Hybrid Partial Evaluation
OOPSLA'11
(best student paper)

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About me

PhD Brown University, 1989 w/Peter Wegner

- Denotational Semantics of Inheritance
- Mixins, F-Bounds, Class reorganization, ADT/OOP

AppleScript

- Lead designer and group manager

Allegis: Indirect Sales Chain Management

- Founder, VP Engineering CTO (1997-2003)
- 150 employees, $60M in venture capital
- Customers: Microsoft, HP, Charles Schwab, etc.

University of Texas at Austin, Computer Science

- Joined 2003

Motivation

Goal

We want to write *general* programs/libraries

But use them in *specific situations*

Partial Evaluation

Can *specialize* a general program to some inputs

Desires

Easy to understand

Easy to implement

Works well in practice

Partial Evaluation (by hand)

Example: Power function

pow(n, x) = if (n==0) then 1 else x*pow(n-1, x)

What if you know n?

pow(3, x) = x*pow(2, x)

if (3==0) then 1
else x*pow(3-1, x)

This depends on pow(2, x)

pow(2, x) = x*pow(1, x)

pow(1, x) = x*pow(0, x)

pow(0, x) = 1

Partial Evaluation (by hand)

Example: Power function

pow(n, x) = if (n==0) then 1 else x*pow(n-1, x)

What if you know n?

pow3(x) = x*pow2(x)

if (3==0) then 1
else x*pow(3-1, x)

This depends on pow(2, x)

pow2(x) = x*pow1(x)

pow1(x) = x*pow0(x)

pow0(x) = 1

Partial Evaluation

Example: Power function

pow(n, x) = if (n==0) then 1 else x*pow(n-1, x)

Lets call this final function "pow3":

pow3(x) = x*x*x

Partial evaluation

- Eliminates computations that depend on known inputs
- Result is "residual program"
- Doesn't always work:
  - pow(n, 19) = if (n==0) then 1 else 19*pow(n-1, 19)
- Useful when raising many numbers to 3rd power

Automatic Partial Evaluation

Example: Power function

pow(n, x) = if (n==0) then 1 else x*pow(n-1, x)

Can we compute residual code automatically?

peval(pow, 3) ➔ fun(x) x*x*x ≡ pow3

Partial evaluation function: peval

Inputs:

- Source code of a function
- Value of the first argument

Output:

- Residual code from partially evaluating

Automatic Partial Evaluation

Example: Power function

pow(n, x) = if (n==0) then 1 else x*pow(n-1, x)

Can we compute residual code automatically?

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Partial evaluation function: peval

Inputs:

- Source code of a function
- Value of the first argument

Output:

- Residual code from partially evaluating

Example

```
String pat = CT("(a(*|*)b)*(abb(*|*)a+b)")
Regex regex = CT(RegexParser.parse(pat));

String buffer = in.readLine(...)

regex.execute(buffer);
```

Pure 1st-order Functional Language

x : Variable v : Value

$e = x \mid v \mid$ **`if`** e **`then`** e **`else`** $e \mid e$`+`$e \mid$ `f(`$e, \ldots, e$`)`

ρ environment maps *all* variables to values

$E[v]\rho = v$

$E[x]\rho = \rho(x)$

$E[$**`if`** e_1 **`then`** e_2 **`else`** $e_3]\rho =$ **if** $E[e_1]\rho$ **then** $E[e_2]\rho$ **else** $E[e_3]\rho$

$E[e_1+e_2]\rho = E[e_1]\rho + E[e_2]\rho$

$E[$`f(`$e_1, \ldots, e_n$`)`$]\rho = E[e]\rho'$

lookup function definition: `f(`$x_1, \ldots, x_n$`)=`e

$\rho' = \{ x_1{=}E[e_1]\rho, \ldots, x_n{=}E[e_n]\rho \}$

Evaluation to Partial Evaluation

The type of eval

E : Expression → Environment → Value

Environment = Variable → Value

FreeVars(e) $\subseteq$ Domain(v)

All variables are bound

What about a partial evaluator?

