Partial Evaluation for Class-Based Object-Oriented Languages

Ulrik P. Schultz
Center for Pervasive Computing
University of Aarhus

22 May 2001

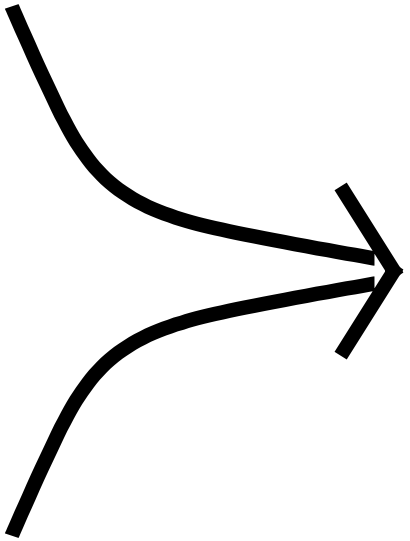
PE & OO

Partial Evaluation

inheritance vs. specialization

objects, classes, methods, ...

analysis & design



OOPE

Object-Oriented Paradigm

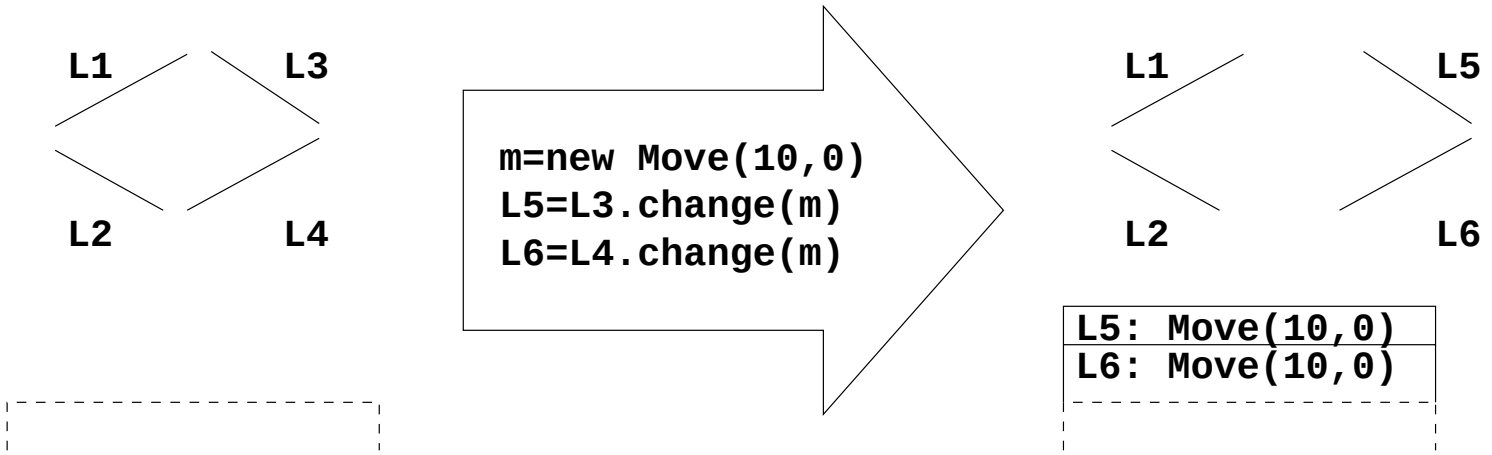
Overview

- Goals for OOPE
  - specialize programs for known input
  - specialize a program slice
- Earlier work
  - prototype PE for Java
  - specialization of typical object-oriented designs
- This work: minimal, formal, and scalable approach
- This presentation: explanation and motivation

Plan

1. An example: modifiable shapes
2. OOPE specialization approach
3. Formalization of OOPE
4. Scaling up OOPE
5. Discussion of speedups
6. Conclusion and perspectives

Example: modifiable shapes (command pattern)



Modifiable shapes, implementation

```
class Shape { Shape change(Mod m) { return ⊥; } }

class Point extends Shape {
 int x, y;
 Point(int x,int y) { this.x=x; this.y=y; }
 Shape change(Mod m) { return m.mod(this); }
}

class Mod { Point mod(Point x) { return ⊥; } }

class Swap extends Mod {
 Point mod(Point p) { return new Point(p.y,p.x); }
}
```

