

The Hot Path SSA Form in LLVM

Algorithms & Applications

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This presentation presents the details of building a robust and efficient implementation of the **Hot Path SSA (HPSSA)** form in the LLVM compiler infrastructure.

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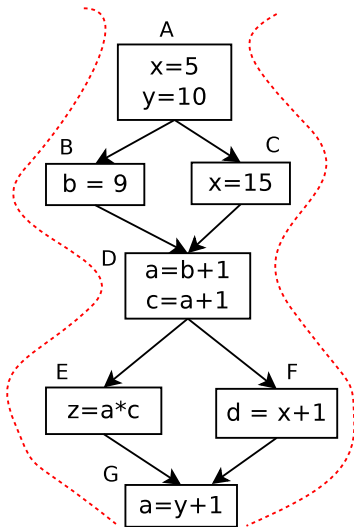
The Hot Path SSA form is based on the following research papers.

- Subhajit Roy and Y.N. 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?
 - Introduction to Path Profile Guided Optimizations
 - Profile Guided SpecSCCP Analysis using HPSSA Form
- 2 What is HPSSA form?
 - 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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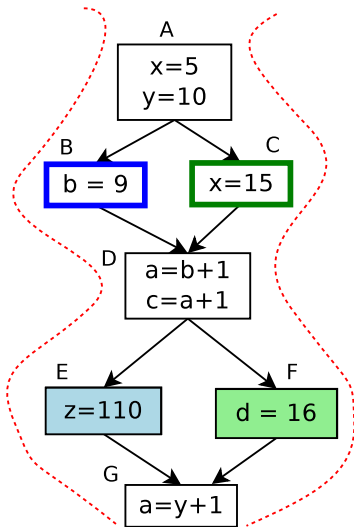
Profile-guided analysis on paths



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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- 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

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

- **Code understanding**
 - Can expose refactoring opportunities

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- **Program testing and verification**
 - Data-driven synthesis of invariants
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 - Can expose refactoring opportunities
- **Program testing and verification**
 - Data-driven synthesis of invariants
 - Guided testing for low frequency paths
- **Profile-guided optimizations**

Why is path-profile-guided analysis hard?

disparate data-structures, one for **program representation** and other for **profile information**.

Program Representation

```
int main(void) {  
    int a = 90;  
    ....  
}
```

CFG, AST,
TAC, ASM ...



Profile Information

```
BB1→BB7→BB3→ ... : 7890  
BB1→BB2→BB8→ ... : 9500
```

Array,
HashTable, Map, ...

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.
 - ...

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

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....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

... and PGO is easy with the Hot Path SSA (HPSSA) Form!

```
1 // Function to process "llvm.tau" function intrinsic.
2 void SpecSCCPInstVisitor::visitTauNode(Instruction &Tau) {
3     // Code similar to that in visitPHINode(...).
4     if (Tau.getType()->isStructTy())
5         return (void)markOverdefined(&Tau);
6     if (TauState.isOverdefined())
7         return (void)markOverdefined(&Tau);
8     // additional code.
9     unsigned NumActiveIncoming = 0;
10    SpecValueLatticeElement &TauState = getValueState(&Tau),
11    beta = getValueState(Tau.getOperand(1)),
12    x0 = getValueState(Tau.getOperand(0));
13
14    for (unsigned i = 1, e = (Tau.getNumOperands() - 1); i != e; ++i){
15        SpecValueLatticeElement IV = getValueState(Tau.getOperand(i));
16        beta.mergeIn(IV);
17        NumActiveIncoming++;
18        if (beta.isOverdefined())
19            break;
20    }
21
22    if (beta.isConstantRange()
23        && beta.getConstantRange().isSingleElement())
24        beta.markSpeculativeConstantRange(beta.getConstantRange());
25    if (beta.isConstant())
26        beta.markSpeculativeConstant(beta.getConstant());
27
28    x0.mergeInSpec(beta, TauState);
29    ... // futher processing similar to visitPHINode();
30 }
```

```
1 // Omit handling of "llvm.tau" intrinsic
2 // as a regular Instruction.
3 void SpecSCCPInstVisitor::solve() {
4     ...
5     ...
6     for (auto& I : *(&(BB))) {
7         CallInst* CI = dyn_cast<CallInst>(&I);
8         if (CI != NULL) {
9             Function* CF = CI->getCalledFunction();
10            if (CF != NULL &&
11                CF->getIntrinsicID() ==
12                Function::lookupIntrinsicID("llvm.tau")){
13                visitTauNode(I);
14            } else {
15                visit(I);
16            }
17        } else {
18            visit(I);
19        }
20    }
21    ... // rest of the code.
22 }
```

