The Hot Path SSA Form in LLVM

Algorithms & Applications

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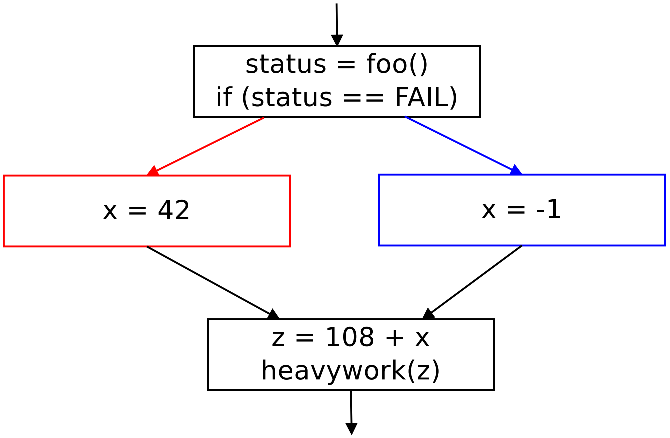
Outline

A case for profile-guided optimizations (PGO)



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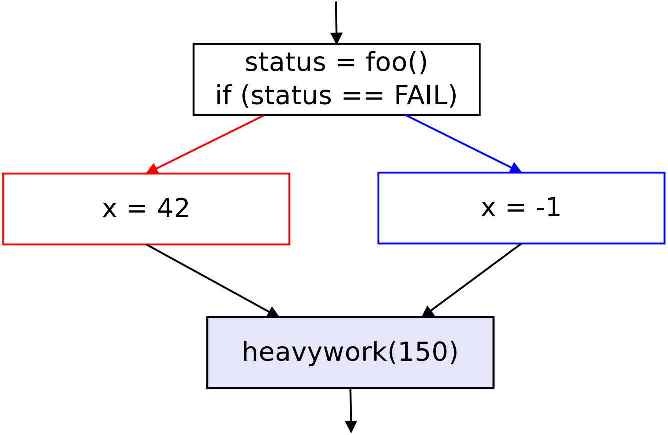
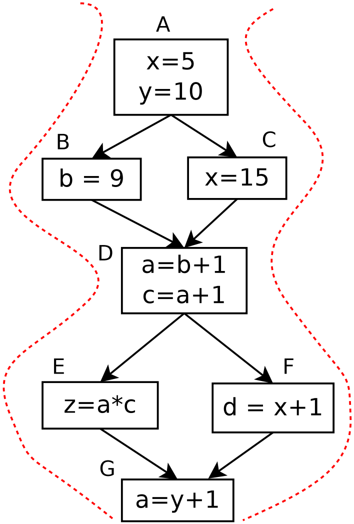


Profile-guided analysis on paths



Summary

- Profile-guided analysis across paths is stronger—can capture correlations between control-flow of basic-blocks
- Collecting path-profiles seems challenging—requires "recording" of a sequence of basic-blocks

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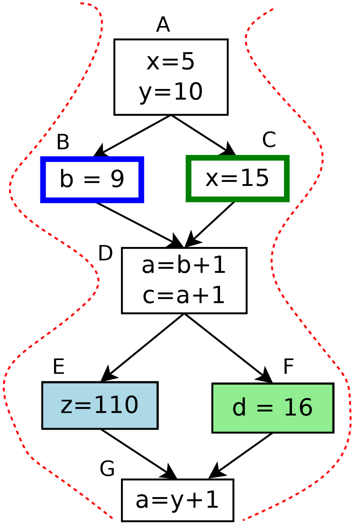

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Profiling acyclic paths

Ball-Larus Acyclic Profiling [Ball & Larus, MICRO'96]

- Core idea: assign an identifier to each path, that can be calculated efficiently at runtime
- Record frequencies against these identifiers (instead of a sequence of node identifiers)

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Capturing still longer paths (k-iteration paths)

- Allows capturing correlations across loop iterations [Roy & Srikant, CGO'09]; a generalization of the Ball-Larus algorithm
- Subsequent work by other groups [D'Elia & Demetrescu, OOPSLA'13]; uses a prefix forest to record BL paths

Profile-guided analyses

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  - Can impact code size (significant impact w/o speculation support in hardware)

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- **Error resilient modules**
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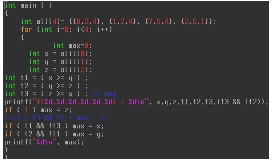
- **Optimizations that don't impact correctness**
  - eg. register allocation
  - No impact on code size