Environment gives values to some variables

P : Expression → Environment → Expression

Result might not be a complete value

P[x+y] {x=3, y=2} ➔ 5

P[x+y] {x=3} ➔ [3+y]

Online Partial Evaluator P

x : Variable v : Value

$e = x \mid v \mid$ **`if`** e **`then`** e **`else`** $e \mid e$`+`$e \mid$ `f(`$e, \ldots, e$`)`

environment maps ***some*** variables to values

$\text{P}[v]\rho = v$

$\text{P}[x]\rho =$ **if** $x \in \text{dom}(\rho)$ **then** $\rho(x)$ **else** $[x]$

returns code $[x]$ if the variable is not defined

Online Partial Evaluator P

x : Variable v : Value

$e = x \mid v \mid$ **`if`** e **`then`** e **`else`** $e \mid e$`+`$e \mid$ `f(`$e, \ldots, e$`)`

environment maps ***some*** variables to values

$P[v]\rho = v$

$P[x]\rho =$ **if** $x \in \mathrm{dom}(\rho)$ **then** $\rho(x)$ **else** «x»

$P[$**`if`** e_1 **`then`** e_2 **`else`** $e_3]\rho =$

case $P[e_1]\rho$ **of**

$v \rightarrow$ **if** v **then** $P[e_2]\rho$ **else** $P[e_3]\rho$

$e \rightarrow$ «**`if`** e **`then`** $P[e_2]\rho$ **`else`** $P[e_3]\rho$»

if its a boolean v, then pick branch.
else create a new if statement

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Online Partial Evaluator P

$P[v]\rho = v$

$P[x]\rho =$ **if** $x \in \text{dom}(\rho)$ **then** $\rho(x)$ **else** «x»

$P[$**`if`** e_1 **`then`** e_2 **`else`** $e_3]\rho =$

case $P[e_1]\rho$ **of**

$v \rightarrow$ **if** v **then** $P[e_2]\rho$ **else** $P[e_3]\rho$

$e \rightarrow$ «**`if`** e **`then`** $P[e_2]\rho$ **`else`** $P[e_3]\rho$»

$P[e_1+e_2]\rho =$

$v_1 + v_2$ **if** $v_i = P[e_i]\rho$

«$e'_1+e'_2$» **if** $e'_i = P[e_i]\rho$

apply operator if arguments are both are values

otherwise generate new expression

Function Calls

$$P[f(e_1, \ldots, e_n)]\rho = «f\_\rho_s(e'_{d_1}, \ldots, e'_{d_k})»$$

1. lookup function definition: $f(x_1, \ldots, x_n) = e$
2. Partially evaluate the arguments
   $e'_i = P[e_i]$
3. partition arguments into "compile time (CT)" and "runtime"
   $\{ s_1, \ldots, s_j \} \cup \{ d_1, \ldots, d_k \} = \{ 1, \ldots, n \}$
   $\vee \; \{ e'_{s_1}, \ldots, e'_{s_j} \} = \{ v_1, \ldots, v_j \}$
4. create environment with CT variables
   $\rho_s = \{ x_{s_1} = v_{s_1}, \ldots, x_{s_j} = v_{s_j} \}$
5. create new function specialized by CT values
   $f\_\rho_s(x_{d_1}, \ldots, x_{d_k}) = E[e]\,\rho_s$
6. Residual code is call with runtime arguments
   $«f\_\rho_s(e'_{d_1}, \ldots, e'_{d_k})»$

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Hybrid Partial Evaluation

- Online style (no static analysis)
- Annotations to begin partial evaluation
- No termination guarantee
- Object-oriented language
  - Imperative (mutable state)
  - Objects "live" at compile-time or runtime (not both)
  - Specialize methods and classes
- Formalized in Haskell (It's fun, check it out!)
- Real compiler for Java (Part of Batches project)

Partial Evaluation Annotations

Two *stages*:

Compile-time: pre execution during partial evaluation/compilation

Runtime: normal execution

Annotation

CT(e)

Marks expression e for execution at compile time

Example

Regex regex = **CT(**Regex.parse("(a|b)*"));

regex.execute(buffer);

Objects

Any object can be instantiated at compile time

if (config.loggingEnabled) ...

dead code elimination

if (config.enabled("logging")) ...

dead code elimination

if (config.enabled(userInput)) ...

inlines "enabled" method using config state

x = new System(config1);

y = new System(config2);

specializes System class, once for each config!

dynamicHashMap.put("c1", config)

compile-time error: Config cannot jump to runtime

Objects exists in exactly one stage

Cannot move
(from compile time to runtime)

Primitive values can move

Mutable State

Mutable state

Supported!

