

The Hot Path SSA Form in LLVM

Algorithms & Applications

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This work is based on the following research papers.

- Subhajit Roy and Y. Srikant. The Hot Path SSA Form: Extending the Static Single Assignment Form for Speculative Optimizations. In CC '10: International Conference on Compiler Construction. 2010. CC 2010:304-323
- Smriti Jaiswal, Praveen Hegde and Subhajit Roy. Constructing HPSSA over SSA. In Proceedings of the 20th International Workshop on Software and Compilers for Embedded Systems. 2017. SCOPES 2017: 31-40

- 1 HPSSA : Why another SSA Form?
 - Path Profile Guided Optimizations
 - Profile Guided SpecSCCP Analysis using HPSSA Form
- 2 What is HPSSA form?
 - Introduction to Path Profile Guided Optimizations
 - Hot Path SSA Form
 - Profile Guided SpecSCCP Pass
- 3 How is HPSSA Implemented?
 - Constructing HPSSA Form
 - Implementing HPSSA Form in LLVM
- 4 Conclusion

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

Our Objective

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

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

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

Why is path-profile-guided analysis hard?

disparate data-structures: program + profile

```
int main ( )
{
    int a[10] = {(0,2,0), (1,2,0), (7,5,0), (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("t1,t2,t3 = %d,%d,%d\n", x,y,z,t1,t2,t3);
        if ( t1 ) max = z;
        if ( t1 && t2 ) max = x;
        if ( t2 && t3 ) max = y;
        printf("%d\n", max);
    }
}
```

| | |
|------------|----|
| 1-2-4-5 | 30 |
| 21-2-5-5-1 | 25 |
| 1-2-4-5 | 30 |
| 21-2-5-5-1 | 25 |
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| 21-2-5-5-1 | 25 |
| 1-2-4-5 | 30 |
| 21-2-5-5-1 | 25 |

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.
 - ...

... but it is easy with the Hot Path SSA (HPSSA) Form!

```
1 // Function to process "llvm.tau" function intrinsic.
2 visitTauNode() {
3     ...
4     SpecValueLatticeElement TauState = getValueState(&Tau),
5     beta = getValueState(Tau.getOperand(1)),
6     x0 = getValueState(Tau.getOperand(0));
7
8     if (TauState.isOverdefined())
9         return (void)markOverdefined(&Tau);
10
11     for (unsigned i = 1, e = (Tau.getNumOperands() - 1); i != e; ++i){
12         SpecValueLatticeElement IV = getValueState(Tau.getOperand(i));
13         beta.mergeIn(IV);
14         NumActiveIncoming++;
15         if (beta.isOverdefined())
16             break;
17     }
18
19     beta.mergeIn(x0);
20     if (beta.isConstant())
21         TauState.markSpeculativeConstant(beta.getConstant());
22
23     if (beta.isConstantRange())
24         TauState.markSpeculativeConstantRange(beta.getConstantRange());
25
26     if (beta.isOverdefined() || x0.isOverdefined())
27         TauState.markOverdefined();
28     ...
29 }
```

```
1 // Omit handling of "llvm.tau" intrinsic
2 // as a regular Instruction.
3 for (auto& I : *(&(BB))) {
4     CallInst* CI = dyn_cast<CallInst>(&I);
5     if (CI != NULL) {
6         Function* CF = CI->getCalledFunction();
7         if (CF != NULL &&
8             CF->getIntrinsicID() ==
9             Function::lookupIntrinsicID("llvm.tau")){
10             visitTauNode(I);
11         } else {
12             visit(I);
13         }
14     } else {
15         visit(I);
16     }
17 }
```

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6     x0 = getValueState(Tau.getOperand(0));
7
8     if (TauState.isOverdefined())
9         return (void)markOverdefined(&Tau);
10
11     for (unsigned int i = 0; i < Tau.getNumActiveValues(); i++) {
12         SpecValueLatticeElement beta_m = beta.getState(i);
13         beta.mergeIn(beta_m);
14         NumActiveValues++;
15         if (beta.isOverdefined())
16             break;
17     }
18
19     beta.mergeIn(x0);
20     if (beta.isConstant())
21         TauState.markSpeculativeConstant(beta.getConstant());
22
23     if (beta.isConstantRange())
24         TauState.markSpeculativeConstantRange(beta.getConstantRange());
25
26     if (beta.isOverdefined() || x0.isOverdefined())
27         TauState.markOverdefined();
28     ...
29 }
```

Only these few lines were enough to create a new path profile guided analysis, *Speculative Sparse Conditional Constant Propagation (SpecSCCP)* from the currently existing SCCP pass in LLVM !

