$rec_{C1}(Tick.C1)$$

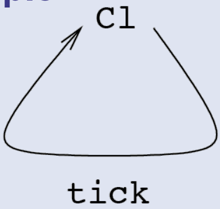


Figure: The transition graph for C1

Labelled graph

- vertices: process expressions
- labelled edges: transitions
- Each derivable transition of a vertex is depicted
- Abstract from the derivations of transitions

Exercise:
What are the possible traces (output sequences) of C1?

CCS : behavioural semantics (1)
Operators and rules

- Action prefix:

$$\frac{}{\mu.P \xrightarrow{\mu} P}$$

- Communication:

$$\frac{P \xrightarrow{a} P' \qquad Q \xrightarrow{\bar{a}} Q'}{P|Q \xrightarrow{\tau} P'|Q'}$$

- Parallelism

$$\frac{P \xrightarrow{\mu} P'}{P|Q \xrightarrow{\mu} P'|Q} \qquad \frac{Q \xrightarrow{\mu} Q'}{P|Q \xrightarrow{\mu} P|Q'}$$

CCS : behavioural semantics (2)
Operators and rules

- Non-deterministic choice

$$\frac{Q \xrightarrow{\mu} Q'}{P+Q \xrightarrow{\mu} Q'} \qquad \frac{P \xrightarrow{\mu} P'}{P+Q \xrightarrow{\mu} P'}$$

- Scope restriction

$$\frac{P \xrightarrow{\mu} P' \qquad \mu \neq a, \overline{a}}{(\nu a)P \xrightarrow{\mu} (\nu a)P'}$$

- Recursive definition

$$\frac{P[\mathrm{rec}_K P / K] \xrightarrow{\mu} P'}{\mathrm{rec}_K P \xrightarrow{\mu} P'}$$

Example

Apply semantic rules to infer one possible behaviour of:

$$\nu a.(a.b|(\overline{a}.c+\overline{a}.\overline{b}))$$

Are the following traces acceptable:

- $\tau.c.b$
- $a.\overline{a}.\tau$
- $\tau.\overline{b}.b$
- $\tau.\tau$

?

Notes on CCS and process algebras

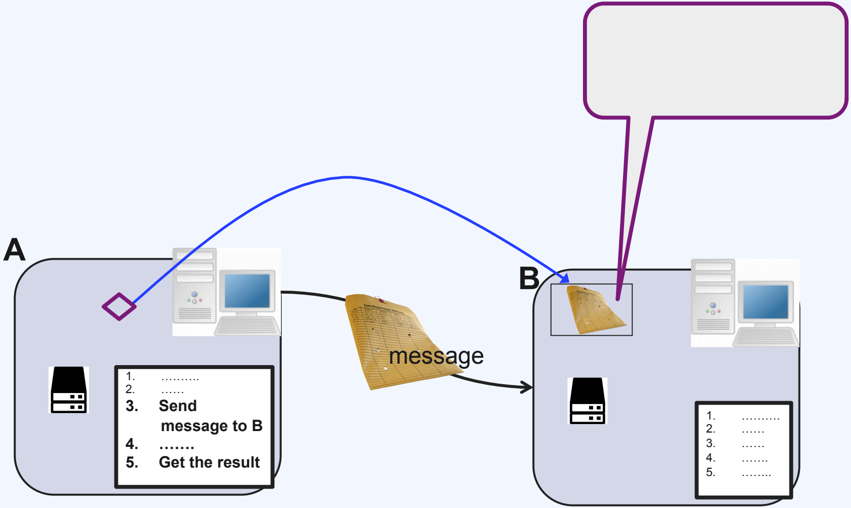
- Different syntax exist, and plenty of variants, among them:
  - Different recursion: define process names
  - Guarded choice / guarded recursion
  - Passing data on channels ($\overline{a}(5) \mid a(x)$)
- More work on π-calculus than CCS. π-calculus is more or less CCS+sending channel names over channels.
  Scopes and restrictions become more complex. You need something like: $(\nu x)(P|Q) \equiv (\nu x)P|Q$
- many research works on equivalence relations between CCS/pi-calculus programs: Bisimulation and other equivalences.