A mutable object is either compile-time or runtime

Within stage, all mutations happen in correct order

```
Regex regex = CT(Regex.parse("(a|b)*"));
regex.execute(buffer);
```

Behavior maybe different with/without PE

Annotated program may have different behavior

e.g. Print statements may happen at compile time

Program may be rejected (if statements)

Annotations create a *new language*

Reflection

Reflection becomes static

```
String name = CT("getSize");
Method m = o.getClass().getMethod(name);
m.invoke(o);
```

converts to:

```
o.getSize();
```

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Termination

No Termination Guarantee

The compiler may diverge

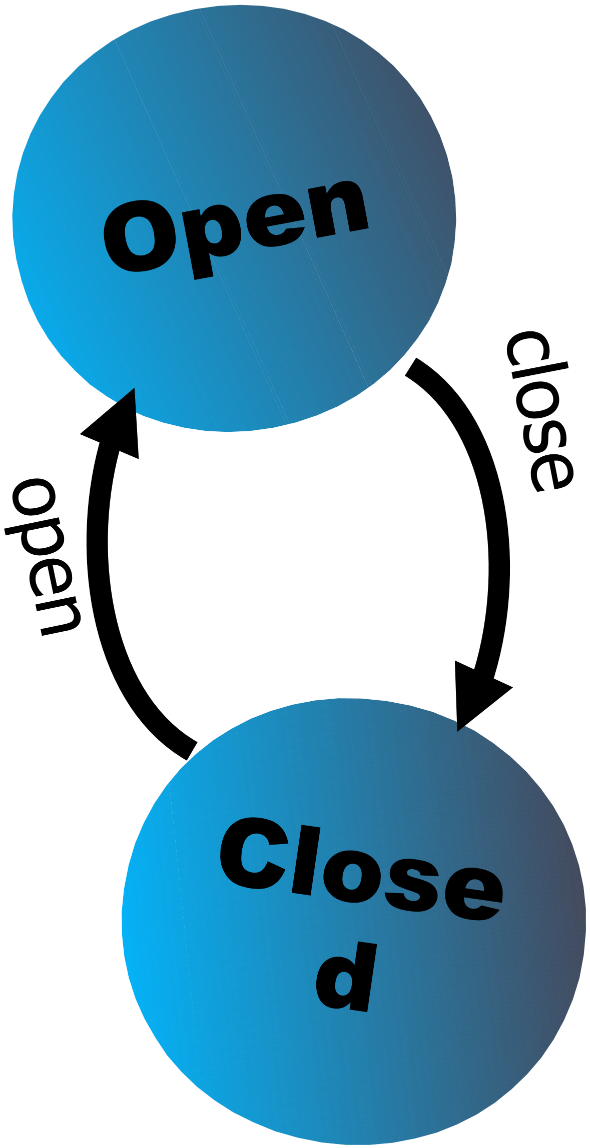
This is true of C++ compiler

Hit Ctrl-C and modify the program....

Example Model Interpreter

Interpreter

```
int run(State current) {
  print(current.label);
  String input = in.readLine()
  nxt = current.trans.lookup(input);
  run(nxt);
}
```