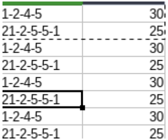
Outline

Why is path-profile-guided analysis hard?

disparate data-structures: program + profile



```
int main ( )
{
    int a[][4]= {{8,2,4}, {1,2,4}, {7,5,4}, {2,5,1}};
    for (int i=0; i<4; i++)
    {
            int max=0;
       int x = a[i][0];
       int y = a[i][1];
       int z = a[i][2];
int t1 = ( x >= y ) ;
int t2 = ( y >= z ) ;
int t3 = ( z >= x ) ; // bug
printf("f(%d,%d,%d,%d,%d,%d) = %d\n", x,y,z,t1,t2,t3,(t3 && !t2));
if ( 1 ) max = z;
//if ( t3 && t2 ) max = z;
if ( t1 && !t3 ) max = x;
if ( t2 && !t1 ) max = y;
printf("%d\n", max);
}
}
```



1-2-4-5	30
21-2-5-5-1	25
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Why is path-profile-guided analysis hard?

- There has been enough interest in path-profile-guided analysis and optimizations....
- ...however, designing path-profile-guided variants of traditional optimizations remained hard
- ...hard enough to justify *publications per optimization*
  - Gupta, Benson, Fang. Path profile guided partial dead code elimination using predication. PACT '97.
  - Gupta, Benson, Fang. Path profile guided partial redundancy elimination using speculation. ICCL '98.
  - ...

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Can we **weave** profile information into the program representation

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... that provides the convenience and elegance of an **SSA-like** intermediate form

...allowing the design of profile-guided versions of “traditional” optimizations with **trivial algorithmic modification** of the base algorithms

...providing a **common representation** for both “traditional” as well as profile-guided analysis and optimizations

Semantics of a ϕ-function

$$y = \phi(x_1, x_2, \ldots, x_n)$$

The Hot Path SSA Form (HPSSA)

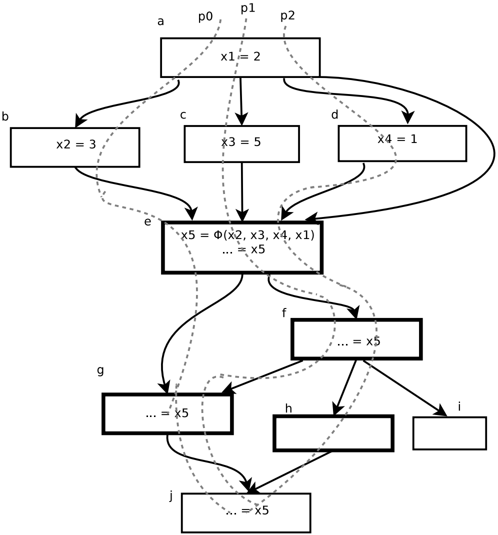
Semantics of a ϕ-function

$y = \phi(x_1, x_2, \ldots, x_n)$

Semantics of a τ-function

$$\tau(x_0, x_1, x_2, \ldots, x_n) = \begin{cases} x_0 & \text{safe interp.} \\ \phi(x_1, x_2, \ldots, x_n) & \text{speculative interp.} \end{cases}$$

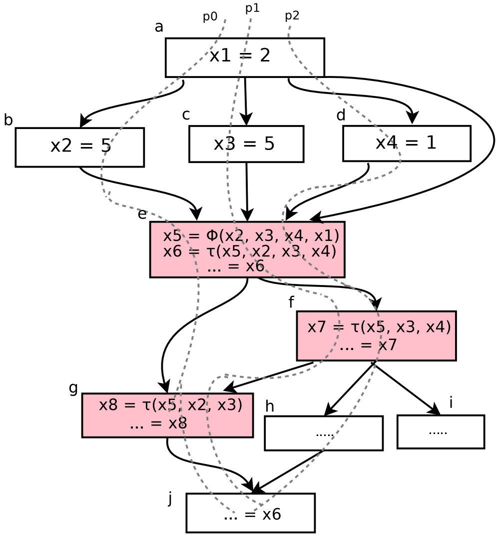
The SSA form



No frequent path carrying:

- def $x_2 = 3$ to use at block **f**
- def $x_4 = 1$ to use at block **g**
- def $x_1 = 2$ to either **f** or **g**

The Hot Path SSA Form



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If a program is in the Hot Path SSA form, then,

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- each use of a variable is reachable by a single definition; [SSA-like form]
- **safe interpretation**: [supports traditional analysis]
  - each use of a variable is reachable by the *meet-over-all-paths* reaching definition chains;
- **speculative interpretation**: [supports profile-guided analysis]
  - each use of a variable in a basic-block is reachable by the *meet-over-frequent-paths* reaching definitions. [a]

