Constant Propagation w/ SSA- and Predicated SSA Form

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This is joint work with Oliver Rüthing
Outline of the Talk

- Part I: Constant Propagation
- Part II: Constant Propagation w/ SSA Form
- Part III: Constant Propagation w/ Predicated SSA Form
Part I: Constant Propagation
Constant Propagation

The very idea...

Original program

After simple constant propagation
Constant Propagation Reconsidered

Remember

- Kildall’s algorithm for simple constants (SC) (POPL’73)

and Kenneth’s talk on Monday morning on further attacks...

- Wegbreit (1st attack)
- Lewis, Tarjan, and Reif (2nd attack)
- Wegman and Zadeck (3rd attack)
- ...
Advancements of Kildall’s work on SC aimed at...

- **Scope**
  - **Interprocedurally**
    Callahan, Cooper, Kennedy, Torczon (SCC’86)
    Grove, Torczon (PLDI’93)
    Metzer, Stroud (LOPLAS, 1993)
    Sagiv, Reps, Horwitz (TAPSOFT’95)
    Duesterwald, Gupta, Soffa (TOPLAS, 1997)
  - **Explicitly parallel**
    Lee, Midkiff, Padua (J. of Parallel Prog., 1998)
    Knoop (Euro-Par’98)
Constant Propagation Reconsidered (Cont’d)

- **Performance**
  - **SSA**: Wegman, Zadeck (POPL’85)

- **Expressivity**
  - “SC+”: Kam, Ullman (Acta Inf., 1977)
  - **Conditional Constants**: Wegman, Zadeck (POPL’85)
  - **Finite Constants**: Steffen, Knoop (MFCS’89)
Why Striving for Greater Expressivity?

a) Original program

b) After simple constant propagation

It’s ok, isn’t it?
Actually, it is not

Simple constants are weak...

After simple constant propagation
(Note: No effect at all!)

After simple constant propagation
enhanced by the "look-ahead-of-one" heuristics of Kam and Ullman
Decidability Issues of Constant Propagation

As a matter of fact...

- Constant propagation is undecidable

On the other hand...

- Constant propagation is decidable on DAGs
Finite Constants (FC)

...are optimal on DAGs!
Finite Constants (Cont’d)

Intuitively

- FC are a systematic, exhaustive, and finitely computable extension of Kam&Ullman’s “look-ahead of one” heuristics

Key Facts on Finite Constants

- Proper extension of SC for unrestricted control flow
- Optimal on DAGs
- Exponential worst-case time complexity (even on DAGs)
Note

- Constant Propagation on DAGs is Co-NP-Complete

Knoop, Rüthing (CC’00)
Müller-Olm, Rüthing (ESOP’01)
Reconsidering the Running Example

a) Failed to be detected!

After simple constant propagation
(Note: No effect at all!)

b) Failed to be detected!

After simple constant propagation
enriched by the "look-ahead-of-one" heuristics
of Kam and Ullman

c) The effect of the new algorithm
A New CP Algorithm

...carefully balancing

- Expressivity and Performance

This new algorithm is...

- based on the Value Graph of Alpern, Wegman, and Zadeck (POPL’88)
- which itself is based on SSA

Hence: CP w/ SSA form (instead of on SSA form)
Part II: Constant Propagation w/ SSA Form
Own Work Related to Part II of the Talk

Joint work with Oliver Rüthing...

- Constant Propagation w/ SSA Form
The Value Graph of Alpern, Wegman, and Zadeck

Original Program  SSA Form  Value Graph

1) $x := x - 1$
2) $x := x + 1$
3) $x := 0$

$\Phi$
Constant Propagation on the Value Graph

After the initialization step

After the 1st iteration step

After the 2nd iteration step

After the 3rd iteration step: Stable

Hence: $x_2$ and $x_3$ have constant values!
Constant Propagation on the Value Graph

...comes in two flavours

- The Basic Algorithm
  ...computes SC

- The Full Algorithm
  ...goes beyond and integrates the look-ahead heuristics
A New Example for Illustrating the Full Algorithm

Original Program  SSA Form  Value Graph
The Full Algorithm on the Value Graph

Clou: Introducing $\Phi$-Constants and
Adapting the Evaluation Function on Value Graphs!
Main Results

Unrestricted Control-Flow...
- The full algorithm detects a superset of SC (even constants, which are no finite constants!)

Acyclic Control-Flow...
- The full algorithm detects every constant, which is only composed of operators, which are injective in their relevant arguments

Overall...
- Nicely balances expressivity and performance
- SSA and the Value Graph are key
Part III: Constant Propagation w/ Predicated SSA Form
Own Work Related to Part III of the Talk

Joint work with Oliver Rüthing...