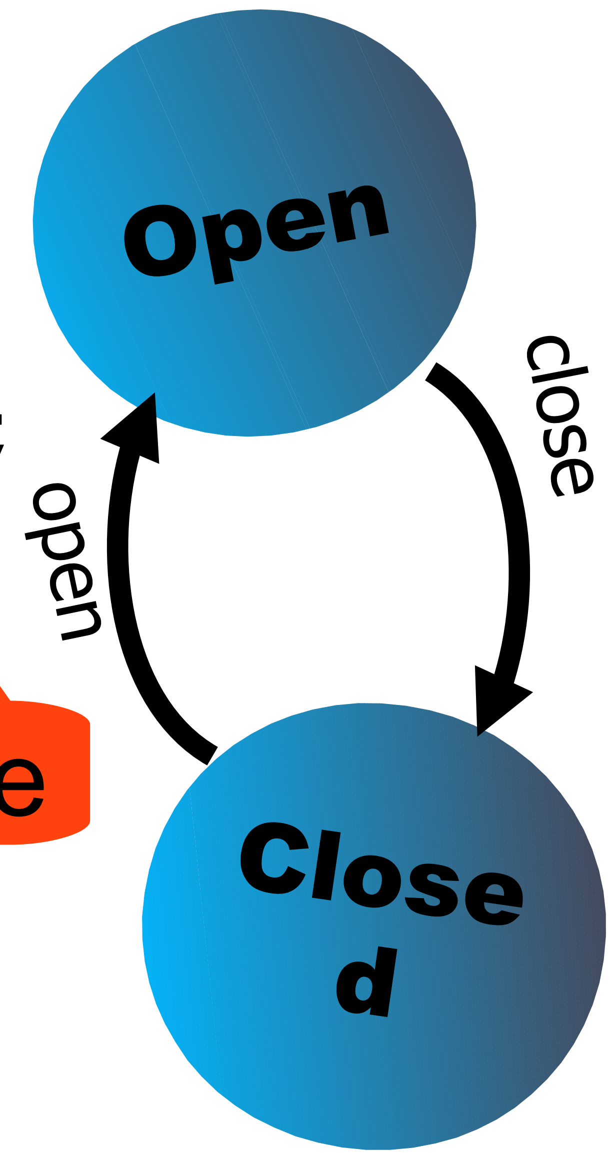
Example Model Interpreter

Interpreter

```
int run(State current) {
  print(current.label);
  String input = in.readLine();
  nxt = current.trans.lookup(input);
  run(nxt);
}
```

compile time

Runtime



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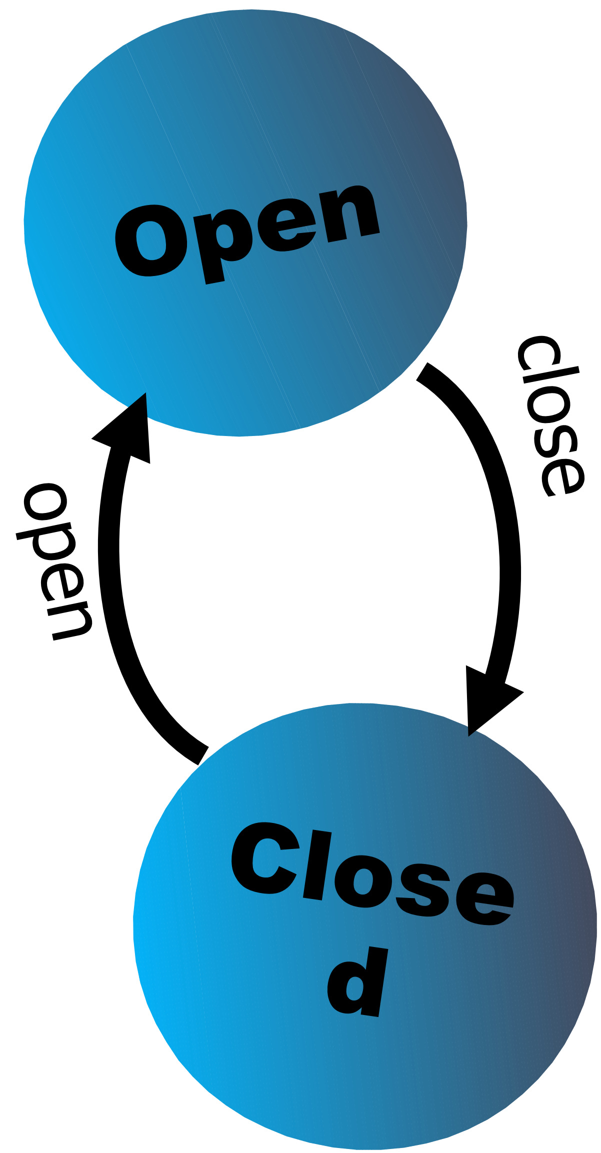
“The Trick” (Binding-time improvement)

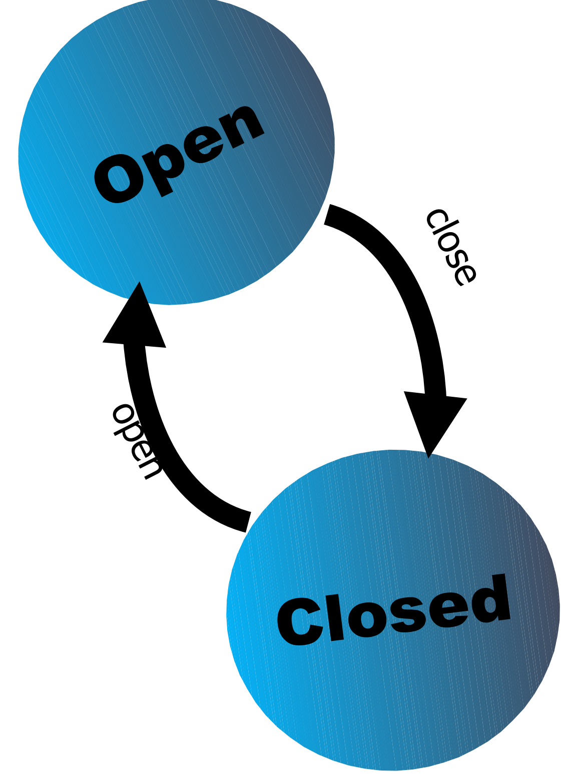
Interpreter

```
int run(State current) {
  print(current.label);
  String input = in.readLine();
  for (Trans t : current.trans)
    if (t.event == input)
      return run(t.to);
  return run(current);
}
```