[a] or the meet-over-all-paths reaching definition chains, if the use is not reachable from any meet-over-hot-paths reaching definition chain

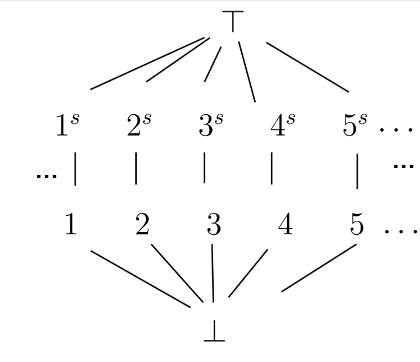
Speculative Sparse Conditional Constant Propagation (SpecSCCP)

- Introduce new speculative values $\{\ldots, 1^s, 2^s, \ldots\} \in C^S$
- Operation with *speculative* values result in *speculative* results (with same semantics as base operator)

$$\alpha^s \ \langle op \rangle \ \beta = (\alpha \ \langle op \rangle \ \beta)^s$$

- Transfer function for τ-functions
($\beta = x_1 \sqcup x_2 \sqcup \cdots \sqcup x_n$, i.e. join of speculative args.)

$$\tau(x_0, x_1, \ldots, x_n) \sqcup \begin{cases} \top & \text{if } \beta = \top \\ \beta & \text{if } \beta \neq \top \wedge x_0 \sqsubseteq \beta \\ \beta^s & \text{otherwise} \end{cases}$$



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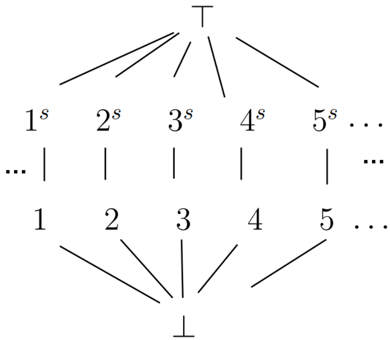

Almost trivial to generate profile-guided variants of standard analyses—an afternoon to "port" SCCP to SpecSCCP!

Speculative Sparse Conditional Constant Propagation (SpecSCCP)

Table 1. Speculative Constants discovered by the SSCP algorithm. ('~' indicates *almost*; **grp**, **prg**, & **src** refer to inputs **graphic**, **program** & **source** respectively).

Program	Inpt	Variable Uses		Expression Uses		Total		
		Uses	HitRt	Uses	HitRt	Hits	Misses	HitRt
181.mcf	-	33110	100.00	49665	100.00	82775	0	100.00
175.vpr	-	6938074	100.00	8110837	100.00	15048911	0	100.00
164.gzip	grp	26592	100.00	5	100.00	26597	0	100.00
	prg	17412	100.00	5	100.00	17417	0	100.00
	src	4721	99.98	5	100.00	4725	1	99.98
197.parser	-	165970964	~100.00	340	97.94	165970861	443	~100.00
256.bzip2	grp	132106650	~100.00	938	76.97	132107372	216	~100.00
	prg	100819492	~100.00	6576416	15.67	101849942	5545966	94.84
	src	108134316	~100.00	5256006	17.94	109077366	4312956	96.20

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Optimized on "train" inputs, results produced on "ref" inputs... Shows the value of profile-guided analysis for code understanding and optimizations...

Profile-Guided Register Allocation [Jain et al., HiPC'16]

```
# BB#4:                              # %if.then
                                     #   in Loop: Header=B
        addl    %edi, 32(%esp)       # 4-byte Folded Spill |
        addl    $20, %esi
        addl    $117, %ebp
        jmp     .LBB0_6
        .align  16, 0x90
.LBB0_5:                             # %if.else
                                     #   in Loop: Header=B
        addl    $101, 40(%esp)       # 4-byte Folded Spill
                                     >
        subl    40(%esp), %ecx       # 4-byte Folded Reloa |
                                     >
        addl    $33, %edi
        addl    $-11, %ebp
```

