Supporting Objects in Run-Time Bytecode Specialization

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Run-Time Specialization (RTS)

RTS optimizes program code at run-time

More precisely:

$$\text{static input} + \text{original code} \xrightarrow{\text{RTS}} \text{residual code}$$

Typical applications:

- computations done:
  - repeatedly with similar inputs
  - with an unfortunate timing
- input not available at compile-time

Motivation

Optimize object-oriented (OO) programs by RTS

OO programs are typically slower than imperative programs:

- they are more generic
- object-orientation is costly

RTS is well adapted:

- specialization trades genericity for performance
- it is a general optimization technique
- RTS has proved to be efficient for several languages

Contributions

Design and implement RTS for an OO language, namely Java:

- efficient residual code regarding OO overheads
  - elimination of dynamic allocation
  - elimination of memory accesses (including destructive updates)
  - elimination of virtual dispatches
- better automation of the specialization process
  - as few annotations by the user as possible
- correctness statement

We hope it can lead ultimately to:

- a system easier to use
- favoring extensive residual code reuse

Outline

1. **Effectiveness of OO Specialization**
2. Potential Problems with Objects
3. Techniques for Correctness and Efficiency
4. Generalization and Formalization
5. Preliminary Experiments
6. Conclusion and Future Work

Complex Arithmetic

A class for complex numbers:

```
class Complex {
  float re, im;
  Complex mul (Complex z) {
    return new Complex (...);
  }
  Complex add (Complex c) {
    return new Complex (...);
  }
}
```

A complex function:

```
// f(z,c) = z · z + c
Complex f (Complex z, Complex c) {
  Complex prod = z.mul (z);
  return prod.add (c);
}
```

Original, To-Be Optimized Application

Computation of an array of complex numbers:

```
for (int i = 0; i < n; n++) {
  c[i] = f (a[i], b[i]);
}
```

Assume that `a[i]` happens to be always i

⇒ Optimization by specialization of `f` w.r.t. its first argument

Off-Line Specialization

z static, c dynamic

```
Complex f (Complex z, Complex c) {
  Complex prod = z.mul (z);
  return prod.add (c);
}
Complex mul (Complex z) {
  return new Complex
      (re * z.re − im * z.im,
       re * z.im + im * z.re);
}
Complex add (Complex c) {
  return new Complex
      (re + c.re, im + c.im);
}
```

$z = i$

```
// f_res(c) = −1 + c
Complex f_res (Complex c) {
  return new Complex
         (−1 + c.re, 0 + c.im);
}
```

The residual code features:

- less calculations
- less object creations
- less method calls

⇒ OO specialization is effective

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One-Dimensional Geometry

A class for one-dimensional points:

```
class Point {
  int x = 0;
  void update (int a) { x = x + a; }
  static Point make (int s, int d) {
    Point p = new Point ();
    p.update (s);
    p.update (d);
    p.update (s);
    return p;
  }
}
```

Original Application

Computation of two one-dimensional points:

```
int u = Console.getInt ();
Point a = Point.make (u, 7);
Point b = Point.make (u, 11);
int v = a.x + b.x;
int w = a == b;
```

⇒ Specialization of `make` w.r.t. `u`

Naive and Incorrect Off-Line Specialization

s static, d dynamic

```
static Point make (int s , int d) {
  Point p = new Point ();
  p.update (s);
  p.update (d);
  p.update (s);
  return p;
}
```

s = 42

```
static Point make_res (int d) {
  _p.update (d);
  _p.update (42);
  return _p;
}
```

(_p is the point created during specialization; we say it is stored in the *specialization store*)

Problems with Objects

The original application cannot be simply rewritten:

```
int u = Console.getInt ();
Point a = Point.make (u, 7);
Point b = Point.make (u, 11);
int v = a.x + b.x; // 91 + 95
int w = a == b; // false
```

⇎

```
int u = Console.getInt ();
Point a = make_res (7);
Point b = make_res (11);
int v = a.x + b.x; // 144 + 144
int w = a == b; // true
```

Original cause: Application, specializer and residual code share the same heap

Approaches

Immediate approaches:

- perform over-specialization
- require annotations by the user
- enforce residualization

⇒ None is satisfactory

Our approach:

- as few annotations as possible
- efficiency achieved by improving specialization rules

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About Specialization Rules (1/2)

Main idea:
distinguish operations in terms of staticness

For instance, memory accesses as in statements of the form:

$$\mathit{lhs} = \mathtt{p.x};$$

- if `p.x`, then the memory access can be evaluated during specialization
- if `p.x`, then the memory access must be residualized during specialization

But in general, this static/dynamic dichotomy is not sufficient

About Specialization Rules (2/2)

Key idea:
distinguish operations in terms of visibility

For instance, (static) object creations as in statements of the form:

$$lhs = \texttt{new}\ class\_name(\ldots);$$

or (static) destructive updates as in statements of the form:

$$\texttt{p.x} = rhs;$$

- if visible, residualization and evaluation during specialization
- if invisible, evaluation during specialization

“If Visible, Residualization and Evaluation”

s static, d dynamic

```
static Point make (int s, int d) {
  Point p = new^VIS Point ();
  p.update (s);
  p.update (d);
  p.update (s);
  return p;
}
```

s = 42

```
static Point make_res (int d) {
  Point p = new Point ();
  p.x = 42 + d;
  p.x = p.x + 42;
  return p;
}
```

- Enforced residualization guarantees *correctness*
- Evaluation during specialization enables *efficient* residual code

“If Invisible, Evaluation” (1/2)

Extraction of small segments:

```
Set set = new Set ();
for (int i = 0; i < n; i++) {
  if ( areClose  (a[i ], b[i]))
    set.add (new Segment (a[i], b[i]));
}
```

Assume that `a[i]` happens to be always 42

⇒ Optimization by specialization of `areClose` w.r.t. it first argument

“If Invisible, Evaluation” (2/2)

s static, d dynamic

```
boolean areClose (int s, int d) {
  Point a = new^INVIS Point ();
  Point b = new^INVIS Point ();
  a.update (s);
  b.update (d);
  return a.distance (b) < 10;
}
```

s = 42

```
boolean areClose_res (int d) {
  _b.update (d);
  return _a.distance (_b) < 10;
}
```

(_b and _a are the points stored in the specialization store)

- Reuse of objects yield more *efficient* residual code
- Specialization of destructive updates does not infringe *correctness*

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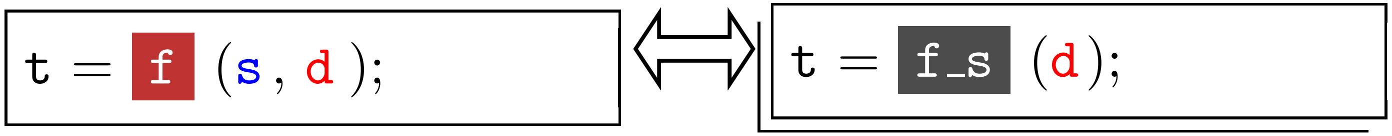
Correctness Statement for RTS

Two components:

1. **valid code replacement :**
   the residual code may substitute for the original code
   whenever the static input is used
2. **valid specialization usage :**
   RTS may happen
   as soon as the static input is available

Valid Code Replacement

Mix equation (reminder):



`t = f (s, d);` ⟺ `t = f_s (d);`

Valid Code Replacement

Mix equation (extended with heaps):

$$\boxed{(\mathtt{t}, H_t) = \mathtt{f}\ (\mathtt{s}, H_s\ ,\ \mathtt{d}, H_d\ );} \iff \boxed{(\mathtt{t}, H_t) = \mathtt{f}_{\mathtt{s},H_s}\ (\mathtt{d}, H_d\ );}$$

⇒ Describe arguments and results in terms of:

- *heap equivalence* (including a notion of *reachability*)
- additional requirements for the values of references
  - because of *reference lifting*
  - because references can be compared

(see the paper for more details)

Valid Code Replacement

Example:

```
Point a = Point.make (s, d);
```

⟺

```
Point a' = make_res (d);
```

Condition on arguments:
`s` is expected to be indeed 42

Condition on results:
Points `a` and `a'` must have the same coordinate

Additional requirement:
`a` and `a'` must be *fresh* references

Valid Specialization Usage

Informally:

$statement_1$;
`f_s` = *spec* (`f`, `s`);
$statement_2$;
$statement_3$;
`t` = `f_s` (`d`);