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5         return (void)markOverdefined(&Tau);
6     if (TauState.isOverdefined())
7         return (void)markOverdefined(&Tau);
8     // additional code.
9     unsigned NumActiveIncoming = 0;
10    SpecValueLatticeElement &TauState = getValueState(&Tau),
11    beta = getValueState(Tau.getOperand(1)),
12    x0 = getValueState(Tau.getOperand(0));
13
14    for (un
15        SpecV
16        beta.
17        NumAct
18        if (beta.isOverdefined())
19            break;
20 }
21
22 if (beta.isConstantRange()
23     && beta.getConstantRange().isSingleElement())
24     beta.markSpeculativeConstantRange(beta.getConstantRange());
25 if (beta.isConstant())
26     beta.markSpeculativeConstant(beta.getConstant());
27
28 x0.mergeInSpec(beta, TauState);
29 ... // futher processing similar to visitPHINode();
30 }
```

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 void SpecSCCPInstVisitor::solve() {
4     ...
5     ...
6     for (auto& I : *(&(BB))) {
7         CallInst* CI = dyn_cast<CallInst>(&I);
8         if (CI->isCallTo("llvm.tau")) {
9             visitTauNode(I);
10        } else {
11            visit(I);
12        }
13    }
14    ... // rest of the code.
15 }
```

... and PGO is easy with the Hot Path SSA (HPSSA) Form!

```
1 // Function to process "llvm.tau" function intrinsic.
2 void SpecSCCPInstVisitor::visitTauNode(Instruction &Tau) {
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5         return (void)markOverdefined(&Tau);
6     if (TauState.isOverdefined())
7         return (void)markOverdefined(&Tau);
8     // additional code.
9     unsigned NumActiveIncoming = 0;
10    SpecValueLatticeElement &TauState = getValueState(&Tau),
11        beta = getValueState(Tau.getOperand(1)),
12        x0 = getValueState(Tau.getOperand(0));
13
14    for (unsigned i =
15        SpecValueLattice
16        beta.mergeIn(IV),
17        NumActiveIncoming++;
18        if (beta.isOverdefined())
19            break;
20    }
21
22    if (beta.isConstantRange())
23        && beta.getConstantRange().isSingleElement()
24        beta.markSpeculativeConstantRange(beta.getConstantRange());
25    if (beta.isConstant())
26        beta.markSpeculativeConstant(beta.getConstant());
27
28    x0.mergeInSpec(beta, TauState);
29    ... // futher processing similar to visitPHINode();
30 }
```

It took us only an afternoon to transform SCCP to SpecSCCP

```
1 // Omit handling of "llvm.tau" intrinsic
2 // as a regular Instruction.
3 void SpecSCCPInstVisitor::solve() {
4     ...
5     ...
6     for (auto& I : *(&(BB))) {
7         CallInst* CI = dyn_cast<CallInst>(&I);
8         if (CI != NULL) {
9             Function* CF = CI->getCalledFunction();
10            ID() ==
11            Function::lookupIntrinsicID("llvm.tau")){
12                visitTauNode(I);
13            } else {
14                visit(I);
15            }
16        } else {
17            visit(I);
18        }
19    }
20    ... // rest of the code.
21 }
22 }
```