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# BB#4:                              # %if.then
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        jmp     .LBB0_6
        .align  16, 0x90
.LBB0_5:                             # %if.else
                                     #   in Loop: Header=B
        addl    $101, 40(%esp)       # 4-byte Folded Spill
        movl    36(%esp), %edx       # 4-byte Reload
        subl    40(%esp), %edx       # 4-byte Folded Reloa
        movl    %edx, 36(%esp)       # 4-byte Spill
        addl    $33, %edi
        addl    $-11, %ebp
```

.LBB0_5 is hot: 40(%esp) is cached in %ecx	BB#4 is hot: 32(%esp) is cached in %ecx

ILP based register allocator

- Implements integer linear programming based profile-guided register allocation
- Base allocator (without profile information) is simplified version of [Goodwin and Wilken, 1996]

Base Allocator

$$\mathbf{min} \sum_{v \in V, l \in L} S_{v,l} \,.\, x_{v,l,\sigma}, \quad \text{(minimize spills)} \quad \textit{such that}$$

$$\forall_{v \in V} \forall_{l \in L} \sum_{r \in R} x_{v,l,r} = 1 \quad \text{(a variable to at least one location)}$$

$$\forall_{r \in R - \sigma} \forall_{l \in L} \sum_{v \in V} x_{v,l,r} \leq 1 \quad \text{(a register holds at most one variable)}$$

Cost for τ-functions

Modelling τ-functions

The cost for $t = \tau(safe, t_1, t_2, ..., t_n)$:

$$TauCost = \sum_{i=1}^{i=n} (loc(t, t_i) * freq(t_i))$$

where $loc(t, t_i)$ is 1 for the locations where t and t_i are different, else 0.

The objective function

The objective function for register allocation over HPSSA is modified to include the *TauCost* discussed above.

The objective fuction

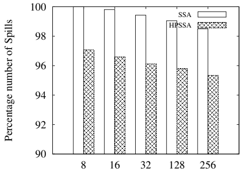
$$\min \sum_{v \in V, l \in L} S_{v,l} \cdot x_{v,l,\sigma} + \sum_{i=1}^{i=m} TauCost_i \tag{1}$$

where, $TauCost_i$ is the cost for the i^{th} τ-function (and m is the total number of τ-functions in the program), and

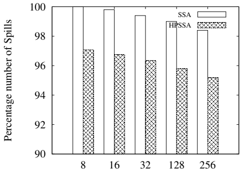
$$S_{v,l} = \begin{cases} 100, & \text{if v has further uses along hot path;} \\ 15, & \text{if v has further uses only along cold path;} \\ 0, & \text{if v has no further use.} \end{cases}$$

Almost a trivial modification to the objective function...

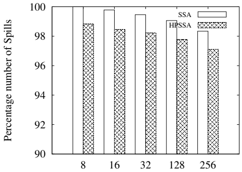
Percentage of spills for different register sizes



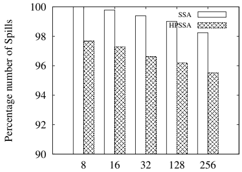
(a) gzip



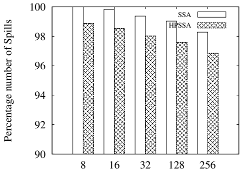
(b) bzip2



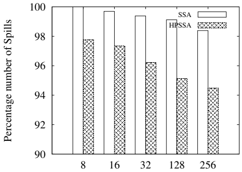
(c) mcf



(d) Crafty



(e) GAP



(f) Parser

Outline

Hot/Cold Paths

Definition 1. Hot/Cold Paths

A program path $p : n_1 \rightsquigarrow n_2$ is said to be hot (cold) if the sequence of edges from node n_1 to n_2 appears (does not appear) in any profiled path that occurs frequently in the program profile.

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- hot: if the node (edge) is present on a hot path;
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Definition 3. Hot/Cold Reaching Definitions and Definition Chains