Overall a vast topic

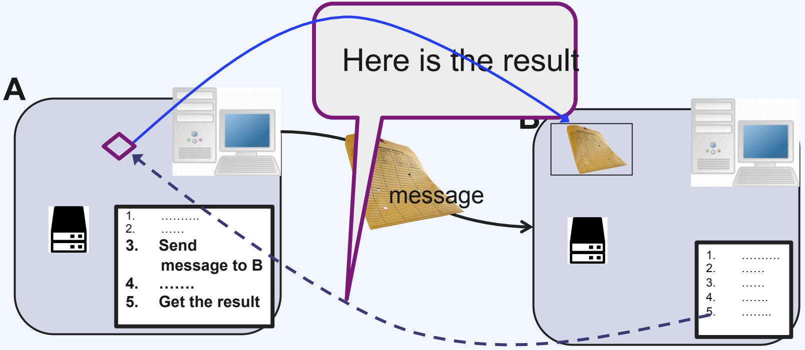
2 Two case studies from the literature: Message passing and futures

- Operational semantics of CCS
- Futures and Semantics

Requests and replies



Requests and replies



A **simple** λ-calculus with futures: Syntax

Terms: λ-calculus + futures:

$$e ::= (e\ e') \mid \lambda x.\, e \mid x \mid get\ e \mid f \mid async(e)$$

f appears during execution.

v is a value (fully evaluated term), i.e. $v ::= f \mid \lambda x.\, e$.

We could add other values, e.g. int.

A <u>configuration</u> consists of

- futures: $fut(f)$ (unresolved) or $fut(f\ v)$ (resolved with a value)
- and tasks ($task(f\ \ e)$).

References:

- A more complete lambda calculus with futures can be found in: *Joachim Niehren, Jan Schwinghammer, Gert Smolka. A Concurrent Lambda Calculus with Futures. Theoretical Computer Science, 2006,*
- simple lambda calculus with futures has been used in *Fernandez-Reyes, K., Clarke, D., Castegren, E., Vo, H-P. Forward to a Promising Future. Coordination 2018*

A **simple** λ-calculus with futures: Semantics

RED-LAMBDA

$$task(g\ E[(\lambda x.e)\ v]) \Rightarrow task(g\ E[e\{v/x\}])$$

RED-ASYNC

$$\frac{\textit{fresh } f}{task(g\ E[async(e)]) \Rightarrow fut(f)\ \ task(f\ e)\ \ task(g\ E[f])}$$

CONTEXT

$$\frac{cn \Rightarrow cn'}{cn\ cn'' \Rightarrow cn'\ cn''}$$

END-TASK

$$fut(f)\ task(f\ v) \Rightarrow fut(f\ v)$$

RED-GET

$$task(f\ E[get f])fut(f\ v) \Rightarrow task(f\ E[v])\ fut(f\ v)$$

Note: configurations identified modulo reordering of tasks / futures,

What is E?

Evaluation contexts

Evaluation contexts (sometimes called reduction contexts) used to focus on part of the configuration and reduce it. Compared to context rules they are more versatile: you can better choose what is in/out of the context.

For lambda-calculus with futures:

$$E ::= E\ e \mid v\ E \mid \bullet \mid get\ E$$

This ensures call-by-value.

$$E[e] = E\{\bullet \leftarrow e\}$$

Reduction context

$$\boxed{(\lambda x.x)\ ((\lambda y.y)\ (\boxed{(\lambda z.z)\ T}))}$$

Reduced term

$E = (\lambda x.x)\ ((\lambda y.y)\ (\bullet))$ and Red-Lambda can be applied.

Example of lambda-fut evaluation

What is the initial configuration?

• a task containing the program to be evaluated: $task(f\ e)$ where e is the program and f is a future that will never be used.

What is the behaviour of $\big(\lambda x.\, get(async((\lambda y.\, y + y)\ x))\big)\ 3$?
Suppose we have a <u>print</u> operation in the language of the form `print "A";e`. Write a simple program that can print either first "A" then "B" or first "B" then "A". add <u>get</u> to the program so that only one output is possible.