Partial Evaluation

```
int runOpen() {
  print("Open");
  String input = in.readLine();
  if ("close" == input)
    return runClosed();
  return runOpen();
}
int runClosed() {
  print("Closed");
  String input = in.readLine();
  if ("open" == input)
    return runOpen();
  return runClosed();
}
```




```
int run(State current) {
  print(current.label);
  String input = in.readLine();
  for (Trans t : current.trans)
    if (t.event == input)
      return run(t.to);
  return run(current);
}
```

Goal: Partial Evaluation of WebDSL

web(UI, Schema, db, request) : HTML

UI : description of user interface (pages, sections)

schema: description of data (constraints, etc)

db : data store (described by schema)

request : an HTTP request

web : interpreter, with design knowledge

Partial Evaluation

$web_{[UI,\ Schema]}$ (db, request) : HTML
compiletime runtime

$web_{[UI,\ Schema]}$ is partial evaluation of web with respect to UI model and data schema

Supports both dynamic interpretation and compiled execution in same framework

Civet: A Partial Evaluator for Java

Civet: A Partial Evaluator for Java

Usable but not complete

Implemented as extension to javac

Testing on Real Applications

ModelTalk -- dynamic pricing application

more?

Initial results for ModelTalk (3rd party test)

Original: 3,153 ms

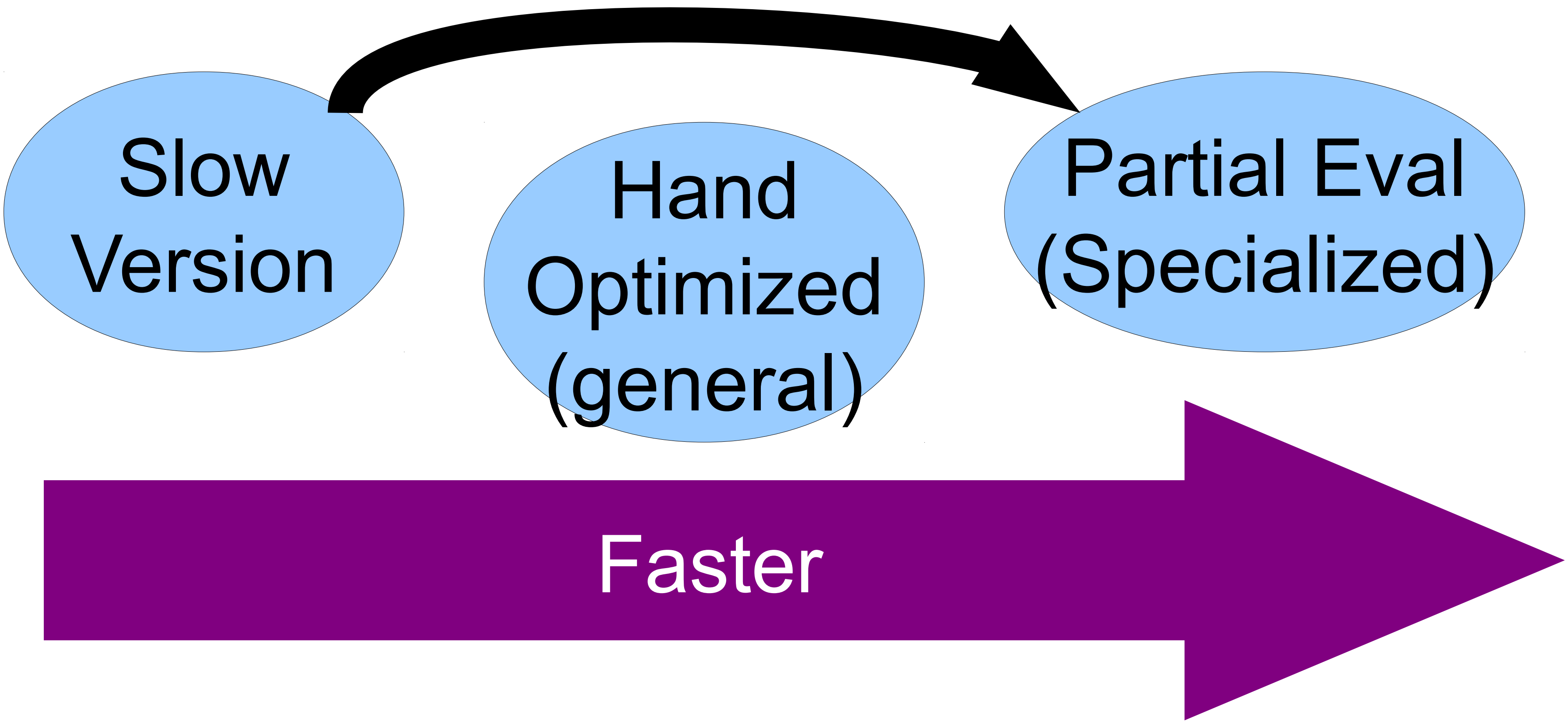
Optimized: 293 ms

Performance of RegEx example

Uses Derivative-based interpreter for regular expressions

Program	**Time (ms)**
Original regex state machine	1189
Specialized regex state machine	573
dk.brics.automaton regex library	816

Paradox of Performance with Partial Evaluation



Future

Currently AST based transformation

Should move to byte-code partial evaluation

Conclusion

Hybrid Partial Evaluation

- Online strategy
- Offline power

Practicalities

- Annotations to begin partial evaluation
- No termination guarantee
- Compile-time structures are never residualized
- Imperative effects within each stage
- Programmers must be aware of “the trick”
- No self-application (First Futamura projection only)

Futamura (1971)

Partial evaluation
of an interpreter
with respect to a program
is a
compiled version
of the program

Partial Evaluation of Interpreters

Interpreter

python("notify.pl", "in.txt") → o

Futamura Projections I

Interpreter