- Constant Propagation w/ Predicated SSA Form
Predicated Code

cmp.unc p,q = a<b

(p) x = ...

(q) x = 3

(p) y = x+3

...resulting from if-conversion.
Performing CP Naively on Predicated Code Fails...

a)  
cmp.unc p,q = a<b  
(p) x = ...  
(q) x = 3  
(p) y = x+3

b)  
cmp.unc p,q = a<b  
(p) x = ...  
(q) x = 3  
(p) y = 6
...naive sound CP is likely to be too conservative and to miss many optimization opportunities!
Workplan: Handling Predicated Code more Smartly

Hyperblocks

...important building blocks in predicated code.
A Hyperblock

Single entry, multiple exits...

```
A
 a = random()
 b = random()
 c = 3
 d = > 0 ?

B
 x = 3
 y = 3

C
 b > 0 ?

D
 x = 3
 y = 2

E
 z = 2
 x = 4
 y = 1

F
 odd(z) ?

G
 u = 5
 v = 7
 w = z mod 2

H
 u = 7
 v = 5
 w = x

J
 s = x+u
 i = y+v
 z = s+t
```
Embedded into a Program

The running example...

```
b > 0 ?
  C
  H
  w = x
  v = 5
  u = 7

x = 3
y = 2
D
x = 2
y = 3
B
b = random()
z = 3
a > 0 ?
  a = random()

odd(z) ?
  F
  y = 1
  x = 4
  z = 2
E
  v = 7
  u = 5

J
  z = s + t
  t = y + v
  s = x + u
```

Hyperblock

Hyperblock

Hyperblock

Hyperblock

Hyperblock

Hyperblock
The New CP Algorithm on Predicated Code

...comes in two/plus flavours

• The Basic Algorithm
• The Full Algorithm

plus

• Performance-tuned Variants

Each consisting of a

• global
• local

stage.
Discussing the Local Stage

The hyperblock we will focus on...

Original Hyperblock
Optimization of the Basic Algorithm

The Non-Deterministic Path-Precise Basic Optimization
Optimization of the Full Algorithm

The Deterministic Path–Precise
Full Optimization
Optimizations of Basic and Full Alg. at a Glance

b) A
\[ a = \text{random()} \]
\[ b = \text{random()} \]
\[ z = 3 \]
\[ a > 0 ? \]

B

\[ x = 2 \]
\[ y = 3 \]

true
false

C

\[ b > 0 ? \]

D

\[ x = 3 \]
\[ y = 2 \]

true
false

E

\[ z = 2 \]
\[ x = 4 \]
\[ y = 1 \]

F

odd(z) ?

G

\[ u = 5 \]
\[ v = 7 \]
\[ w = z \text{ mod } 2 \]

H

\[ u = 5 \]
\[ v = 7 \]
\[ w = x \]}

J

\[ s = x + u \]
\[ t = y + v \]
\[ z = 17 \]

The Non–Deterministic Path–Precise
Basic Optimization

The Deterministic Path–Precise
Full Optimization

The Non–Deterministic Path–Precise
Optimizations of Basic and Full Alg. at a Glance

Original Hyperblock

The Non-Deterministic Path—Precise
Basic Optimization

The Deterministic Path—Precise
Full Optimization
begin \ \ Original Hyperblock | begin \ \ After if-Conversion
(a,b) = (random(),random()); | (p0) (a,b) = (random(),random());
z = 3; | (p0) z = 3;
if a>0 then | (p0) cmp.unc B,C (a>0);
x = 2; | (B) x = 2;
y = 3 | (B) y = 3;
elsif b>0 then | (C) cmp.unc D,E (b>0);
x = 3; | (D) x = 3;
y = 2 | (D) y = 2;
else | (E) z = 2;
z = 2; | (E) x = 4;
x = 4; | (E) y = 1;
y = 1 fi; | (E) w = x fi;
if odd(z) then | (p0) cmp.unc G,H (odd(z));
u = 5; | (G) u = 5;
v = 7; | (G) v = 7;
w = z mod 2 | (G) w = z mod 2;
else | (H) u = 7;
u = 7; | (H) v = 5;
v = 5; | (H) w = x;
w = x fi;
s = x+u; | (p0) s = x+u;
t = y+v; | (p0) t = y+v;
z = s+t end. | (p0) z = s+t end.
Predicated SSA