Notes: Use some e_A of the form $e_A =$ print "A"; 1 and call it asynchronously.

You can use or define a let statement.

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- Shared memory
- Asynchronous function calls and futures
- Typing futures in mini-while
- Preservation: Principles

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Mini-While Syntax (OLD) 1/2

Expressions:

$$
\begin{array}{lll}
e & ::= & c \,|\, e+e \,|\, e \times e \,|\, ... \\
 & | & x \qquad\qquad\qquad \textit{variable}
\end{array}
$$

Statements:

$$
\begin{array}{llll}
S(Smt) & ::= & x := expr & \text{assign} \\
 & | & x := f(e_1, .., e_n) & \text{simple function call} \\
 & | & skip & \text{do nothing} \\
 & | & S_1; S_2 & \text{sequence} \\
 & | & \texttt{if } b \texttt{ then } S_1 \texttt{ else } S_2 & \text{test} \\
 & | & \texttt{while } b \texttt{ do } S \texttt{ done} & \text{loop}
\end{array}
$$

Mini-While Syntax (OLD) 2/2

Programs with function definitions and global variables

$$
\begin{array}{rcll}
Prog & ::= & D \;\; FunDef \;\; Body & \text{Program} \\
Body & ::= & D; S & \text{Function/main body} \\
D & ::= & var\; x : \tau | D; D & \text{Variable declaration} \\
FunDef & ::= & \tau \;\; f(x_1 : \tau_1, .., x_n : \tau_n) \; Body; return\; e & \\
 & | & FunDef \;\; FunDef & \text{Function def}
\end{array}
$$

Structural Op. Semantics (SOS = small step) for mini-while (OLD – no fun)

$$(x := a, \sigma) \Rightarrow \sigma[x \mapsto Val(a, \sigma)]$$

$$(\texttt{skip}, \sigma) \Rightarrow \sigma$$

$$\frac{(S_1, \sigma) \Rightarrow \sigma'}{\big((S_1; S_2), \sigma\big) \Rightarrow (S_2, \sigma')} \quad \frac{(S_1, \sigma) \Rightarrow (S_1', \sigma')}{\big((S_1; S_2), \sigma\big) \Rightarrow (S_1'; S_2, \sigma')}$$

$$\frac{Val(b, \sigma) = tt}{(\texttt{if}\ b\ \texttt{then}\ S_1\ \texttt{else}\ S_2, \sigma) \Rightarrow (S_1, \sigma)}$$

$$\frac{Val(b, \sigma) = ff}{(\texttt{if}\ b\ \texttt{then}\ S_1\ \texttt{else}\ S_2, \sigma) \Rightarrow (S_2, \sigma)}$$

Mini-while + shared memory

Add parallel composition to statements

$$S ::= ...|S||S'$$

And 2 reduction rules for parallelism:

PARALLEL1
$$\frac{(S_1, \sigma) \Rightarrow (S_1', \sigma')}{(S_1||S_2, \sigma) \Rightarrow (S_1'||S_2, \sigma')}$$

PARALLEL2
$$\frac{(S_2, \sigma) \Rightarrow (S_2', \sigma')}{(S_1||S_2, \sigma) \Rightarrow (S_1||S_2', \sigma')}$$

And 2 special cases when a parallel task finishes:

ENDTASK1
$$\frac{(S_1, \sigma) \Rightarrow \sigma'}{(S_1||S_2, \sigma) \Rightarrow (S_2, \sigma')}$$

ENDTASK2
$$\frac{(S_2, \sigma) \Rightarrow \sigma'}{(S_1||S_2, \sigma) \Rightarrow (S_1, \sigma')}$$

Example mini-while shared memory

Compute the semantics of:

- $x := 0; (x := 2; x := x + 1 || x := 3)$
- $x := 0; (x := 2 || \texttt{while}\ x < 3\ \texttt{do}\ x := x + 1\ \texttt{done})$

A final note: $||$ is not often practical in the syntax one would prefer a spawn statement (different because spawn can create infinitely many tasks).