```
1 // Omit handling of "llvm.tau" intrinsic
2 // as a regular Instruction.
3 for (auto& I : *(&(BB))) {
4     CallInst* CI = dyn_cast<CallInst>(&I);
5     if (CI && CI->getIntrinsicID() == Intrinsic::llvm_tau) {
6         visitTauNode(I);
7     } else {
8         visit(I);
9     }
10 } else {
11     visit(I);
12 }
13 } else {
14     visit(I);
15 }
16 }
17 }
```

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11     for (unsigned i = 1, e = (Tau.getNumOperands() - 1); i != e; ++i){
12         SpecValueLatticeElement IV = getValueState(Tau.getOperand(i));
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20     if (beta.isConstant())
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26     if (beta.isOverdefined() || x0.isOverdefined())
27         TauState.markOverdefined();
28     ...
29 }
```

It took us only an afternoon to transform SCCP to SpecSCCP

```
1 // Omit handling of "llvm.tau" intrinsic
2 // as a regular Instruction.
3 for (auto& I : *(&(BB))) {
4     CallInst* CI = dyn_cast<CallInst>(&I);
5     if (CI != NULL) {
6         Function* CF = CI->getCalledFunction();
7         if (CF ==
8             Function::lookupIntrinsicID("llvm.tau")){
9             visitTauNode(I);
10        } else {
11            visit(I);
12        }
13    } else {
14        visit(I);
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```

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SCCP vs SpecSCCP

SCCP

```
1 int main() {
2   int x = 2, m, n, y, z = 9, c = 1;
3   std::cin >> m;
4   switch(m) {
5     case 2 : x = 2 * c + 5; n = 10; break;
6     case 4 : x = 2 * c + 5; n = x - 2; break;
7     case 6 : x = 2 * c + 1; n = x + 2; break;
8     default : break;
9   }
10  y = 2 * x + 10;
11  if (y <= z + x) {
12    // ..
13  } else {
14    z = n + 3 * x;
15    switch(z) {
16      default : break;
17      case 200 : goto end;
18      case 300 : exit(0); }
19  }
20  m = y + x;
21  end:
22  z = x;
23  return 0;
24 }
```

SpecSCCP

```
1 int main() {
2   int x = 2, m, n, y, z = 9, c = 1;
3   std::cin >> m;
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5     case 2 : x = 2 * c + 5; n = 10; break;
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8     default : break;
9   }
10  y = 2 * x + 10;
11  if (y <= z + x) {
12    // ..
13  } else {
14    z = n + 3 * x; // n : Speculative Constant 5
15    switch(z) {
16      default : break;
17      case 200 : goto end;
18      case 300 : exit(0); }
19  }
20  m = y + x; // x : Speculative Constant 7
21  end:
22  z = x;
23  return 0;
24 }
```

Legend: Overdefined Discovered Constants Real Constants Speculative Constants

SCCP vs SpecSCCP

SCCP

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1 int main() {
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7         case 6 : x = 2 * c + 1; n = x + 2; break;
8         default : break;
9     }
10    y = 2 * x + 10;
11    if (y <= z)
12        // ..
13    } else {
14        z = n + 3 * x;
15        switch (z) {
16            default : break;
17            case 200 : goto end;
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```

SpecSCCP

```
1 int main() {
2     int x = 2, m, n, y, z = 9, c = 1;
3     std::cin >> m;
4     switch(m) {
5         case 2 : x = 2 * c + 5; n = 10; break;
6         case 4 : x = 2 * c + 5; n = x - 2; break;
7         case 6 : x = 2 * c + 1; n = x + 2; break;
8         default : break;
9     }
10    y = 2 * x + 10;
11    if (y <= z)
12        // ..
13    } else {
14        z = n + 3 * x; // n : Speculative Constant 5
15        switch (z) {
16            default : break;
17            case 200 : goto end;
18            case 300 : exit(0); }
19    }
20    m = y + x; // x : Speculative Constant 7
21    end:
22    z = x;
23    return 0;
24 }
```

SpecSCCP discovers n & x as speculative constants.

Legend: Overdefined Discovered Constants Real Constants Speculative Constants

SCCP vs SpecSCCP

Standard SCCP VS. Speculative SCCP Pass.