$\Longleftrightarrow$

$statement_1$;
$statement_2$;
`f_s` = *spec* (`f`, `s`);
$statement_3$;
`t` = `f_s` (`d`);

⇒ Specify the interactions between specialization and the application:

- *specialization* cannot break the semantics of the *application*
- the *application* cannot break the semantics of *specialization*

Valid Specialization Usage

Example:

$statement_1$;
`make_res` $=$ $spec$ (`make`, `s`);
$statement_2$;
$statement_3$;
`Point a` $=$ `Point.make_res` (`d`);

$\Longleftrightarrow$

$statement_1$;
$statement_2$;
`make_res` $=$ $spec$ (`make`, `s`);
$statement_3$;
`Point a'` $=$ `make_res` (`d`);

Condition on the interaction:
$spec$ cannot perform *visible* side-effects

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Implementation Strategy

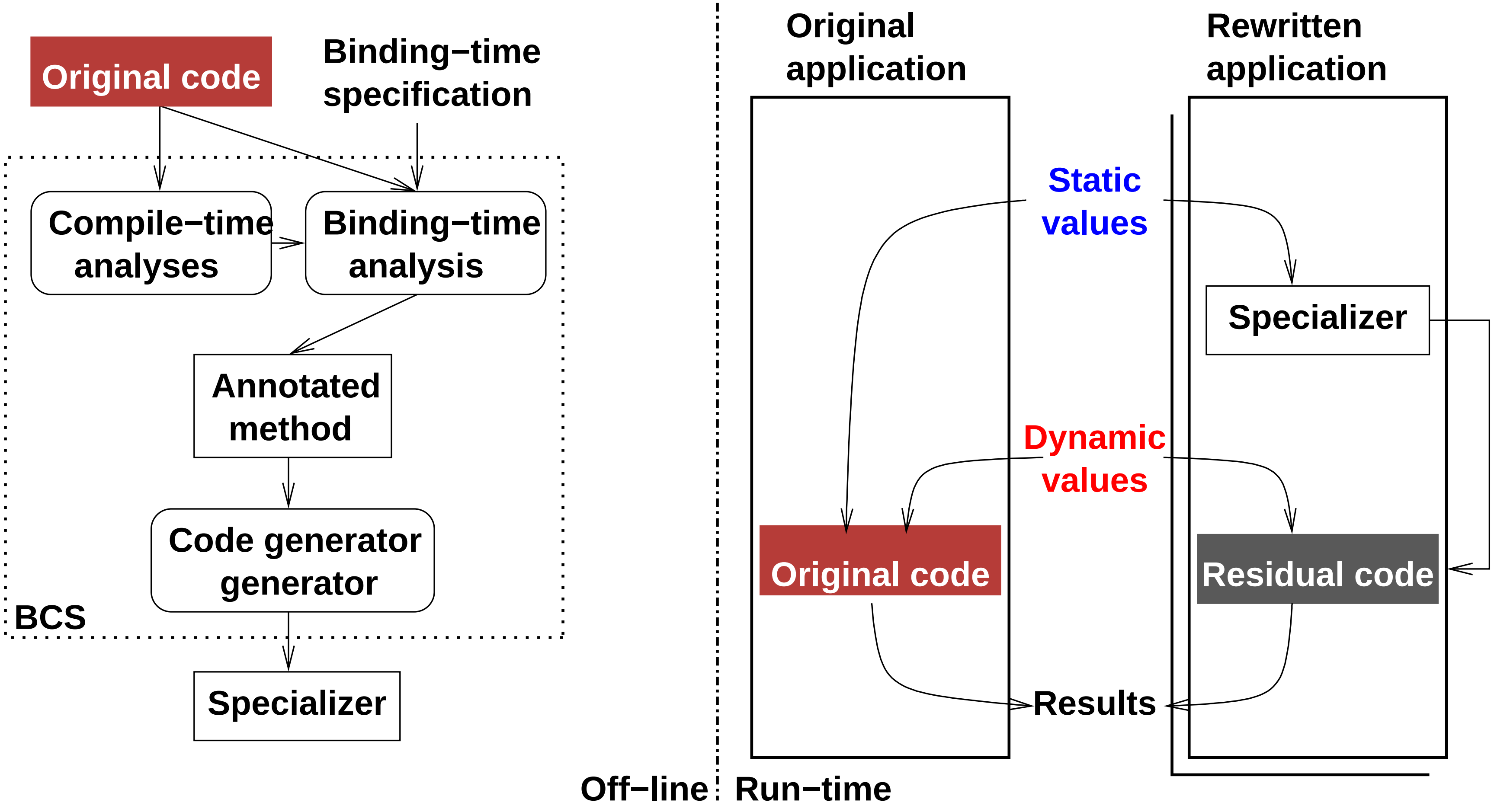
Based on Masuhara and Yonezawa's BCS:

- RTS for the Java bytecode language
- end-to-end bytecode-level approach:
  - type-based binding-time analysis
  - cogen-by-hand approach
  - run-time code generation

Extended to:

- an OO subset of the Java bytecode language
- new rules for binding-time analysis and code generation
- interface with compile-time analyses

Implementation Overview



Original code

Binding−time specification

Compile−time analyses

Binding−time analysis

Annotated method

Code generator generator

BCS

Specializer

Off−line

Run−time

Original application

Rewritten application

Static values

Specializer

Dynamic values

Original code

Residual code

Results

Performance Measurements

Test Programs:

Object-oriented version of standard applications:

- Power function
- Mandelbrot sets drawer
- Ray tracer

Environment for Experiments:

Standard virtual machines with Just-in-time compilation

Power Function

		Speed-up `raise`/`raise_res`	
		Recursive	Iterative
UltraSparc	Hotspot (Sun 1.3)	*5.4*	*1.5*
Intel x86	Hotspot (Sun 1.3)	*1.9*	*1.3*
Intel x86	Classic (IBM 1.3)	*5.9*	*4.4*

Mandelbrot Sets Drawer

		Speed-up `eval`/`eval_res`
UltraSparc	Hotspot (Sun 1.3)	*1.07*
Intel x86	Hotspot (Sun 1.3)	*0.95*
Intel x86	Classic (IBM 1.3)	*1.05*

Ray Tracer

		Speed-up `closest`/ `closest_res`	Overhead (ms)		
			Specialization	JIT	
				Subject method	Residual code
UltraSparc	Hotspot (Sun 1.3)	*1.18*	10	196	200
Intel x86	Hotspot (Sun 1.3)	*1.25*	7	115	100
Intel x86	Classic (IBM 1.3)	*1.26*	6	208	557

	Break-even points	
	No JIT overhead	JIT overhead
Hotspot (Sun 1.3)	5,646 $\sim$ 138,421	$< 0 \sim$ 9,755
Classic (IBM 1.3)	277,582	174,939

Measurements' Summary

Speed-ups are comparable to related work:

- compile-time specialization for Java
- run-time specialization for C++

The environment for experiments complicates interpretation:

- unfriendly environment:
  - dynamic compilation → more overhead
  - small time window → less optimizations
- overlapping optimizations
- behavior hard to predict

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Related Work: Compile-time Techniques

Compile-time specialization for C:

- C-Mix [Andersen93]
- Tempo [Consel & Noël96]

Specialization and object-orientation:

- Elimination of virtual dispatches [Lea90, Dean et al.94]
- Partial evaluation formalization and implementation [Schultz99-01]

Partial evaluation during interpretation:

- Correctness and experiments [Asai01]

Related Work: Run-time Techniques

Run-time specialization for imperative languages:

- Tempo [Consel & Noël96]
- DyC [Grant et al.97]
- BCS [Masuhara & Yonezawa01]

Run-time specialization for object-oriented languages:

- C++ [Fujinami98]
- Specialization classes [Volanschi et al.97]

Conclusion

Design RTS for an OO subset of Java:

- efficient residual code regarding OO operations
- better automation of the specialization process
- correctness statement

Experimental implementation:

- end-to-end bytecode-level approach
- effective in practice (e.g., 26% speed-up for a ray tracer)

Future Work

Complete the implementation:

- access modifiers, constructors, . . .

Increase effectiveness:

- selective inlining
- allow visible side-effects during specialization

Reuse of objects in the specialization store as presented here:

- is not thread-safe
- may withhold many objects

Formal proof of correctness