3 Adding parallelism to Mini-while

- Shared memory
- Asynchronous function calls and futures
- Typing futures in mini-while
- Preservation: Principles

OLD SOS with functions (1/2)

Runtime configuration
$(\texttt{Optional-Statement}, \texttt{Call-Stack}, \texttt{Stack}, \texttt{Store})$:

$$cn ::= (S, Ctx, \Sigma, sto) \mid (Ctx, \Sigma, sto)$$

$$(x := e, Ctx, \Sigma, sto) \Rightarrow (Ctx, \Sigma, sto[\Sigma(x) \mapsto Val(e, sto \circ \Sigma)])$$

$$\frac{(S_1, Ctx, \Sigma, sto) \Rightarrow (Ctx, \Sigma', sto')}{\big((S_1; S_2), Ctx, \Sigma, sto\big) \Rightarrow (S_2, Ctx, \Sigma', sto')}$$

$$\frac{(S_1, Ctx, \Sigma, sto) \Rightarrow (S_1', Ctx, \Sigma', sto')}{\big((S_1; S_2), Ctx, \Sigma, sto\big) \Rightarrow (S_1'; S_2, Ctx, \Sigma', sto')}$$

+ rules for if, skip, and while

OLD SOS with functions (2/2)

CALL

$$\frac{bind_3(f, e_1..e_n, \Sigma, sto) = (S', \Sigma', sto')}{(x := f(e_1, .., e_n); S, Ctx, \Sigma, sto) \Rightarrow (S', (\Sigma, x := R(f); S) :: Ctx, \Sigma', sto')}$$

Ctx is a list of $(Stack, Stm)$. $x := f(e_1, .., e_n); S$ must be the whole current statement (imposed by the rule SEQ). $R(f)$ is a marker that remembers the name of the function called

$bind_3(f, e_1..e_n, \Sigma, sto) = (S_f, \Sigma', sto[\ell_1 \mapsto v_1..\ell_n \mapsto v_n])$ if $body(f) = D_f; S_f$,
$params(f) = [x_1..x_n]$, $Vars(D_f) = \{y_1..y_k\}$
$\ell_1..\ell_n$ fresh, $\ell'_1..\ell'_k$ fresh $\forall i \in [1..n]. Val(e_i, sto \circ \Sigma) = v_i$,
$\Sigma' = \Sigma[x_1 \mapsto \ell_1..x_n \mapsto \ell_n][y_1 \mapsto \ell'_1..y_k \mapsto \ell'_k]$.

$$\frac{v = Val(ret(f), sto \circ \Sigma')}{((\Sigma, x := R(f); S) :: Ctx, \Sigma', sto) \Rightarrow (S, Ctx, \Sigma, sto[\Sigma(x) \mapsto v])}$$

Futures: syntax and principles

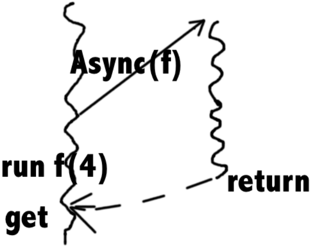
Statements:

$S(Smt)$	$::=$	$x := expr$	assign
	$\mid$	$x := f(e_1, .., e_n)$	simple function call
	$\mid$	$x :=$ ***Async***$(f(e_1, .., e_n))$	Asynchronous function call
	$\mid$	$x := get(e)$	future access (synchronisation)
	$\mid$	$skip$	do nothing
	$\mid$	$S_1; S_2$	sequence
	$\mid$	`if` b `then` S_1 `else` S_2	test
	$\mid$	`while` b `do` S `done`	loop

Example (informally)

```
int f (int x) (
  int z;
  z:=x+x
) return z

(
  int x,y;
  fut<int> t;
  t:=Async(f(3));
  y:=f(4);
  x:=get(t)
)
```



Design choice: no global state

We have the choice between

1. Have a global state and allow race-condition between tasks. Versatile and looks like C threads but non-deterministic behaviour of programs.
2. Forget the global state that we had in function evaluation to have a more predictable semantics: no races between two tasks writing on the same memory.

The second case corresponds to MiniC where we have no global variable.

We specify the semantics for the second solution. To implement the first solution a global memory should be added to the configuration.