```
1  # Running Regular SCCP Pass on Program.
2  $ opt -sccp -time-passes -debug-only=sccp \
3    IR/LL/test.ll -S -o \
4    IR/LL/test_sccp_onbaseline.ll \
5    -f 2> output/custom_sccp_onbaseline.log
6
7  ...
8  Output:
9    ...
10   Constant: i32 2 = %mul = mul nsw i32 2, 1
11   Constant: i32 7 = %add = add nsw i32 2, 5
12   Constant: i32 2 = %mul2 = mul nsw i32 2, 1
13   Constant: i32 7 = %add3 = add nsw i32 2, 5
14   Constant: i32 5 = %sub = sub nsw i32 7, 2
15   Constant: i32 2 = %mul5 = mul nsw i32 2, 1
16   Constant: i32 3 = %add6 = add nsw i32 2, 1
17   Constant: i32 5 = %add7 = add nsw i32 3, 2
```

```
1  # Running HPSSA Transformation followed by Speculative SCCP Pass.
2  $ opt -load build/SCCPSolverTau.cpp.so
3    -load build/HPSSA.cpp.so \
4    -load-pass-plugin=build/SpecSCCP.cpp.so \
5    -passes="specsccp" \
6    -time-passes -debug-only=specsccp \
7    IR/LL/test.ll -S -o IR/LL/test_spec_sccp.ll \
8    -f 2> output/custom_speculative_sccp.log
9
10  ...
11  Output :
12    ...
13    (TauState) tau1 : speculative constantrange<5, 6>
14    (TauState) tau7 : speculative constantrange<7, 8>
15    ...
16    Constant: i32 2 = %mul = mul nsw i32 2, 1
17    Constant: i32 7 = %add = add nsw i32 2, 5
18    Constant: i32 2 = %mul2 = mul nsw i32 2, 1
19    Constant: i32 7 = %add3 = add nsw i32 2, 5
20    Constant: i32 5 = %sub = sub nsw i32 7, 2
21    Constant: i32 2 = %mul5 = mul nsw i32 2, 1
22    Constant: i32 3 = %add6 = add nsw i32 2, 1
23    Constant: i32 5 = %add7 = add nsw i32 3, 2
```

Using the HPSSA Form for writing new analyses

- Include the header file `HPSSA.h` to use `llvm::HPSSAPass` class.
- Load shared object using `opt` tool. `opt -load HPSSA.cpp.so ...`

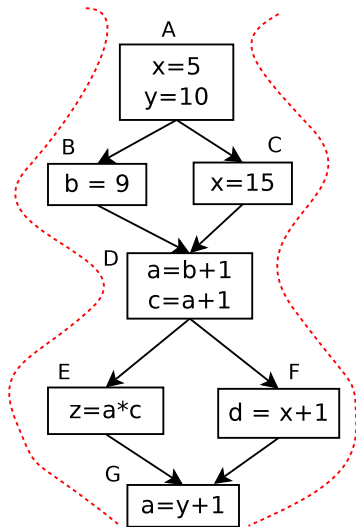
```
1 #include <HPSSA.h> // import the header.
