The Hot Path SSA Form in LLVM

Algorithms & Applications

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References

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

Presentation Outline

1. HPSSA : Why another SSA Form?
   - Path Profile Guided Optimizations
   - Profile Guided SSCCP 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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disparate data-structures: program + profile

```c
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
1-2-4-5	30
21-2-5-5-1	25
1-2-4-5	30
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.
  - ...

Our Objective

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

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

```
// Function to process "llvm.tau" function intrinsic.
visitTauNode() {
  ...
  SpecValueLatticeElement TauState = getValueState(&Tau),
    beta = getValueState(Tau.getOperand(1)),
    x0 = getValueState(Tau.getOperand(0));
  if (TauState.isOverdefined())
    return (void)markOverdefined(&Tau);
  for (unsigned i = 1, e = (Tau.getNumOperands() - 1); i != e; ++i){
    SpecValueLatticeElement IV = getValueState(Tau.getOperand(i));
    beta.mergeIn(IV);
    NumActiveIncoming++;
    if (beta.isOverdefined())
    break;
  }

  beta.mergeIn(x0);
  if (beta.isConstant())
    TauState.markSpeculativeConstant(beta.getConstant());

  if (beta.isConstantRange())
    TauState.markSpeculativeConstantRange(beta.getConstantRange());

  if (beta.isOverdefined()   x0.isOverdefined())
    TauState.markOverdefined();
  ...
}
```

```
// Omit handling of "llvm.tau" intrinsic
// as a regular Instruction.
for (auto& I : *&(*(BB))) {
  CallInst* CI = dyn_cast<CallInst>(&I);
  if (CI != NULL) {
    Function* CF = CI->getCalledFunction();
    if (CF != NULL &&
    CF->getIntrinsicID() ==
      Function::lookupIntrinsicID("llvm.tau")){
      visitTauNode(I);
    } else {
      visit(I);
    }
  } else {
    visit(I);
  }
}
```

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

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  ...
  SpecValueLatticeElement TauState = getValueState(&Tau),
    beta = getValueState(Tau.getOperand(1)),
    x0 = getValueState(Tau.getOperand(0));
  if (TauState.isOverdefined())
    return (void)markOverdefined(&Tau);
  for (unsigned i = 1, e = (Tau.getNumOperands() - 1); i != e; ++i){

    break;
  }

  beta.mergeIn(x0);
  if (beta.isConstant())
    TauState.markSpeculativeConstant(beta.getConstant());

  if (beta.isConstantRange())
    TauState.markSpeculativeConstantRange(beta.getConstantRange());

  if (beta.isOverdefined()   x0.isOverdefined())
    TauState.markOverdefined();
  ...
}
```

```
// Omit handling of "llvm.tau" intrinsic
// as a regular Instruction.
for (auto& I : *&(*(BB))) {
  CallInst* CI = dyn_cast<CallInst>(&I);

      Function::lookupIntrinsicID("llvm.tau")){
      visitTauNode(I);
    } else {
      visit(I);
    }
  } else {
    visit(I);
  }
}
```

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!

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

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// Function to process "llvm.tau" function intrinsic.
visitTauNode() {
  ...
  SpecValueLatticeElement TauState = getValueState(&Tau),
    beta = getValueState(Tau.getOperand(1)),
    x0 = getValueState(Tau.getOperand(0));
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  for (unsigned i = 1, e = (Tau.getNumOperands() - 1); i != e; ++i){
    SpecValueLattic
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    if (beta.isOverdefined())
    break;
  }

  beta.mergeIn(x0);
  if (beta.isConstant())
    TauState.markSpeculativeConstant(beta.getConstant());

  if (beta.isConstantRange())
    TauState.markSpeculativeConstantRange(beta.getConstantRange());

  if (beta.isOverdefined()  x0.isOverdefined())
    TauState.markOverdefined();
  ...
}
```

It took us only an afternoon to transform SCCP to SpecSCCP !

```
// Omit handling of "llvm.tau" intrinsic
// as a regular Instruction.
for (auto& I : *&(*(BB))) {
  CallInst* CI = dyn_cast<CallInst>(&I);

                   CalledFunction();

    CF->getIntrinsicID() ==
      Function::lookupIntrinsicID("llvm.tau")){
      visitTauNode(I);
    } else {
      visit(I);
    }
  } else {
    visit(I);
  }
}
```

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 ...`

```
#include <HPSSA.h> // import the header.
#include <SCCP.h>

class SpecSCCPPass : public PassInfoMixin<SpecSCCPPass> {
  public: PreservedAnalyses run(Function &F,
  FunctionAnalysisManager &AM);
};
...