...by Carter, Simon, Calder, Ferrante (PACT’99)
begin (p0)  A = OR(TRUE);
    (A)  (a1,b1) = (random(),random());
    (A)  z1 = 3;
    (A)  cmp.unc BA,CA (a1>0);
    (p0)  B = OR(BA);
    (p0)  C = OR(CA);
    (B)  x1 = 2;
    (B)  y1 = 3;
    (C)  cmp.unc DCA,ECA (b1>0);
    (p0)  D = OR(DCA);
    (p0)  E = OR(ECA);
    (D)  x2 = 3;
    (D)  y2 = 2;
    (E)  z2 = 2;
    (E)  x3 = 4;
    (E)  y3 = 1;
    (BA)  FBA = OR(TRUE);
    (DCA)  FDCA = OR(TRUE);
    (ECA)  FECA = OR(TRUE);
    (p0)  F = OR(FBA,FDCA,FECA);
    (FBA)  cmp.unc GFBA,HFBA (odd(z1));
    (FDCA)  cmp.unc GFDCA,HFDCA (odd(z1));
    (FECA)  cmp.unc GFECA,HFECA (odd(z2));
    [+] (p0)  G = OR(GFBA,GFDCA,GFECA);
    [+] (p0)  H = OR(HFBA,HFDCA,HFECA);
    (GFBA)  w1 = z1 mod 2;
    (GFDCA)  w1 = z1 mod 2;
    [+] (GFECA)  w1 = z2 mod 2;
    (G)  u1 = 5;
    (G)  v1 = 7;
    (J)  z3 = s1+t1;
end.
The Basic Predicated Value Graph based on PSSA Form

W/out taking advantage of guarding predicates...
After CP on the Basic PVG / Basic Algorithm
Optimization of the Basic Algorithm

Original Hyperblock

The Non-Deterministic Path-Precise Basic Optimization
The Predicated Value Graph

Taking advantage of guarding predicates...
After CP on the PVG / Full Algorithm
Optimization of the Full Algorithm

Original Hyperblock

The Deterministic Path–Precise Full Optimization
The Optimized Hyperblock in PSSA Form
begin (p0) A = OR(TRUE);
(A) a1 = random();
(A) b1 = random();
(A) z1 = 3;
(A) cmp.unc BA, CA (a1 > 0);
(p0) B = OR(BA);
(p0) C = OR(CA);
(B) x1 = 2;
(B) y1 = 3;
(C) cmp.unc DCA, ECA (b1 > 0);
(p0) D = OR(DCA);
(p0) E = OR(ECA);
(D) x2 = 3;
(D) y2 = 2;
(E) z2 = 2;
(E) x3 = 4;
(E) y3 = 1;
(BA) FBA = OR(TRUE);
(DCA) FDCA = OR(TRUE);
(ECA) FECA = OR(TRUE);
(p0) F = OR(FBA, FDCA, FECA);
(FBA) cmp.unc GFBA, HFBA (TRUE));
(FDCA) cmp.unc GFDCA, HFDC (TRUE);
(FECA) cmp.unc GFEC, HFEC (FALSE);

[-] (p0) G = OR(GFBA, GFDCA);
[-] (p0) H = OR(HFECA);
(G) w1 = 1;
(G) u1 = 5;
(G) v1 = 7;
(HFEC) w2 = 4;
(H) u2 = 7;
(H) v2 = 5;
(GFBA) JGFBA = OR(TRUE);
(GFDCA) JGFDC = OR(TRUE);
(HFEC) JHFEC = OR(TRUE);
[-] (p0) J = OR(JGFBA, JGFEC, JHFEC);

end.
Main Results

Soundness

- The global CP-Algorithm is sound (for both the basic and full algorithm of the local stage)

Completeness/Optimality

- The basic algorithm of the local stage is trace-precise wrt non-deterministic interpretation of branches
- The full algorithm of the local stage is predicate-sensitive trace-precise
Tuning the Performance: Basic Algorithm
Tuning the Performance: Basic Alg. (Cont’d)
Tuning the Performance: Full Algorithm
Tuning the Performance: Full Alg. (Cont’d)
Conclusions

Constant Propagation and SSA/PSSA...

- a perfect match – SSA/PSSA really help!
- Key: Value Graph and Predicated Value Graph

Open to extensions, e.g.

- Value Graph: Conditional Constants

Overall

- Especially neat example demonstrating the benefits of SSA
Constant Propagation w/SSA on the Value Graph

...with Triple E Rating: Expressive, Efficient, Easy!

After the initialization step
After the 1st iteration step
After the 2nd iteration step
After the 3rd iteration step: Stable
Interests – Final Slide

In general...

- programming languages, compilers and everything related to it, especially
  - program analysis, transformation/optimization
  - WCET analysis
Regarding SSA...

SSA & SSA extensions

- as intermediate program representation

and their usage/applications in

- program analysis, transformation/optimization