Example: `new Point(4,5).change( new Swap() )`

Example continued

- A new kind of shape:

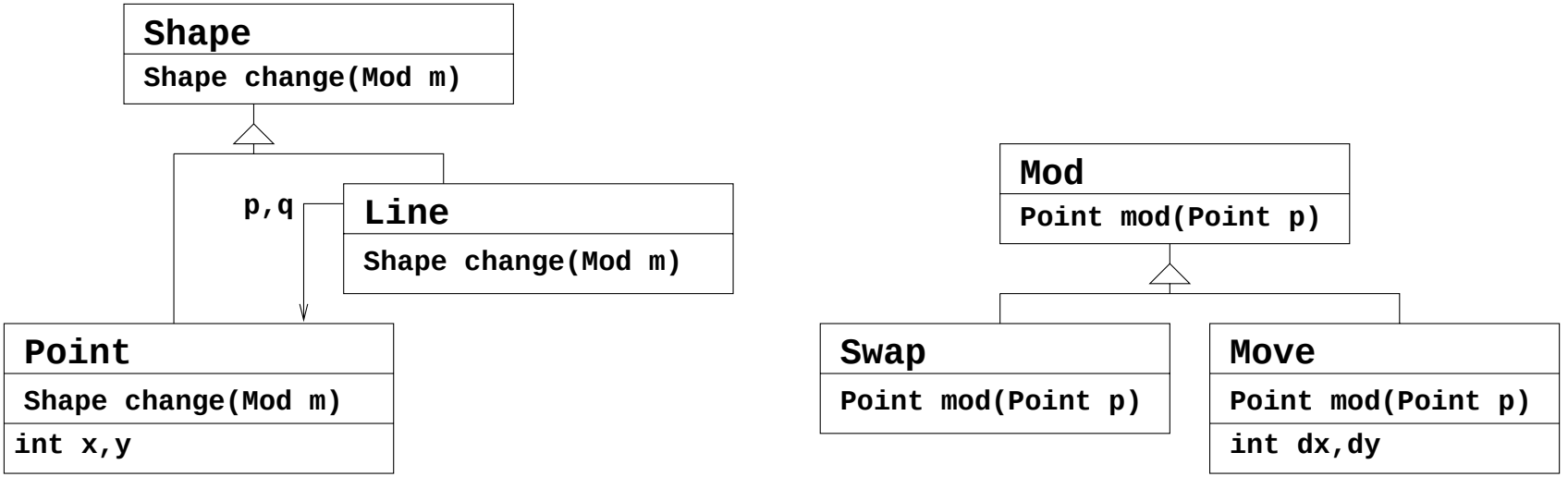
```
class Line extends Shape {
 Point p, q;
 Line(Point p,Point q) { this.p=p; this.q=q; }
 Shape change(Mod m) { return new Line( m.mod(this.p), m.mod(this.q) ); }
}
```

- A new kind of modification command:

```
class Move extends Mod {
 int dx, dy;
 Move(int x,int y) { this.dx=x; this.dy=y; }
 Point mod(Point p) { return new Point(p.x+this.dx,p.y+this.dy ); }
}
```