PreservedAnalyses SpecSCCPPass::run(Function &F,
FunctionAnalysisManager &AM) {
  if (F.getName() != "main")
    return PreservedAnalyses::all();

  HPSSAPass hpssaUtil; // Make a HPSSAPass Object.
  hpssaUtil.run(F, AM);  // Call the HPSSAPass::run() function.

  std::vector<Instruction *> TauInsts
  = hpssaUtil.getAllTauInstrunctions(F); // Calling HPSSA utility function.

  std::cout << "\t\tTotal Tau Instructions : " << TauInsts.size() << "\n";
  ...
}

/// [output] Total Tau Instructions : 7
```

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SCCP vs SpecSCCP

SCCP

```cpp
int main() {
  int x = 2, m, n, y, z = 9, c = 1;
  std::cin >> m ;
  switch( m ) {
    case 2 : x = 2 * c + 5; n = 10; break;
    case 4 : x = 2 * c + 5; n = x - 2; break;
    case 6 : x = 2 * c + 1; n = x + 2; break;
    default : break;
  }
  y = 2 * x + 10;
  if ( y <= z + x ) {
    // ..
  } else {
    z = n + 3 * x ;
    switch ( z ) {
      default : break;
      case 200 : goto end;
      case 300 : exit(0); }
  }
  m = y + x ;
  end:
    z = x ;
  return 0;
}
```

SpecSCCP

```cpp
int main() {
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    default : break;
  }
  y = 2 * x + 10;
  if ( y <= z + x ) {
    // ..
  } else {
    z = n + 3 * x ; // n : Speculative Constant 5
    switch ( z ) {
      default : break;
      case 200 : goto end;
      case 300 : exit(0); }
  }
  m = y + x ;  // x : Speculative Constant 7
  end:
    z = x ;
  return 0;
}
```

Legend: Overdefined, Discovered Constants, Real Constants, Speculative Constants

SCCP vs SpecSCCP

SCCP

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int main() {
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    case 4 : x = 2 * c + 5; n = x - 2; break;
    case 6 : x = 2 * c + 1; n = x + 2; break;
    default : break;
  }
  y = 2 * x + 10;
  if ( y <= z
    // ..
  } else {
    z = n + 3 * x ;
    switch ( z ) {
      default : break;
      case 200 : goto end;
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SpecSCCP

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    case 6 : x = 2 * c + 1; n = x + 2; break;
    default : break;
  }
  y = 2 * x + 10;
    // ..
  } else {
    z = n + 3 * x ; // n : Speculative Constant 5
    switch ( z ) {
      default : break;
      case 200 : goto end;
      case 300 : exit(0); }
  }
  m = y + x ; // x : Speculative Constant 7
  end:
    z = x ;
  return 0;
}
```

SpecSCCP discovers n & x as speculative constants.