A definition δ at a basic-block n_1 is said to reach a respective use at a basic-block n_2 hot if there exists a hot path from n_1 to n_2, and δ is not killed along that path. A definition δ at a basic-block n_1 is said to reach a respective use at a basic-block n_2 cold if there does not exist a hot path from n_1 to n_2, and δ is not killed at least along one cold path from n_1 to n_2.

Inserting τ-*functions*

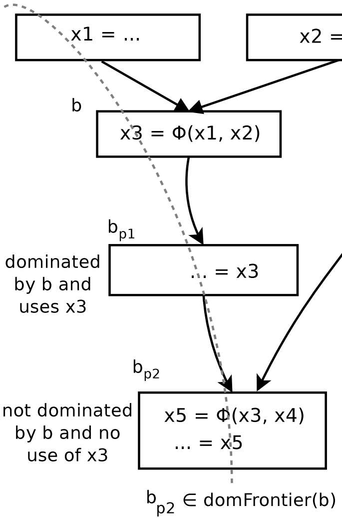
Necessary condition for τ-functions

Lemma 1. A node n requires a τ-function for variable x due to a definition d^x (of a variable x) if

1. n is the junction of a hot and a cold path, i.e., paths at different temperatures meet at this node;
2. n is reachable by at least two different definitions of the variable x.

Proof. If condition I fails, a τ -function is unnecessary as n can then be reachable by only hot or only cold definitions of x. If condition II fails, a τ -function is again unnecessary as the node is then dominated by a definition of x.

Inserting τ-functions



Inserting $\tau - functions$

Definition 4. Thermal Frontier (TF)

For definition d defined at a node u reaching v, v is in the Thermal Frontier of (u,d), $v \in TF(u, d)$, iff

1. the node v is also exposed to a reaching definition d' defined at a node $u \notin Dom(w)$ (w not dominated by u)
2. $\theta(u \rightsquigarrow v) \neq \theta(w \rightsquigarrow v)$
3. v is the first node on the paths $u \rightsquigarrow v$ and $w \rightsquigarrow v$ that satisfies the above properties.

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3. v is the first node on the paths $u \rightsquigarrow v$ and $w \rightsquigarrow v$ that satisfies the above properties.

Theorem

For a set of visible definitions of a variable x at a set of nodes κ, τ-statements are only required at the Iterated Thermal Frontier ITF^x for variable x.

HPSSA construction [Roy et al., CC'10]

- Insert ϕ-functions:
  - insert ϕ-functions at the *iterated dominance frontiers*
- **Insert τ-functions**
  - insert τ-functions at the *iterated thermal frontiers*
- Allocate arguments to ϕ-functions
  - use a variable stack to allocate the ϕ-function arguments
- **Allocate arguments to τ-functions**
  - maintain path-sensitive reaching definitions for each program variable corresponding to each hot path on a path-sensitive stack;
  - for each instruction in the program, the algorithm update the respective stack to record the change in the path-sensitive reaching definitions due to the instruction;
  - when a τ-function is encountered, the current set of reaching definitions on the stack is used to allocate the speculative arguments for the τ-function.

HPSSA construction over SSA [Jaiswal et. al., SCOPES'17]

Difficulties

- Needs the SSA construction identified, broken into and retrofitted with the HPSSA construction phases.
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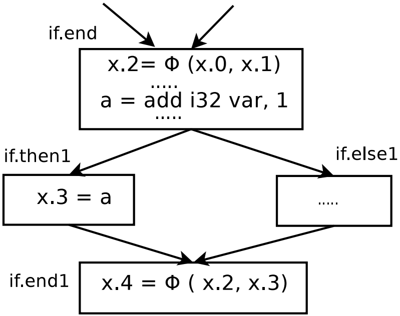
HPSSA over SSA

- Easily incorporated within existing compilers: Construction over the SSA form
- Efficient: Lesser instructions have to be traversed