python("notify.pl", "in.txt") → o

First Futamura projection

peval(python, "notify.pl") → g where g("in.txt") = o

g is compiled version of notify.pl

Futamura Projections (pattern)

Interpreter

python("notify.pl", "in.txt") ➔ o

First Futamura projection

peval(python, "notify.pl") ➔ g where g("in.txt") = o

g is compiled version of notify.pl

Futamura Projections II

Interpreter

python("notify.pl", "in.txt") ➔ o

First Futamura projection

peval(python, "notify.pl") ➔ g   where g("in.txt") = o

g is compiled version of notify.pl

Second Futamura projection

peval(peval, python) ➔ c   where c("notify.pl") = g

c is a python compiler

Futamura Projections III

Interpreter

python("notify.pl", "in.txt") → o

First Futamura projection

peval(python, "notify.pl") → g where g("in.txt") = o

g is compiled version of notify.pl

Second Futamura projection

peval(peval, python) → c where c("notify.pl") = g

c is a python compiler

Third Futamura projection

peval(peval, peval) → z where z(python) = c

z is a compiler compiler!

We only need First Projection

Interpreter

python("notify.pl", "in.txt") ➔ o

First Futamura projection

peval(python, "notify.pl") ➔ g where g("in.txt") = o

g is compiled version of notify.pl

Second Futamura projection

peval(peval, python) ➔ c where c("notify.pl") = g

c is a python compiler

Third Futamura projection

peval(peval, peval) ➔ z where z(python) = c

z is a compiler compiler!

Avoid Need for Self-Applicable peval

Interpreter

python("notify.pl", "in.txt") ➜ o

First Futamura projection

peval(python, "notify.pl") ➜ g where g("in.txt") = o

g is compiled version of notify.pl

Second Futamura projection

peval(peval, python) c where c("notify.pl") = g

c is a python compiler

Third Futamura projection

peval(peval, peval) ➜ z where z(python) = c

z is a compiler compiler!

Futamura in Practice

Interpreters have "good" behavior

- Control flow depends on program first, then input
  - just like pow(n, x): control flow depends on n

Can't make good compilers via 2nd/3rd Futamura

- Trying to make a C compiler via Futamura will fail
- Was that the right goal?
  - Be careful what you pick as challenge problem

Hypothesis:

- First Futamura projection will work well enough for model interpreters
  - solves real problem, simple partial evaluator