Legend: Overdefined Discovered Constants Real Constants Speculative Constants

SCCP vs SpecSCCP

Standard SCCP VS. Speculative SCCP Pass.

```
# Running Regular SCCP Pass on Program.
$ opt -sccp -time-passes -debug-only=sccp \
  IR/LL/test.ll -S -o \
  IR/LL/test_sccp_onbaseline.ll \
  -f 2> output/custom_sccp_onbaseline.log

...
Output:
  ...
  Constant: i32 2 =   %mul = mul nsw i32 2, 1
  Constant: i32 7 =   %add = add nsw i32 2, 5
  Constant: i32 2 =   %mul2 = mul nsw i32 2, 1
  Constant: i32 7 =   %add3 = add nsw i32 2, 5
  Constant: i32 5 =   %sub = sub nsw i32 7, 2
  Constant: i32 2 =   %mul5 = mul nsw i32 2, 1
  Constant: i32 3 =   %add6 = add nsw i32 2, 1
  Constant: i32 5 =   %add7 = add nsw i32 3, 2
```

```
# Running HPSSA Transformation followed by Speculative SCCP Pass.
$ opt -load build/SCCPSolverTau.cpp.so
  -load build/HPSSA.cpp.so \
  -load-pass-plugin=build/SpecSCCP.cpp.so \
  -passes="specsccp" \
  -time-passes -debug-only=specsccp \
  IR/LL/test.ll -S -o IR/LL/test_spec_sccp.ll \
  -f 2> output/custom_speculative_sccp.log

...
Output :
  ...
  (TauState) tau1 : speculative constantrange<5, 6>
  (TauState) tau7 : speculative constantrange<7, 8>
  ...
  Constant: i32 2 =   %mul = mul nsw i32 2, 1
  Constant: i32 7 =   %add = add nsw i32 2, 5
  Constant: i32 2 =   %mul2 = mul nsw i32 2, 1
  Constant: i32 7 =   %add3 = add nsw i32 2, 5
  Constant: i32 5 =   %sub = sub nsw i32 7, 2
  Constant: i32 2 =   %mul5 = mul nsw i32 2, 1
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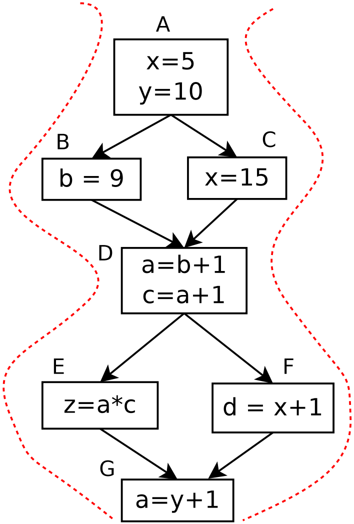
Profile-guided analysis on paths



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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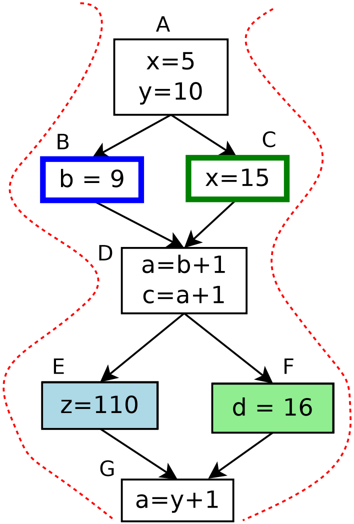

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Profiling acyclic paths

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

- **Code understanding**
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- **Speculation**: *check and retry*
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- **Compensation code**
  - eg. superblock scheduling
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- **Error resilient modules**
  - modules for statistical summarization on samples, generate data for ML models
  - No impact on code size
- **Optimizations that don't impact correctness**
  - eg. register allocation
  - No impact on code size

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The Hot Path SSA Form (HPSSA)

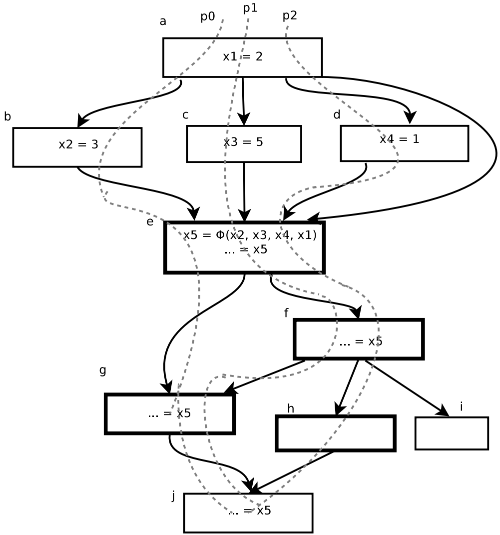
Semantics of a ϕ-function

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

Semantics of a τ-function

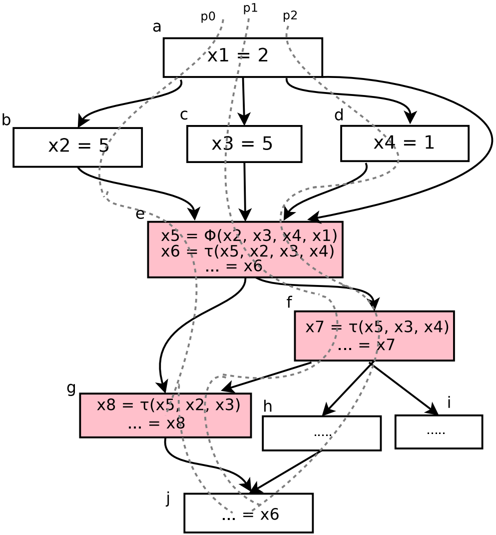
$$\tau(x_0, x_1, x_2, \ldots, x_n) = \begin{cases} x_0 & \text{safe interp.} \\ \phi(x_1, x_2, \ldots, x_n) & \text{speculative interp.} \end{cases}$$