- Simpler: many constructs are eliminated

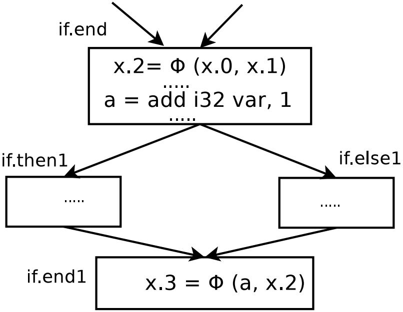
A naïve attempt: Mimic [Roy et al.]

- attempt to "recover" the renamed versions of each base variable that is merged by the ϕ-functions;
- then, allocate a single path-sensitive stack for all versions of the same base variable.

Optimized SSA forms



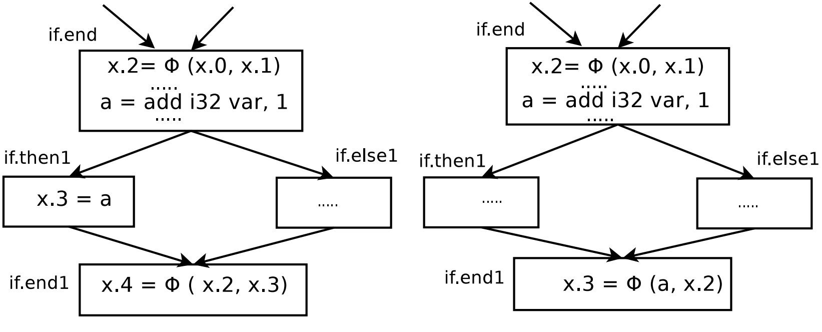
a) Unoptimized version



b) Optimized SSA version

a and x.2 are live simultaneously — hence, cannot be different versions of the same variable

Optimized SSA forms



a) Unoptimized version

b) Optimized SSA version

a and x.2 are live simultaneously — hence, cannot be different versions of the same variable

in the above example, copy propagation breaks the *phi congruence property*...

ϕ − *congruence* property

Shreedhar et al. [SAS'99]

"The occurrences of all resources which belong to the same phi congruence class in a program can be replaced by a representative resource. After the replacement, the phi instruction can be eliminated without violating the semantics of the original program."

- Sreedhar et al. circumvent the problem by translating the optimized SSA form to the conventional SSA form (that satisfies the phi congruence property) before translating out of SSA.
- **We directly build the HPSSA form over the optimized SSA form!**

Brief Algorithm

- **Insert τ-functions**
  - Insert at Thermal Frontiers
- **Allocate arguments to τ-functions**
  - path-sensitive traversal through the program to identify definitions that reach τ-functions through hot paths
  - constrains its inspection to only the ϕ-functions and the τ-functions

Allocating τ-function arguments

Uses a path-sensitive stack: **phiStack**

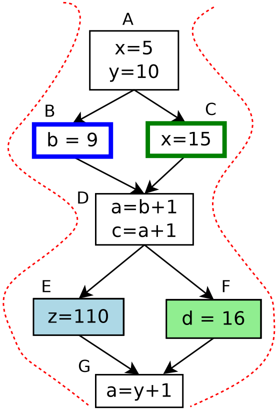
- **phiStack** is a stack of **frames**
- each frame $\langle d_i, \xi_i \rangle$ where $\xi_i = \{p_1, p_2, \dots\}$
- support operations:
  - push(frame f, block b)
  - pop(block b)

High-level algorithm

- Load arguments from ϕ- and τ-functions along with their hot path sets on **phiStack**
- Assign the definition from the topmost frame of **phiStack** to any τ-function encountered

Outline

Profile-guided analysis on paths

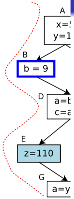


Summary

- Profile-guided analysis across paths is stronger—can capture correlations between control-flow of basic-blocks
- Collecting path-profiles seems challenging—requires “recording” of a sequence of basic-blocks

Summary

Profile-guided analyses to optimizations



- **Speculation**: *check and retry*
  - eg. value speculation
  - Can impact code size (significant impact w/o speculation support in hardware)
- **Compensation code**
  - eg. superblock scheduling
  - Can impact code size
- **Error resilient modules**
  - modules for statistical summarization on samples, generate data for ML models
  - No impact on code size
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  - eg. register allocation
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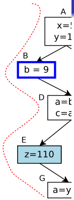