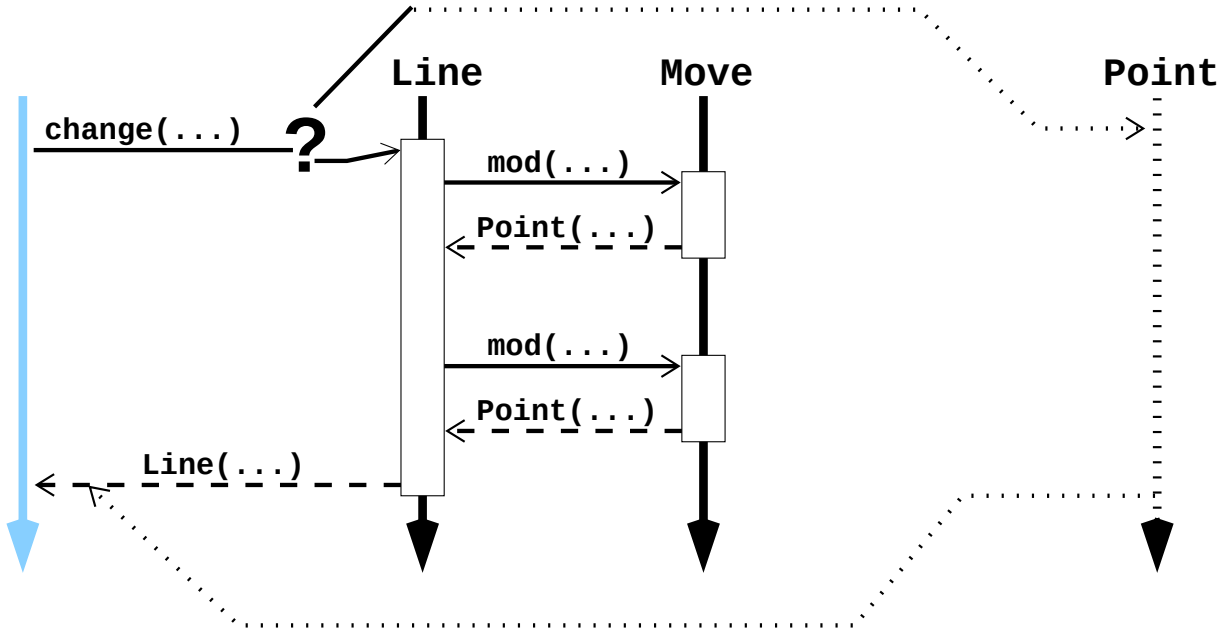
- Example: `new Line(p1,p2).change( new Move(1,1) )`

Example overview



Sample use: Moving a shape to the right

```
Shape dyn_shape = ...; dyn_shape.change( new Move(1,0) );
```



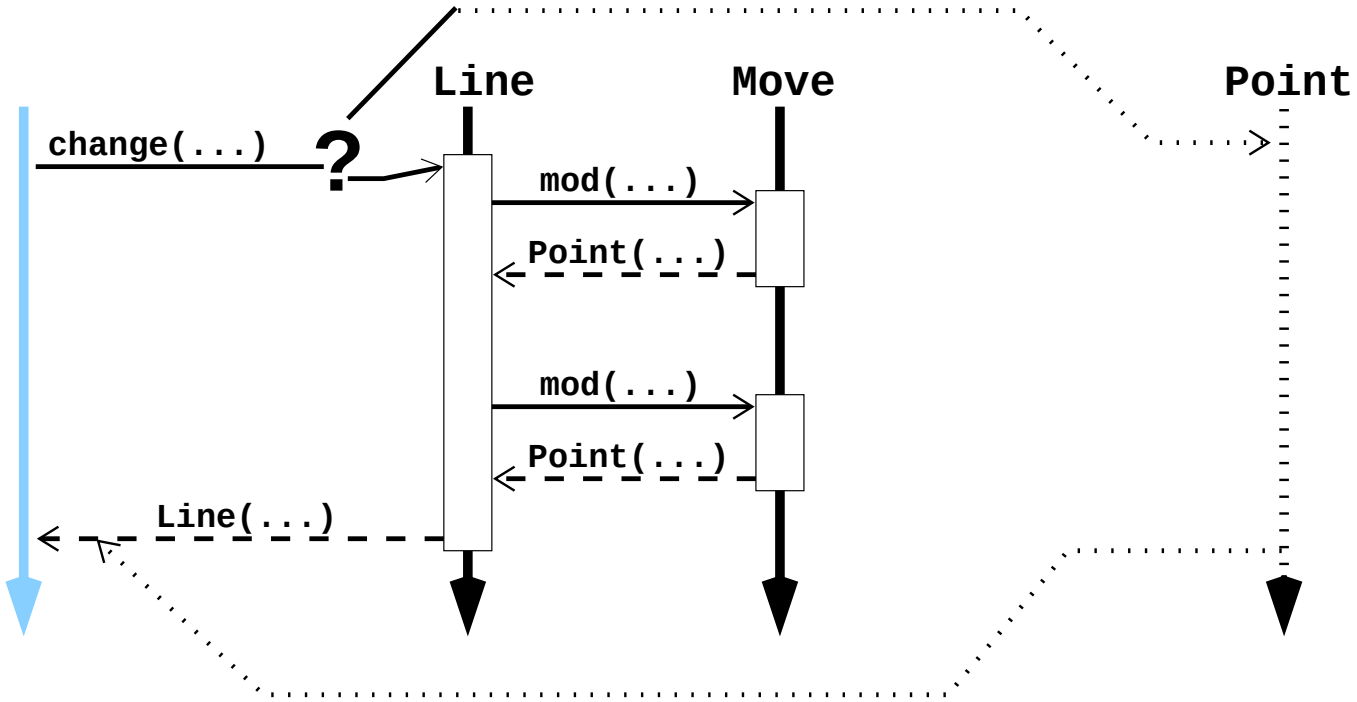
How to specialize this program?