We thus suppose from now on that there is no global variable.

Future semantics for mini-while (1/3)

- Syntax: F, G range over future identifiers. Values (v) can be future identifiers.
- Configurations:

$$\textit{cn} ::= (S, Ctx, \Sigma, sto)_F \mid (Ctx, \Sigma, sto)_F \mid fut(F, v) \mid \textit{cn}\ \ \textit{cn}'$$

  Configurations are identified modulo reordering of tasks.
  Note: compared to λ-calculus+fut we do not put unresolved futures in the configuration (we could).
- Sequential reduction rules adapted straightforwardly:

$$\frac{(S, Ctx, \Sigma, sto) \Rightarrow (S', Ctx', \Sigma', sto')}{(S, Ctx, \Sigma, sto)_F\ \textit{cn} \Rightarrow (S', Ctx', \Sigma', sto')_F\ \textit{cn}}$$

$$\frac{(S, Ctx, \Sigma, sto) \Rightarrow (Ctx', \Sigma', sto')}{(S, Ctx, \Sigma, sto)_F\ \textit{cn} \Rightarrow (Ctx', \Sigma', sto')_F\ \textit{cn}}$$

Future semantics for mini-while (2/3)

A naive solution for asynchronous function call:

ASYNC-CALL (BAD)

$$\frac{bind_3(f, e_1..e_n, \Sigma, sto) = (S', \Sigma', sto') \qquad G \text{ fresh future}}{\begin{array}{c}(x := \textit{Async}(f(e_1, .., e_n)); S, Ctx, \Sigma, sto)_F \ \textit{cn} \Rightarrow \\ (x := G; S, Ctx, \Sigma, sto)_F \ (S', \emptyset, \Sigma', sto')_G \ \textit{cn}\end{array}}$$

Problem: we have lost the return expression that was somehow remembered by $R(f)$ in the synchronous call. We do not know what to fill the future G with.

Future semantics

On board: try to design rules for async, get (and return)

Future semantics for mini-while (3/3)

A possible solution: add $return(e)$ to the valid Ctx and store the returned expression in the call-stack:
Ctx is a list of $(Stack, Stm)$ possibly with $return(e)$ as the last element of the list.

ASYNC-CALL

$$\frac{bind_3(f, e_1..e_n, \Sigma, sto) = (S', \Sigma', sto') \qquad G \text{ fresh future}}{\begin{array}{c}(x := \textit{Async}(f(e_1, .., e_n)); S, Ctx, \Sigma, sto)_F \ \textit{cn} \Rightarrow \\ (x := G; S, Ctx, \Sigma, sto)_F \ (S', return(ret(f)), \Sigma', sto')_G \ \textit{cn}\end{array}}$$

End of function execution and future access:

FUT-RESOLVE

$$\frac{v = Val(e, sto \circ \Sigma)}{\begin{array}{c}(return(e), \Sigma, sto)_F \ \textit{cn} \Rightarrow \\ fut(F, v) \ \textit{cn}\end{array}}$$

GET

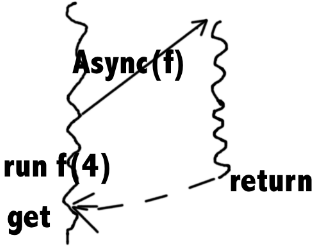
$$\frac{G = Val(e, sto \circ \Sigma)}{\begin{array}{c}(x := get(e); S, Ctx, \Sigma, sto)_F \ fut(G, v) \ \textit{cn} \\ \Rightarrow (x := v; S, Ctx, \Sigma, sto)_F \ fut(G, v) \ \textit{cn}\end{array}}$$

Example (semantics)

use the semantics to evaluate the previous example

```
int f (int x) (
  int z;
  z:=x+x
) return z

(
  int x,y;
  fut<int> t;
  t:=Async(f(3));
  y:=f(4);
  x:=get(t)
)
```



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Base Type System (OLD)