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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 = n + 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;
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; // n : Speculative Constant 5
15        switch (z) {
16            default : break;
17            case 200 : goto end;
18            case 300 : exit(0); }
19    }
20    m = n + x; // x : Speculative Constant 7
21    end:
22    z = x;
23    return 0;
24 }
```

Legend: Overdefined Real Constants Speculative Constants

SCCP vs SpecSCCP

SCCP

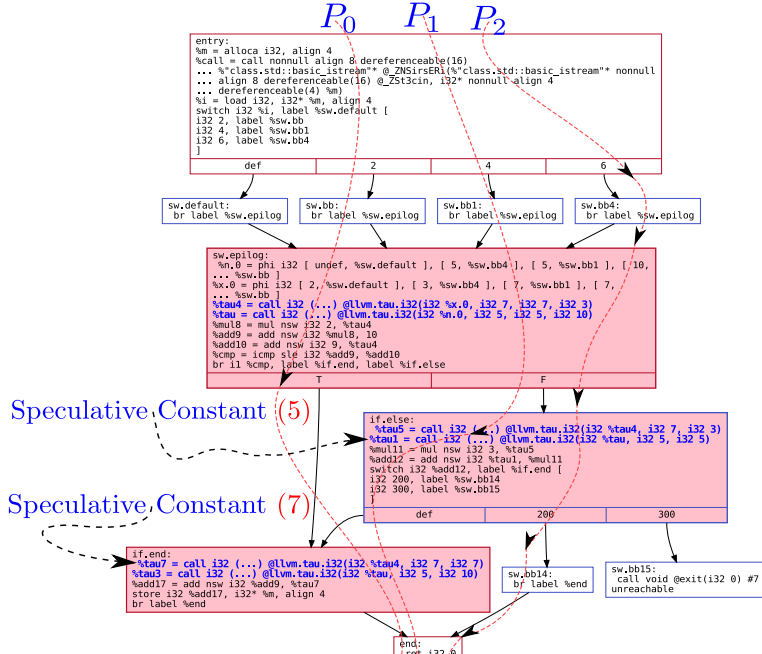
```
1 int main() {
2   int x = 2, m, n, y, z = 9, c = 1;
3   std::cin >> m;
4   switch(m) {
5     case 2 : x = 2 * c + 5; n = 10; break;
6     case 4 : x = 2 * c + 5; n = x - 2; break;
7     case 6 : x = 2 * c + 1; n = x + 2; break;
8     default : break;
9   }
10  y = 2 * m + 10;
11  if (y <= 10) {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

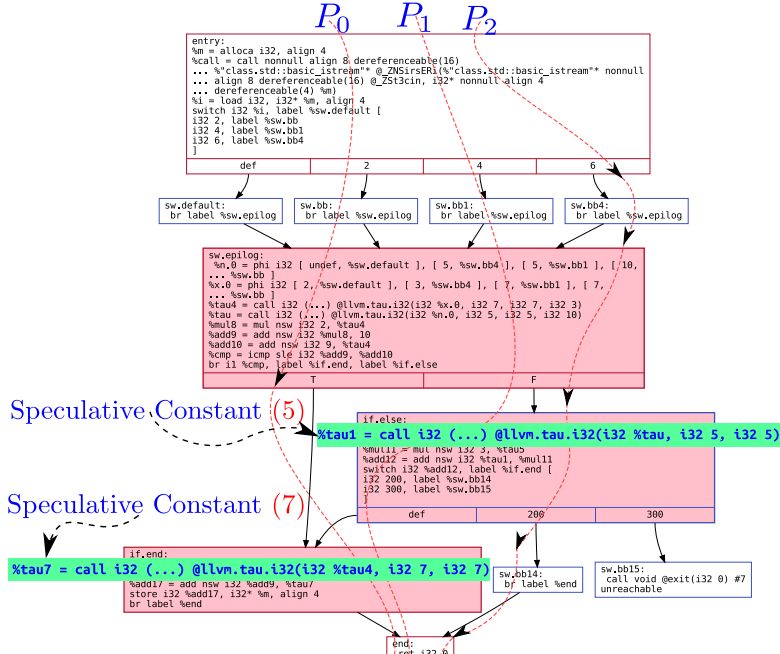
SpecSCCP

```
1 int main() {
2   int x = 2, m, n, y, z = 9, c = 1;
3   std::cin >> m;
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 * m + 10;
11  if (y <= 10) {
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 = n + x; // x : Speculative Constant 7
21  end:
22  z = x;
23  return 0;
24 }
```

SpecSCCP discovers n & x as speculative constants.

Legend: Overdefined Real Constants Speculative Constants





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
18
19
20
21
```

```
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 Constant: i32 2 = %mul = mul nsw i32 2, 1
13 Constant: i32 7 = %add = add nsw i32 2, 5
14 Constant: i32 2 = %mul2 = mul nsw i32 2, 1
15 Constant: i32 7 = %add3 = add nsw i32 2, 5
16 Constant: i32 5 = %sub = sub nsw i32 7, 2
17 Constant: i32 2 = %mul5 = mul nsw i32 2, 1
18 Constant: i32 3 = %add6 = add nsw i32 2, 1
19 Constant: i32 5 = %add7 = add nsw i32 3, 2
20 Speculative Constant: i32 5 = %tau1 = call i32 (...)
21 @llvm.tau.i32(i32 %tau, i32 5, i32 5)
22 Speculative Constant: i32 7 = %tau7 = call i32 (...)
23 @llvm.tau.i32(i32 %tau4, i32 7, i32 7)
```

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 YourPGOPass : public PassInfoMixin<YourPGOPass> {
5     public: PreservedAnalyses run(Function &F,
6         FunctionAnalysisManager &AM);
7 };
8
9 PreservedAnalyses YourPGOPass::run(Function &F,
10     FunctionAnalysisManager &AM) {
11     ...
12     HPSSAPass hpssaUtil; // Make a HPSSAPass Object.
13     hpssaUtil.run(F, AM); // Call the HPSSAPass::run() function.
14     ...
15     // Rest of the code ..
16 }
```