Our Objective

Can we **weave** profile information into the program representation

....into a **single, consistent** data-structure

... that provides the convenience and elegance of an **SSA-like** intermediate form

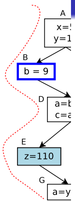
...allowing the design of profile-guided versions of "traditional" optimizations with **trivial algorithmic modification** of the base algorithms

...providing a **common representation** for both "traditional" as well as profile-guided analysis and optimizations

Summary

Introduction ○○●○○○ The H

Profile-guided analy



Introduction ○○○○○○ The H

Our Objective

Can we **w**

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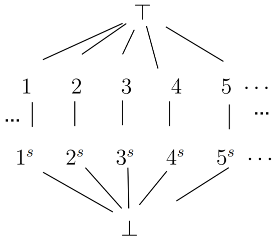
Speculative Sparse Conditional Constant Propagation (SSCCP)

- Introduce new speculative values $\{\ldots, 1^s, 2^s, \ldots\} \in C^S$
- Operation with *speculative* values result in *speculative* results (with same semantics as base operator)

$$\alpha^s \ \langle op \rangle \ \beta = (\alpha \ \langle op \rangle \ \beta)^s$$

- Transfer function for τ-functions ($\beta = x_1 \sqcup x_2 \sqcup \ldots$)

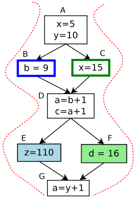


$$\tau(x_0, x_1, \ldots, x_n) \sqcup \begin{cases} x_0 \sqcup \top & \text{if } x_0 \sqcup \beta \neq \top \\ \beta & \text{if } x_0 \sqcup \beta = \top \wedge \beta \in C^s \\ \beta^s & \text{otherwise} \end{cases}$$

Almost trivial to generate profile-guided variants of standard analyses—it took us an afternoon to "port" SCCP to SSCCP!

Summary

Profile-guided analysis on paths



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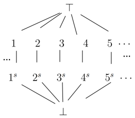

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References

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- Subhajit Roy and Y. N. Srikant. The Hot Path SSA Form: Extending the Static Single Assignment Form for Speculative Optimizations. CC'10.
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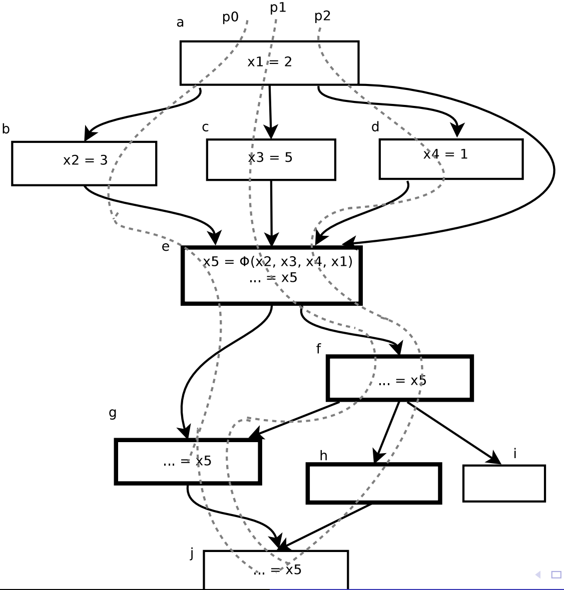
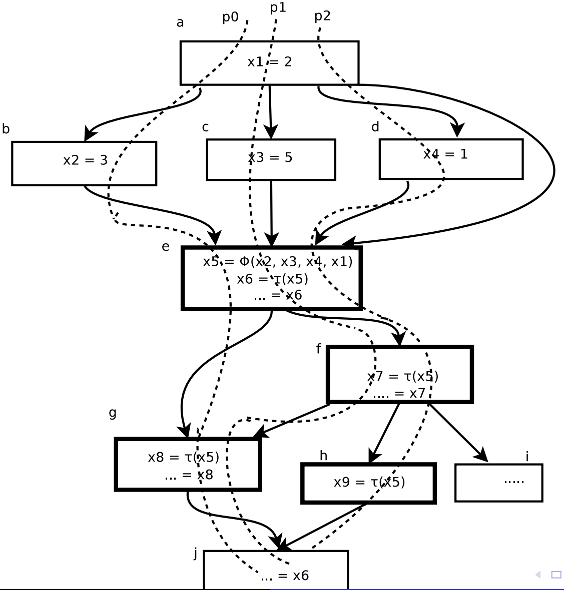
- Era Jain and Subhajit Roy. Phase Directed Compiler Optimizations. HiPC'16.
- Smriti Jaiswal, Praveen Hegde, and Subhajit Roy. Constructing HPSSA over SSA. SCOPES'17.

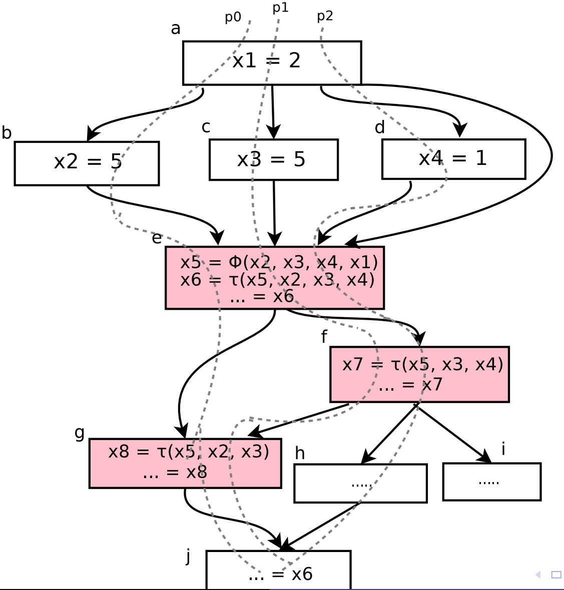
SSA program



τ-functions inserted



τ-arguments allocated



Conclusions

- We propose a new algorithm that converts SSA programs to HPSSA. Being built over the SSA form, our new algorithm is much more suited for compiler frameworks that offer an SSA-based intermediate representation. This algorithm is also simpler and more efficient than the existing algorithm that builds HPSSA programs from non-SSA programs.
- Our algorithm is capable of operating on optimized SSA forms (resulting from compiler optimizations on the SSA form) that do not satisfy the *Phi Congruence Property*.
- We design an ILP-based path-profile guided register allocation. We provide experimental evaluation of the performance of our approach on eight benchmarks of SPEC CINT2000 benchmark suite.