From declarations we infer $\Gamma : Var \to Basetype$ with a judgment $\to_d$. From program we infer a function table $\Gamma_f : FuncName \to (\tau_1..\tau_n \to \tau)$ with a judgment $\to_f$ Then a typing judgment for expressions is $\Gamma \vdash e : \tau \in Basetype$. Typing of statements has the form : $\Gamma, \Gamma_f \vdash S$.

$$\frac{\Gamma \vdash e_1 : \texttt{int} \quad \Gamma \vdash e_2 : \texttt{int}}{\Gamma \vdash e_1 + e_2 : \texttt{int}} \qquad \frac{}{\Gamma \vdash x : \Gamma(x)}$$

$$\frac{\Gamma, \Gamma_f \vdash S_1 \quad \Gamma, \Gamma_f \vdash S_2}{\Gamma, \Gamma_f \vdash S_1; S_2}$$

$$\frac{\Gamma \vdash x : \tau \quad \Gamma \vdash e : \tau}{\Gamma, \Gamma_f \vdash x := e}$$

$$\frac{\Gamma \vdash b : \texttt{bool} \quad \Gamma, \Gamma_f \vdash S_1 \quad \Gamma, \Gamma_f \vdash S_2}{\Gamma, \Gamma_f \vdash \texttt{if } b \texttt{ then } S_1 \texttt{ else } S_2}$$

$$\frac{\Gamma \vdash b : \texttt{bool} \quad \Gamma, \Gamma_f \vdash S}{\Gamma, \Gamma_f \vdash \texttt{while } b \texttt{ do } S \texttt{ done}}$$

Type function calls and typing program

To type a program we type all method bodies:

$$\frac{\begin{array}{c} \mathit{Fundef} \rightarrow_f \Gamma_f \\ \forall(\tau\ f(x_1:\tau_1,..,x_n:\tau_n)\ D_f; S_f; \mathit{return}\ e \in \mathit{Fundef}). \\ \qquad \Gamma_g + \Gamma_l \vdash e:\tau \wedge \Gamma_l, \Gamma_f \vdash S_f \text{ with } x_1:\tau_1;..;x_n:\tau_n; D_f \rightarrow_d \Gamma_l \\ D_m \rightarrow_d \Gamma_m \qquad \Gamma_m, \Gamma_f \vdash S \end{array}}{\mathit{Fundef}\ D_m; S}$$

CALL

$$\frac{\Gamma_f(f) = \tau_1..\tau_n \rightarrow \tau \qquad \forall i \in [1..n].\, \Gamma \vdash e_i : \tau_i \qquad \Gamma \vdash x : \tau}{\Gamma, \Gamma_f \vdash x := f(e_1,..,e_n)}$$

$+$ merges and overwrite variable declarations, for overriding variables (local over global).

Note: recall there is no global variable.

Adding future types

Previous type syntax:

$$\tau ::= int \mid bool$$

New types can be futures:

$$\tau ::= int \mid bool \mid fut < \tau >$$

Future types can be declared: `fut<int> x,y`

We check structural type equivalence.

On board: try to design rules for typing async and get.

Typing rules for futures

ASYNC

$$\frac{\Gamma_f(f) = \tau_1..\tau_n \to \tau \qquad \forall i \in [1..n].\, \Gamma \vdash e_i : \tau_i \qquad \Gamma \vdash x : fut < \tau >}{\Gamma, \Gamma_f \vdash x := \textbf{\textit{Async}}(f(e_1, .., e_n))}$$

GET

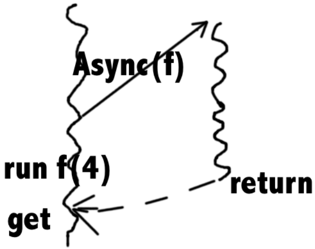
$$\frac{\Gamma \vdash e : fut < \tau > \qquad \Gamma \vdash x : \tau}{\Gamma, \Gamma_f \vdash x := get(e)}$$

Example (type)

Type the previous example (skip the typing of f)

```
int f (int x) (
  int z;
  z:=x+x
) return z

(
  int x,y;
  fut<int> t;
  t:=Async(f(3));
  y:=f(4);
  x:=get(t)
)
```



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Preservation

Definition:

consider a well typed program $Prog$, a configuration *cn* reachable by executing $Prog$, we have

$$cn \Rightarrow cn' \wedge \Gamma_f, \boldsymbol{\Gamma_{fut}} \vdash cn \implies \exists \Gamma'_{fut},\ \Gamma_f, \boldsymbol{\Gamma'_{fut}} \vdash cn'$$

What is a well-typed configuration? i.e. define the assertion $\Gamma_f, \boldsymbol{\Gamma_{fut}} \vdash$ *cn* What is $\boldsymbol{\Gamma_{fut}}$? How to type function bodies?