Specializing an object-oriented program

- Execution of an OO program $\approx$ sequence interactions between objects
- Static input data makes some of these interactions static
- OOPE: specialize away static interactions,
  residualize dynamic interactions

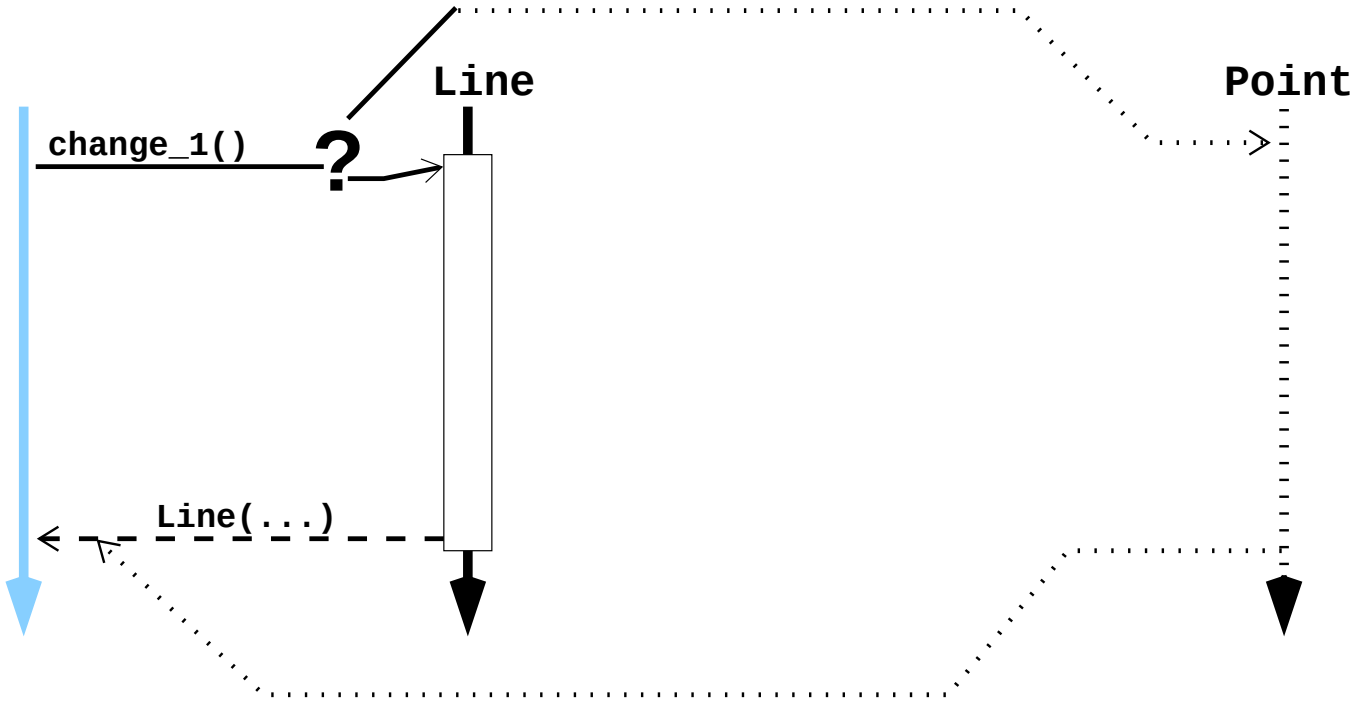
Concretely: specializing the shape example

```
Shape dyn_shape = ...; dyn_shape.change( new Move(1,0) );
```