2 #include <SCCP.h>
3
4 class SpecSCCPPass : public PassInfoMixin<SpecSCCPPass> {
5     public: PreservedAnalyses run(Function &F,
6         FunctionAnalysisManager &AM);
7 };
8 ...
9
10 PreservedAnalyses SpecSCCPPass::run(Function &F,
11     FunctionAnalysisManager &AM) {
12     if (F.getName() != "main")
13         return PreservedAnalyses::all();
14
15     HPSSAPass hpssaUtil; // Make a HPSSAPass Object.
16     hpssaUtil.run(F, AM); // Call the HPSSAPass::run() function.
17
18     std::vector<Instruction *> TauInsts
19     = hpssaUtil.getAllTauInstructions(F); // Calling HPSSA utility function.
20
21     std::cout << "\t\tTotal Tau Instructions : " << TauInsts.size() << ",\n";
22     ...
23 }
```

Output : Total Tau Instructions : 7, ...rest of the logs

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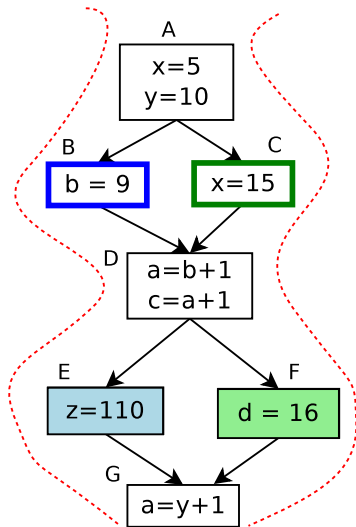
Profile-guided analysis on paths



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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- Collecting path-profiles seems challenging—requires “recording” of a sequence of basic-blocks

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)

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)

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

- **Code understanding**
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 - modules for statistical summarization on samples, generate data for ML models
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- **Optimizations that don't impact correctness**
 - eg. register allocation
 - No impact on code size

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The Hot Path SSA Form (HPSSA)

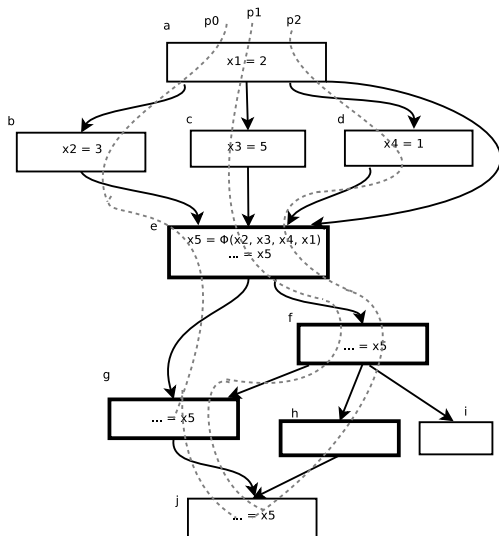
Semantics of a ϕ -function

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