Definition (Configuration typing (very OLD))

$\Gamma \vdash (S, \sigma) \iff (\Gamma \vdash S \wedge \forall x. \emptyset \vdash \sigma(x) : \tau \iff \Gamma(x) = \tau)$

Now we have:

$$cn ::= (S, Ctx, \Sigma, sto)_F \mid (Ctx, \Sigma, sto)_F \mid fut(F, v) \mid cn\ \ cn'$$

With Ctx of the form $(\Sigma, S) :: .. :: (\Sigma_n, S_n) :: return(e)$ (no $return(e)$ for the main task).

Well-typed configuration

Suppose $\Gamma, \Gamma_f \vdash (S, \sigma)$ defined similarly to before (Γ_f added). We can define:

$$\frac{\boldsymbol{\Gamma}, \Gamma_f \vdash (S, sto \circ \Sigma) \qquad Ctx = (\Sigma_0, S_0) :: .. :: (\Sigma_n, S_n) :: return(e) \qquad \forall i \in [1..n].\, \boldsymbol{\Gamma_i}, \Gamma_f \vdash (S_i, sto \circ \Sigma_i) \qquad \boldsymbol{\Gamma_n} \vdash e : \Gamma_{fut}(F)}{\Gamma_f, \Gamma_{fut} \vdash (S, Ctx, \Sigma, sto)_F}$$

$$\frac{\emptyset \vdash v : \Gamma_{fut}}{\Gamma_f, \Gamma_{fut} \vdash fut(F, v)} \qquad \frac{\Gamma_f, \Gamma_{fut} \vdash \mathit{cn} \qquad \Gamma_f, \Gamma_{fut} \vdash \mathit{cn}'}{\Gamma_f, \Gamma_{fut} \vdash \mathit{cn}\ \ \mathit{cn}'}$$

Problem (same as with functions): $\boldsymbol{\Gamma}$ is undefined. It is the environment that types the considered statement, i.e. the typing environment of the function that contains the considered statement. We can for example annotate configurations with the name of the function that is currently evaluated and recover the typing environment.

Now: How to prove that small step semantics preserves well-typed configurations?

About Progress

State a progress property This entails absence of deadlock

Write a program that can deadlock

Alternatively, we can state a weaker progress property:

> *Any well-typed configuration that cannot progress is either a final configuration or exhibits a cycle of dependencies between futures: there is a list of future identifiers such that the task responsible for computing F_1 is performing a get on future F_2, ... the task responsible for computing F_n is performing a get on future F_0.*

formalise In other words: typing rules out all kinds of stuck configurations except cycles of futures.

1. Generalities on Parallelism
2. Two case studies from the literature: Message passing and futures
3. Adding parallelism to Mini-while
4. **Parallel programming languages in practice**
5. MiniC with future: the lab session

Different approaches to implement languages

Classical compilation: as seen in course

Source-to-source compilation: compiling to assembler is tedious and restricted to one architecture. Many source-to-source compilers, e.g. language-to-C / language-to-Java

Libraries / DSL: No translation at all. Relies on software engineering expertise to implement rich libraries DSLs while staying in the restriction of the host language

Next: 2 examples.