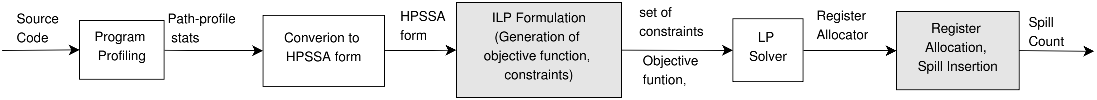
Questions

Questions?

dasd

- The occurrences of all resources which belong to the same phi congruence class in a program can be replaced by a representative resource. After the replacement, the phi instruction can be eliminated without violating the semantics of the original program.

dasd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HPSSA form
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set of constraints
Objective funtion,
LP Solver
Register Allocator
Register Allocation, Spill Insertion
Spill Count

dasd

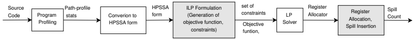
Calculate all caloric connectors in the CFG of the program.
isInserted(I,b)=**false** forall instruction I and basic-block b
Traverse CFG in topological order, performing the following:
for all ϕ-function instruction $I \in$ basic-block b **do**
  for all hot path p passing through b **do**
    for b_p= next basic-blocks on p **till** $b_p \notin$ DomFront(b) **do**
      if $b_p \in$ CaloricConnectors $\wedge \neg \mathit{isInserted}(I, b_p)$ **then**
        insert a τ-function $x_{new} = \tau(x_{phi})$ corresponding to the ϕ-function I: $x_{phi} = \phi(\dots)$ after all ϕ-function statements in block b_p
        $\mathit{isInserted}$(I, b_p) = **true**
      end if
    end for
  end for
end for

dasd

While processing a basic block b,

for all ϕ-function I: $x_o = \phi(x_1, x2, \ldots, x_n) \in b$ **do**
for all x_i for which $\Omega_{x_i}(b)$ exists **do**
$phiStack_{x_i}$.**push**($\Omega_{x_i}(b)$, b)
end for
if $b \in$ IncubationNode **then**
frame = [ ]
for all $(x_i, \xi_i) \in phiStack_{x_i}(b).Top$ **do**
frame = frame.**add**($x_i, \xi_i \cup IncubPaths(b)$)
end for
for all arguments x_i in ϕ-function I **do**
if x_i is a concrete defn. $\wedge$ $b_p \to b$ an incoming edge **then**
frame = frame.**add**(x_i, $pathSet(b_p \to b)$ $\cup$ IncubPaths(b))
end if
if x_i is a ϕ-argument corresponding to a hot backedge **then**
frame = frame.**add**(x_i,IncubPaths(b))
end if
end for
$phiStack_x$.**push**(frame, b)
end if
end for
for all τ-function instructions $I \in b$ **do**
for all $(x_i, \xi_i) \in phiStack_{x_i}(b).Top$ **do**
if $\xi_i \cap pathSet(b) \neq \emptyset$ **then**
add (x_i, $\xi_i \cap pathSet(b)$) to speculative arguments of I
end if
end for
end for
for all outgoing edge $b \to b_s$ **do**
if b_s is a join node **then**
for all $(x_i, \xi_i) \in phiStack_{x_i}.Top$ **do**
if $\xi_i \cap pathSet(b \to b_s) \neq \emptyset$ **then**
$\Omega_{x_i}(b_s) = \xi_i \cap pathSet(b \to b_s)$
end if
end for
end if
end for
Make a recursive call on the children of node b in the dominator tree, traversing them in topological of the nodes in the control-flow graph order.
Pop off all frames pushed by block b from all phiStacks

dasd



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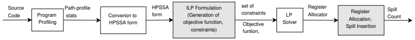

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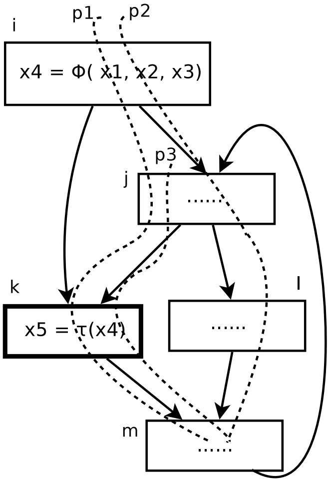
p1
p2
i
x4 = Φ(x1, x2, x3)
p3
j
......
k
x5 = τ(x4)
l
......
m
......