Semantics of a τ -function

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

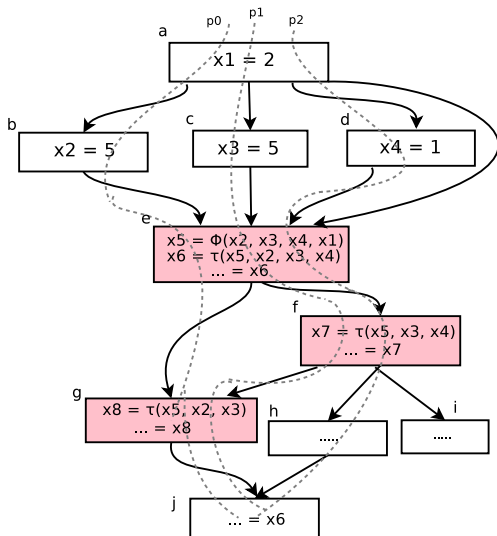
The SSA form



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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- **safe interpretation:** [supports traditional analysis]
 - each use of a variable is reachable by the *meet-over-all-paths* reaching definition chains;

The Hot Path SSA Form

Properties

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

- 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

^aor the meet-over-all-paths reaching definition chains, if the use is not reachable from any meet-over-hot-paths reaching definition chain

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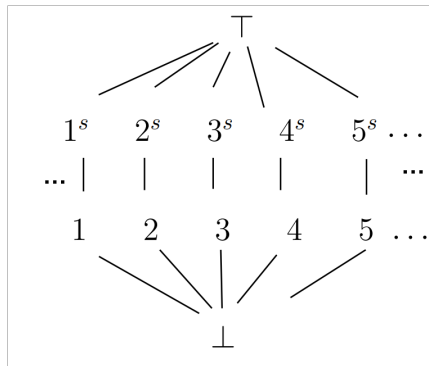
Speculative Sparse Conditional Constant Propagation (SpecSCCP)

- Introduce new speculative values $\{\dots, 1^s, 2^s, \dots\} \in C^S$
- 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
($\beta = x_1 \sqcup x_2 \sqcup \dots \sqcup x_n$, i.e. join of speculative args.)

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



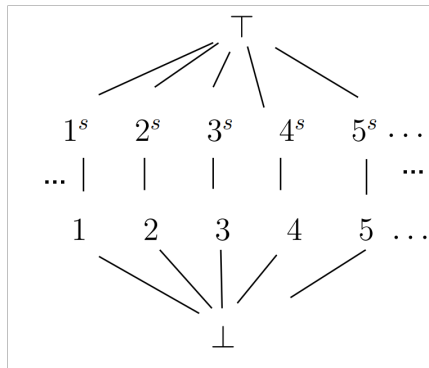
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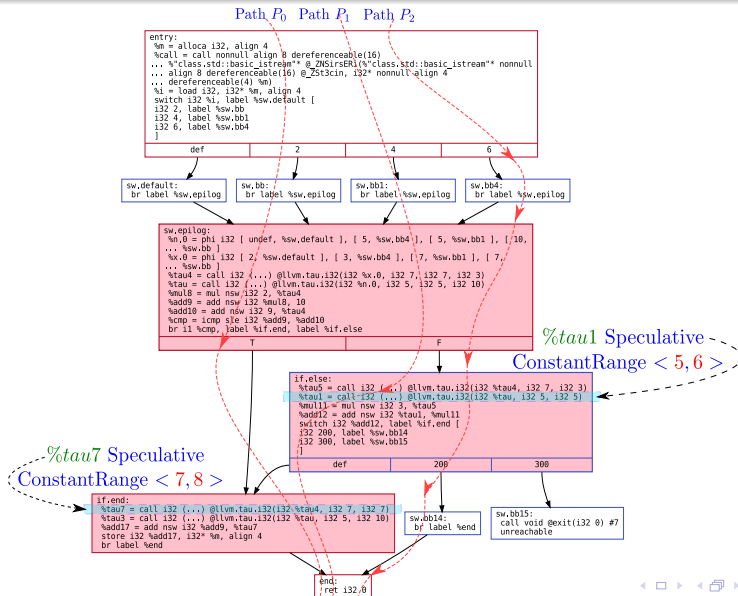
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Almost trivial to generate profile-guided variants of standard analyses—an afternoon to “port” SCCP to SpecSCCP!

Profile Guided SpecSCCP Pass in LLVM



LLVM Implementation : Profile Guided SpecSCCP Pass

- Modified the existing SCCP Pass to add `visitTauNode()` function which handles the special `"llvm.tau"` intrinsic instructions used for τ -functions.¹

¹Since we added the τ -functions as an `"llvm.tau"` intrinsic, we blocked processing it as a regular LLVM Instruction.