ProActive:

A Java API + Tools for Parallel, Distributed Computing

A uniform framework: **An Active Object pattern**
A formal model behind: **Determinism (POPL'04)**

- **Programming Model (Active Objects):**
- **Asynchronous Remote Invocations, Wait-By-Necessity**
- **Groups, Mobility, Components, Security, Fault-tolerance, Load balancing**
- **Environment:**
  - **XML Deployment Descriptors, File Transfers**
  - **Interfaced with:** `rsh, ssh, LSF, PBS, Globus, Jini, SUN Grid Engine`

ObjectWeb
Open Source Middleware

Creating active objects

An object created with `A a = new A (obj, 7);`

can be turned into an active and remote object:

- **Object-based:**

```
a = (A)ProActive.turnActive (a, node);
```

- **Instantiation-based:**

```
A a = (A)ProActive.newActive(«A»,param,node);
```

`The "node" is the AO container.`

Remaining of the code unchanged → "Transparency"

Example 2: The Encore language approach

A language with objects, futures, actors, etc. with a rich type system to optimise data access while preventing data-races. Advanced features: Ownership types, parallel futures, forwarding, ...

Compiled into C (source-to-source compilation)

Relies on a specific C library, and an existing Actor library in C (pony) with a dedicated runtime (PonyRT) for final compilation and execution

Tiny code example (observe the dedicated syntax):

```
defrun() : void {
    let fut = service.provide()
        client =new Client()
    in {
      client.send(get fut);
    ...
    }
}
```

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Structure and approach

Approach restricted to future of integers, typed as a new type `futint`. Corresponds to `fut<int>`. Functions that can be called asynchronously all have a single parameter of type `int` and return an `int`. For other functions it is sufficient if your type-checker only takes into account functions with one single parameter of any type.

- An extended syntax (`get` and `async` and `futint` type) **Provided**
- A source-to-source transformation **Provided**
- A typing visitor: type `get` and `async` **To do**
- A dedicated library using C threads to implement `Async` and `Get` **To do**

Source-to-source transformation

Done by `MiniCPPListener.py`

- add pointers, especially pointer-to-function
- Import the right library (`futurelib.h`) and add a cleanup phase

A practical example:

```
int main(){
  futint fval;
  int val;
  fval = Async(functi,123)
      ;
  println_int(0);
  return 0;
}
```

$\longrightarrow$

```
int main(){
  futint fval;
  int val;
  fval = Async(&functi
      ,123);
  println_int(0);
  freeAllFutures();
  return 0;
}
```

Typing futures

To do: add typing of async and Get in your type-checker: Your new typing visitor should now have:

```
def visitAsyncFuncCall(self, ctx):
  ...
```

Also type the instruction `Get`

```
    def visitGetCall(self, ctx):


            ...
```

What are the typing rules for Async and Get in our particular case?

The futurelib library: `futurelib.h` and `futurelib.c`

```
typedef struct {
    int Id;
    int Value;
    int resolved;
    pthread_t tid;
} FutureInt;
typedef FutureInt* futint;
FutureInt *fresh_future();
void print_futureInt(FutureInt *fut);
void free_future(FutureInt *fut);
void resolve_future(FutureInt *fut, int val);
int Get(FutureInt *fut);
FutureInt *Async(int (*fun)(int), int p);
void freeAllFutures();
```

We use a naive future dictionary (a large array of references)

Summary: what have we seen

- Overview of concepts for parallelism in programming languages and in semantics.
- Example of semantics for communications and futures.
- Designed a semantics for MiniWhile with thread and concurrent memory accesses.
- Designed a semantics for MiniWhile with futures and no concurrent memory access.
- A type system for futures
- Different ways to implement languages (beyond pure compilation solution)
- Illustrated by the extension of our MiniC language with futures

Next course is more advanced notions for parallelism, semantics and futures.

Bonus: Threads in C – Illustrated on board

```
int pthread_create(pthread_t *thread, const pthread_attr_t *
    attr, void *(*start_routine) (void *), void *arg);
```

If attr is NULL, then the thread is created with default attributes.
A possible call:

```
int err = pthread_create(&tid, NULL, &runTask, (args));
```

Notice the function pointer (explanation on board). `tid` can be associated with a future **why?**

```
int pthread_join(pthread_t thread, void **value_ptr);
```

with a non-NULL `value_ptr` argument, the value passed to `pthread_exit()` by the terminating thread shall be made available in the location referenced by `value_ptr`.
usage:

```
pthread_join(tid, NULL);
```