Specialized version of the modifiable shape example

```
Shape dyn_shape = ...; dyn_shape.change_1();
```



OOPE

1: Specialize object interactions by generating specialized methods

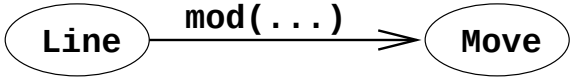
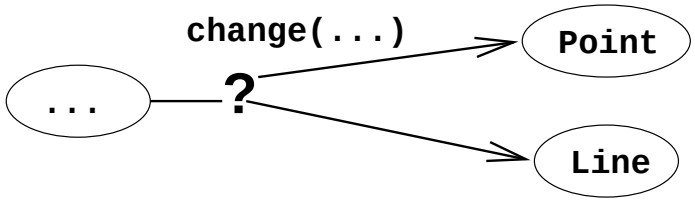
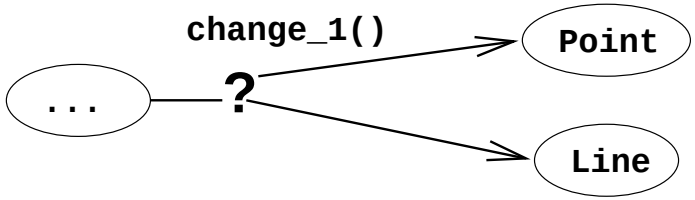
?: How to generate specialized methods?

- specialize for static "`this`" and static formal parameters
- specialize field access, virtual dispatch, functional or imperative computations

Specializing a method

- Static field accesses
  - propagate values, eliminate indirect references
- Static functional or imperative computations
  - reduce as usual
- Virtual dispatches
  - virtual dispatch $\approx$ conditional over the receiver type

Specializing a virtual dispatch

receiver has static "`this`"	receiver has dynamic "`this`"
`m.mod(this.p)` 	`dyn_shape.change(...)` 
reduce virtual dispatch, unfold `Move.mod` into caller	speculatively specialize each `change` into `change_1`, residualize call to `change_1` 

OOPE

1: Specialize object interactions by generating specialized methods

2: Specialize methods for their arguments, by specializing field access, virtual dispatching, and other computations

?: What to do with the specialized methods?

Putting the specialized methods back

- Modular specialization $\Longrightarrow$ must retain generic code

- Put methods directly into existing classes?
  - obscures program
  - complicates maintenance
  - may break encapsulation invariants

Idea: use aspect-oriented programming

- Observation: specialization *cross-cuts* the program class structure

- *Aspect-oriented programming:* modularly express program functionality that cross-cuts the program structure [Kiczales et al, ECOOP'97]

- General approach: produce specialized program in aspect language, use weaver to compile

- Concrete approach: use AspectJ language [Kiczales et al, ECOOP'01]

Result in AspectJ syntax

```
aspect Move_right {

 introduction Shape {
  Shape change_1() { return ⊥; }
 }

 introduction Point {
  Shape change_1() {
   return new Point(this.x+1,this.y+0);
  }
 }

 introduction Line {
  Shape change_1() {
   return new Line(new Point(this.p.x+1,this.p.y+0),
                   new Point(this.q.x+1,this.q.y+0));
 }

}
```

OOPE

1: Specialize object interactions by generating specialized methods

2: Specialize methods for their arguments, by specializing field access, virtual dispatching, and other computations

3: Encapsulate specialized methods in an aspect

In the paper

- Formalization of OOPE for a small Java-like language
- Discussion of scaling up the formalized OOPE to realistic scenarios
- More specialization examples (strategy and visitor)

Formalization

- Minimal Java-like language without side-effects, off-line monovariant PE
- Difficult to concisely express specialization of virtual dispatch
- Well-annotatedness and BTA straightforward
- Proof of correctness is future work

Scaling up to realistic scenarios

- Formalization does not include side-effects
- Side-effects and higher-order values together are difficult
  - Use an alias analysis to track all objects [C-Mix]
  - Use alias and type information to convert virtual dispatches into conditionals ("defunctionalize")
  - Works for Java-like language (statically typed, class based, simple type system)
- Precision of BTA: class-polyvariance, method-polyvariance, matching alias analysis, and partially static data [Tempo]

Experimental verification: JSpec

JSpec:

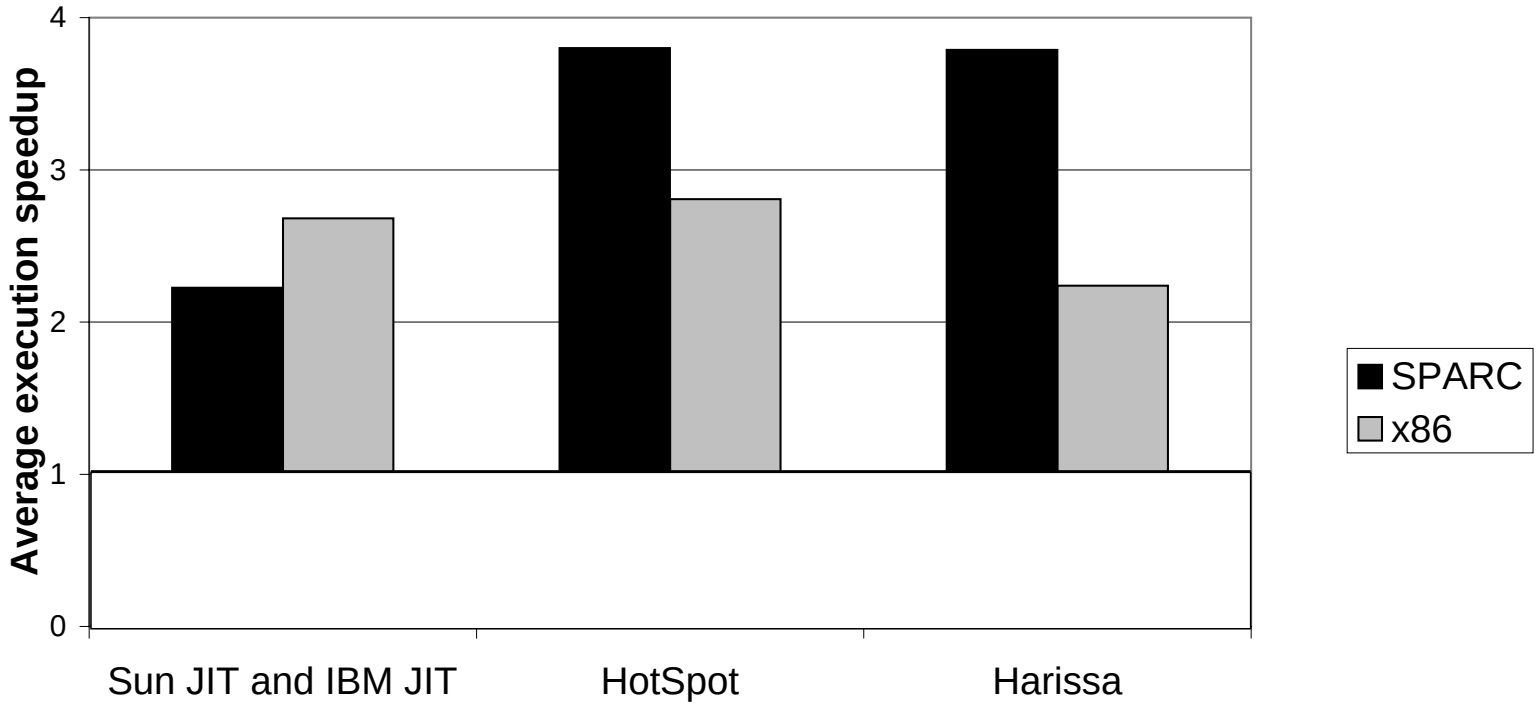
- PE for Java (excluding exception handlers and `finally`)
- Based on OOPE principles presented here; reuses Tempo through translation-based approach
- Has been successfully used to specialize "large" Java programs

Speedups?