LLVM Implementation : Profile Guided SpecSCCP Pass

- Modified the existing SCCP Pass to add `visitTauNode()` function which handles the special `"llvm.tau"` intrinsic instructions used for τ -functions.¹
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- Modified the `SCCPInstVisitor::solve()`. function to process `"llvm.tau"` intrinsic instructions using `visitTauNode()` instead of the standard `visit()` function.

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Definition 1. Hot/Cold Paths

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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 .

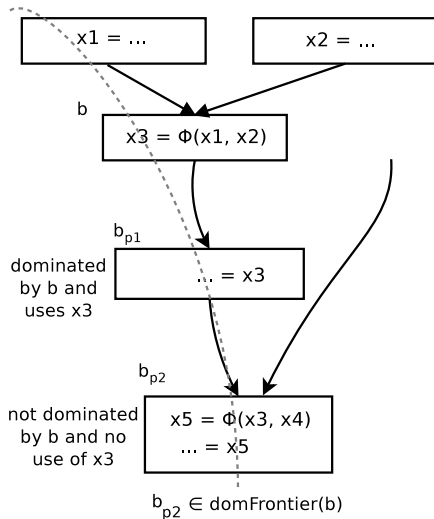
Necessary condition for τ -functions

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



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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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 .

- **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.

Difficulties

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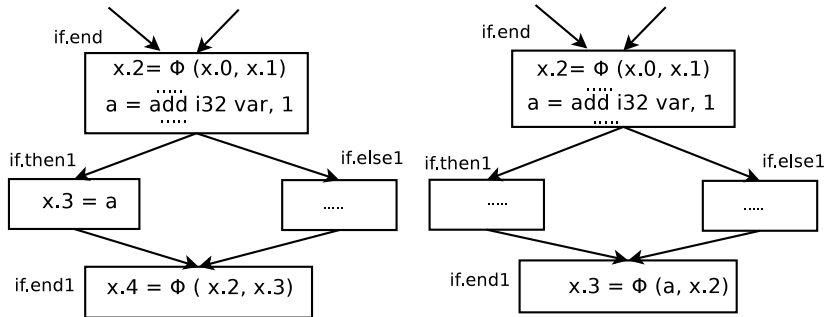
HPSSA over SSA

- **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

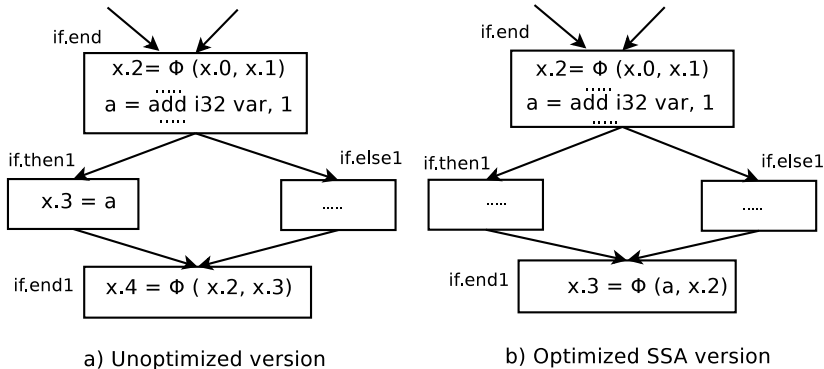


a) Unoptimized version

b) Optimized SSA version

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

Optimized SSA forms



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in the above example, copy propagation breaks the *phi 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!**

- **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

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What we modified in LLVM Source?

- New `llvm::intrinsic` signature, "`llvm.tau`" to support addition and removal of τ -functions to the LLVM SSA IR representation.