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The Hot Path SSA Form (HPSSA)

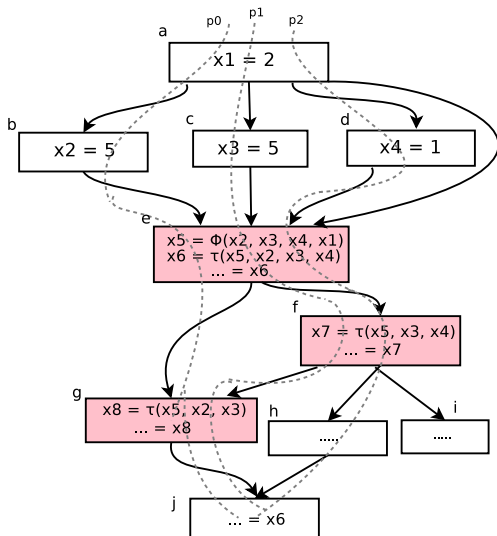
Semantics of a ϕ -function

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

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 Hot Path SSA Form



No frequent path carrying:

- def $x_2 = 3$ to use at block **f**
- def $x_4 = 1$ to use at block **g**

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]

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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;

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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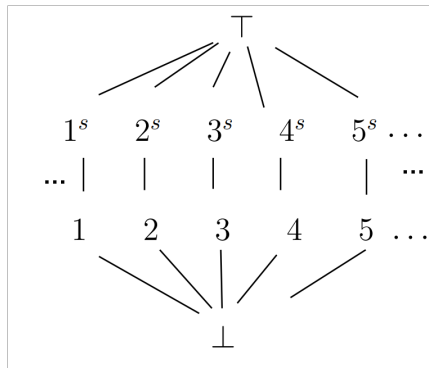
Speculative Sparse Conditional Constant Propagation (SpecSCCP)

- 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.)

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



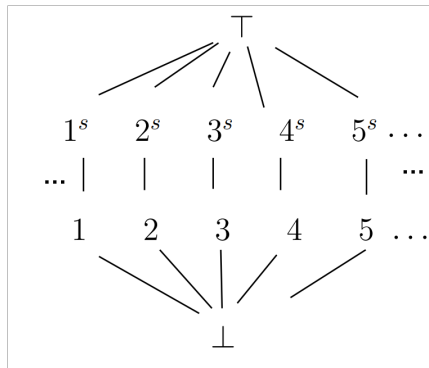
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$$\tau(x_0, x_1, \dots, x_n) \sqcup \begin{cases} \top & \text{if } \beta = \top \\ \beta & \text{if } \beta \neq \top \wedge x_0 \sqsubseteq \beta \\ \beta^s & \text{otherwise} \end{cases}$$



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

From SpecSCCP Pass

Basic blocks from the transformed IR after the SpecSCCP pass with assignSpecValue() calls added.

```
1  if.else:                                     ; preds = %sw.epilog
2  %tau = call i32 (...) @llvm.tau.i32(i32 %tau8, i32 7, i32 3)
3  %tau10 = call i32 (...) @llvm.tau.i32(i32 %tau9, i32 5, i32 5)
4  %tau10_spec = call i32 @assignSpecValue(i32 5)
5  %mul11 = mul nsw i32 3, undef
6  %add12 = add nsw i32 %tau10_spec, %mul11
7  switch i32 %add12, label %sw.default13 [
8      i32 200, label %sw.bb14
9      i32 300, label %sw.bb15
10 ]
```