- Object-oriented compilers such as HotSpot perform (limited) program specialization, guided by profiling

- OOPE (as embodied by JSpec):
  - more thorough and more aggressive
  - less general

Experiments with JSpec



Conclusion

- OOPE: specialize program by specializing object interactions, specialize interactions by specializing methods, and specialize a method by specializing field access, virtual dispatches, and other computations

- Aspect-oriented programming gives a convenient representation of the residual program

- OOPE has been formalized though not proven (this work), and scales up to realistic scenarios (JSpec)

Perspectives

- Improvements to OOPE as presented here. . .
  - arity raising (structure splitting)
  - modifying class definitions
  - . . .
- Specialization for other object-oriented languages
- Run-time specialization for Java

Resources

Publications on OOPE:

- [ECOOP99] Schultz, Lawall, Consel, Muller: Towards Automatic Specialization of Java Programs
- [ASE00] Schultz, Lawall, Consel: Specialization Patterns
- [PhD Dissertation] Schultz: Object-Oriented Software Engineering using Partial Evaluation

JSpec is available (version 0.2) from the JSpec home page:

`http://www.irisa.fr/compose/jspec`

All are accessible from `http://www.daimi.au.dk/~ups`

Inheritance vs. program specialization

- Differences
  - inheritance adds state and behavior
  - partial evaluation fixes state and removes generic behavior
- *Instantiation-time specialization* generates subclasses
- Appropriate form of inheritance could perhaps express method specialization

Instantiation-time specialization

Generic program

```
class Power {
 int e;
 Power(int i) { this.e=i; }
 int raise(int b) {
  int res=1, i=this.e;
  while(i-->0) res*=b;
  return res;
 }
}
...
dynamic_context(new Power(3))
```

Specialized program

```
class Power_3 {
 Power_3() { super(3); }
 int raise(int b) { super.raise(b); }
}
aspect Power_of_three {
 introduction Power {
  int raise_3(int b) {
   return b*b*b;
  }
 }
}
...
dynamic_context(new Power_3())
```

What about block structure?

Generic program	Incorrect specialization

`class A { ... }`
`class B {`
`  class C extends A {`
`   int f(...) { ... }`
`  }`
`  int f(...) { ... }`
`  A m() { return new C(); }`
`}`
`... someA.m().f(...) ...`
	`class A { ... }`
	`class B {`
	`  class C extends A {`
	`   int f(...) { ... }`
	`   int f_1(...) { ... }`
	`  }`
	`  int f(...) { ... }`
	`  A m() { return new C(); }`
	`}`
	`... ((C)(someA.m())).f_1(...) ...`

Solution: interface lifting

Correctly specialized program

```
class A { ... }
abstract class C extends A {
 abstract int f_1(...);
}
class B {
 class X extends C {
  int f(...) { ... }
  int f_1(...) { ... }
 }
 int f(...) { ... }
 A m() { return new X(); }
}
... ((C)(someA.m())).f_1(...) ...
```

JSpec

- JSpec = AspectJ ∘ Assirah ∘ Tempo' ∘ Harissa ∘ `javac`

- Tempo' = Tempo with structure polyvariance and special inlining (but still monovariant alias analysis)

Java	C
`object.field`	`object->field_id`
`object.m(x,y)`	`object->__svtable->m_id(object,x,y)` (transformed into conditional by Tempo)

Generic shape example in JSpec

```
class Point extends Shape {
 int x,y;
 Point(int x,int y) { this.x=x; this.y=y; }
 void change(Mod m) { m.mod(this); }
}

class Move extends Mod {
 int dx,dy;
 Move(int x,int y) { p.x+=this.dx; p.y+=this.dy; }
}
```

Specialized shape example in JSpec

```
aspect Move_right {
 ...
 introduction Point {
  void change_1() { this.x+=1; this.y+=0; }
 }
 ...
}
```

Extending the formalization

- Side-effects with monovariant classes:
  slightly more complex, perhaps more convincing, not really useful in practice

- Class and method polyvariance plus partially static objects:
  definitely more complex, but doable; convincing?

- All of the above (including polyvariant alias analysis):
  really hard, convincing, but useful as a formalization?

Encapsulation invariants

Generic program	Specialized program

`class Client {`
`  ...`
`  void access(Safe s) {`
`  ... s.read(key) ...`
`  }`
`}`
	`class Client {`
	`  ...`
	`  void access_1(Safe s) {`
	`  ... s.read_1() ...`
	`  }`
	`}`

`class Safe {`
`  private Object content;`
`  private int key;`
`  ...`
`  Object read(int k) {`
`  return k==this.key?this.content:null;`
`  }`
`}`
	`class Safe {`
	`  ...`
	`  Object read_1() {`
	`  return this.content;`
	`  }`
	`}`