```
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- Modified `Verifier::verifyDominatesUse()` function since we don't want our intrinsic to interfere with `dominators` computation.

```
1 + //====----- Changes for tau.intrinsic -----====//
2 void Verifier::verifyDominatesUse(Instruction &I, unsigned i) {
3     Instruction *Op = cast<Instruction>(I.getOperand(i));
4     +   if (CallInst *CI = dyn_cast<CallInst>(&I)) {
5     +   Function *CallFunction = CI->getCalledFunction();
6     +   if (CallFunction != NULL && CallFunction->getIntrinsicID()==
7     +       Function::lookupIntrinsicID("llvm.tau")) {
8     +       return;
9     +   }
10    + }
11    ...
```

- `class HPSSAPass : public PassInfoMixin<HPSSAPass>`
 - Implemented `llvm::HPSSAPass` pass using the new LLVM Pass Manager.
 - Function `HPSSAPass::run(Function &F, ...)` runs over a `llvm::Function` and inserts "`llvm.tau`" intrinsic calls with speculative and safe arguments at strategic positions in the LLVM IR and handles argument allocation for "`llvm.tau`" intrinsic calls as described in the previous slides.

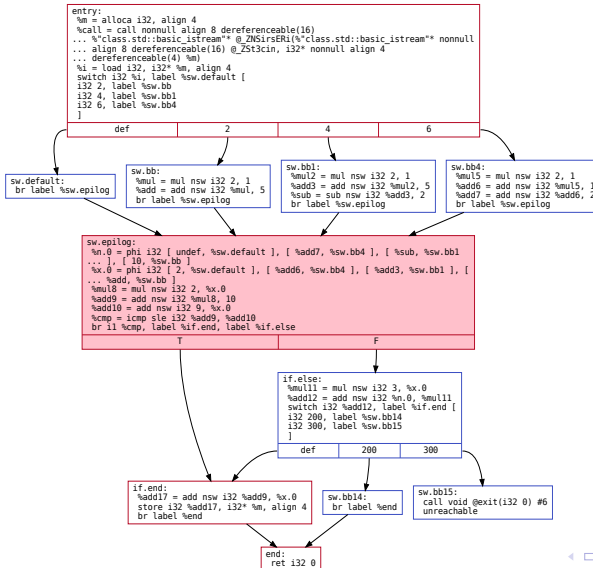
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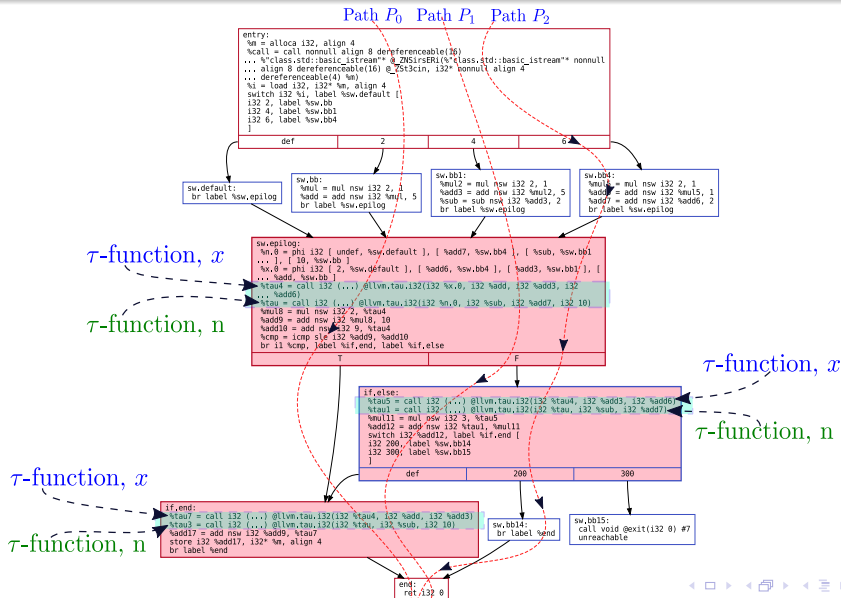
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 - A stack of map values `std::map<Value*, Value*>` to store the most "recent" tau definition encountered so far corresponding for a tau variable used later in variable renaming.

SSA Form



Hot Path SSA Form



- `HPSSAPass::run(Function &F, FunctionAnalysisManager &AM)`
 - Invokes `HPSSAPass::getProfileInfo()` function to get a compact representation of all the profiled **hot paths** in the program and then calls `HPSSAPass::getCaloricConnector()` to get all the caloric connectors from the **hot path** information. This is a precursor to finding strategic positions to place `"llvm.tau"` intrinsic calls in the LLVM IR.

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 - Runs over each basic block in the function "F" in topological order using iterator returned from `llvm::Function::RPOT()` call.
 - Uses the `llvm::dominates()` function from `llvm::DominatorTreeAnalysis` to check for dominance frontier while processing the child nodes of the current basic block. This step is a part of correctly placing `"llvm.tau"` intrinsic calls in the LLVM IR.

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 - Uses the renaming stack and `HPSSAPass::Search()` function to search and replace all use of PHI result operand with that returned by the `"llvm.tau"` intrinsic call.

HPSSAPass : Destruction Pass

- Out of HPSSA Form.
 - A seperate pass using the new LLVM Pass Manager.

```
class TDSTRPass : public PassInfoMixin<TDSTRPass>
```

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 - A separate pass using the new LLVM Pass Manager.
`class TDSTRPass : public PassInfoMixin<TDSTRPass>`
 - Using `TDSTRPass::run(Function &F, ...)`, we replace all use of existing tau operands with first argument of `"llvm.tau"` intrinsic (corresponds to the safe argument) and remove the `"llvm.tau"` intrinsic call from the LLVM IR.
 - The LLVM IR becomes identical to what it was before running the HPSSA Pass.

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- We plan to push this work to LLVM main branch soon.