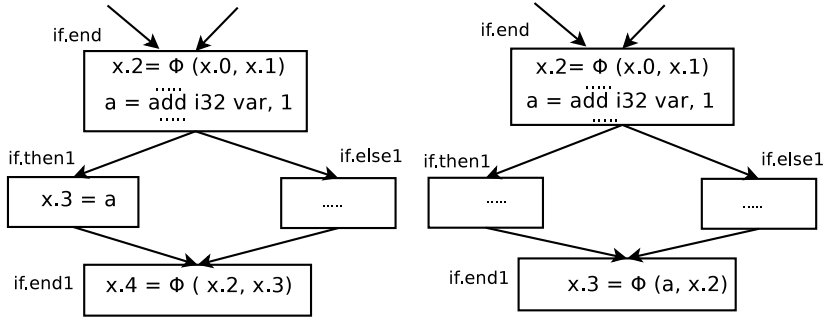
```
1  if.end:                                     ; preds = %sw.epilog, %if.else
2  %tau11 = call i32 (...) @llvm.tau.i32(i32 %tau8, i32 7, i32 7)
3  %tau11_spec = call i32 @assignSpecValue(i32 7)
4  %tau12 = call i32 (...) @llvm.tau.i32(i32 %tau9, i32 5, i32 10)
5  %add17 = add nsw i32 undef, %tau11_spec
6  store i32 %add17, i32* %m, align 4
7  br label %end
```

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- **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

Optimized SSA forms

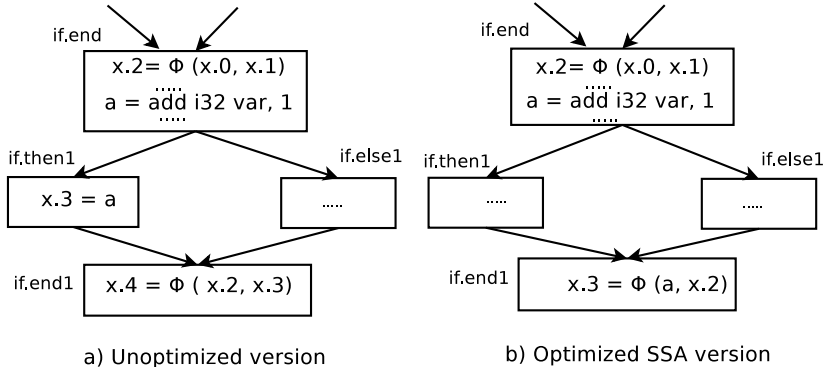


a) Unoptimized version

b) Optimized SSA version

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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!**

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```
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    ...
```

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 - `HPSSAPass::AllocateArgs(BasicBlock* BB, DomTreeNode& DTN)` handles argument allocation for τ -functions inserted.

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

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- Out of HPSSA Form.
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`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.
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$x_3 = \tau(x_0, x_1, x_2)$, τ -function

$x_3 = x_0$, Replace all use of x_3 with x_0 .

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- We plan to open source our work soon and push it to the LLVM “main” branch.

- 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

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- Modified the `SCCPInstVisitor::solve()` function to process `"llvm.tau"` intrinsic instructions using `visitTauNode()` instead of the standard `visit()` function.

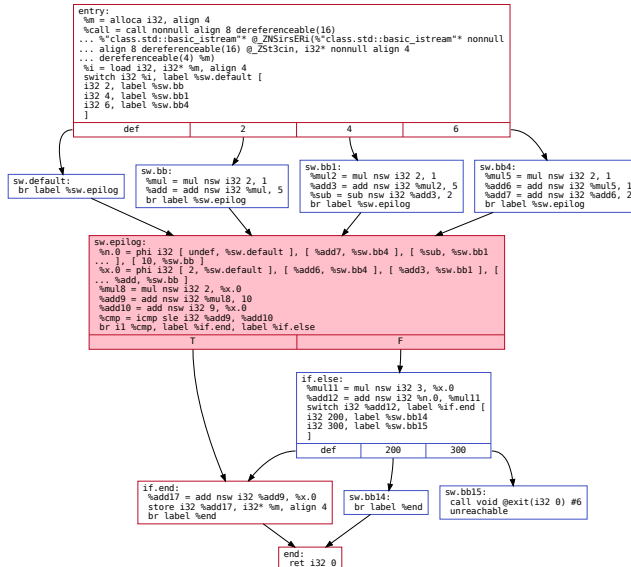
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 - Uses the renaming stack and `HPSSAPass::Search()` function to search and replace all use of PHI result operand with that returned by the `"llvm.tau"` intrinsic call.

Program in SSA Form



Program in Hot Path SSA Form