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**



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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 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]

[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

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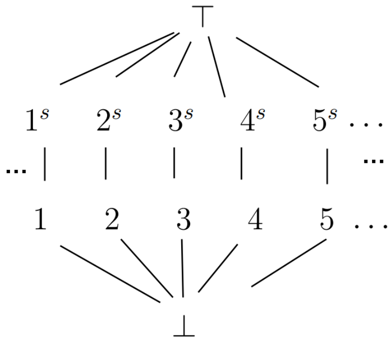
Speculative Sparse Conditional Constant Propagation (SpecSCCP)

- 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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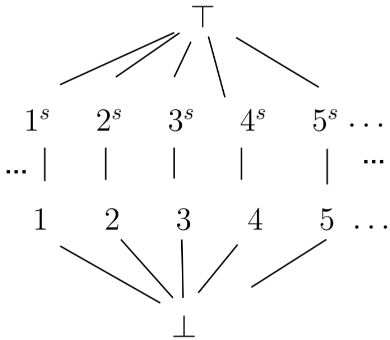
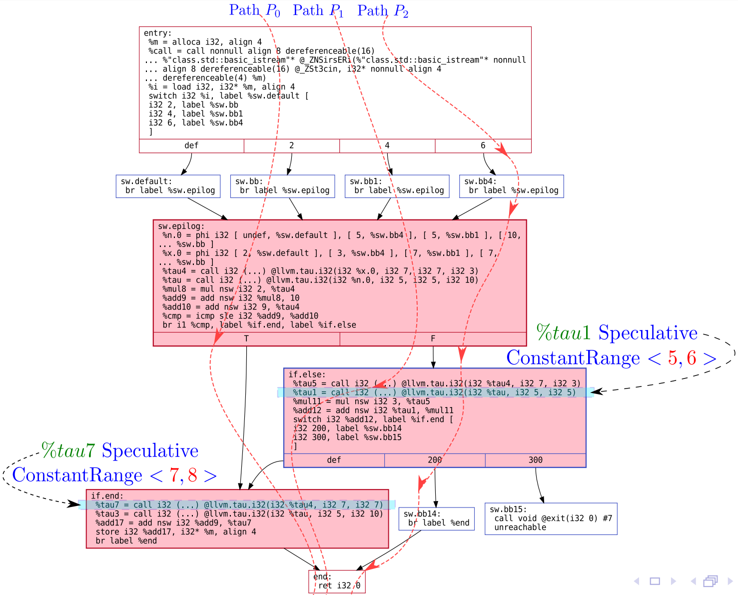


Almost trivial to generate profile-guided variants of standard analyses—an afternoon to "port" SCCP to SpecSCCP!

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]
- Added a new lattice element type `"spec_constant"` in `ValueLattice` class supporting operations on speculative constants. Modified the `SCCPInstVisitor::mergeIn()` function to handle lattice "meet" operation for the new speculative constants introduced.

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

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- Added new functions in the `SCCPInstVisitor` and `SCCPSolver` class to handle operations on speculative constants. Eg. Operands can be marked speculative using as function `markSpeculativeConstant()`.

[1] Since 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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- Added new functions in the `SCCPInstVisitor` and `SCCPSolver` class to handle operations on speculative constants. Eg. Operands can be marked speculative using as function `markSpeculativeConstant()`.
- Modified the `SCCPInstVisitor::solve()`. function to process `"llvm.tau"` intrinsic instructions using `visitTauNode()` instead of the standard `visit()` function.

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   - Path Profile Guided Optimizations
   - Profile Guided SSCCP Analysis using HPSSA Form
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Hot/Cold Paths

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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.

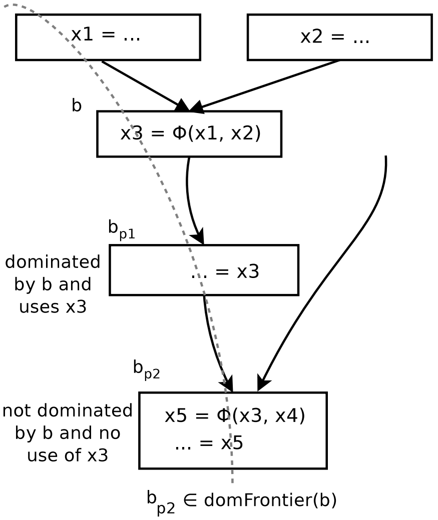
Necessary condition for τ-functions

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. $\theta(u \rightsquigarrow v) \neq \theta(w \rightsquigarrow v)$
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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.

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.
- The algorithm is quite complex!

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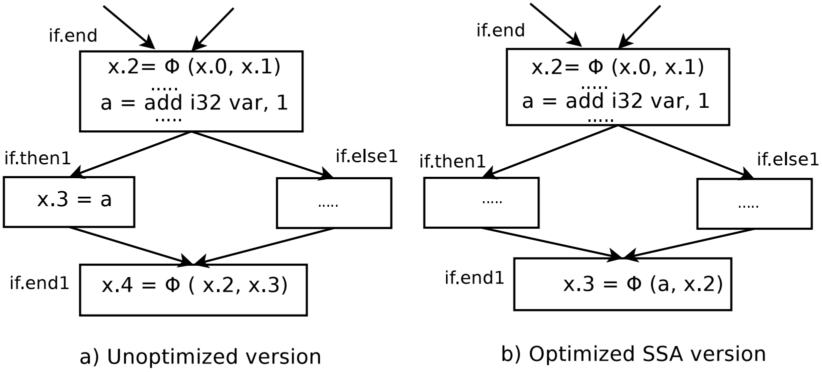
HPSSA over SSA

- 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



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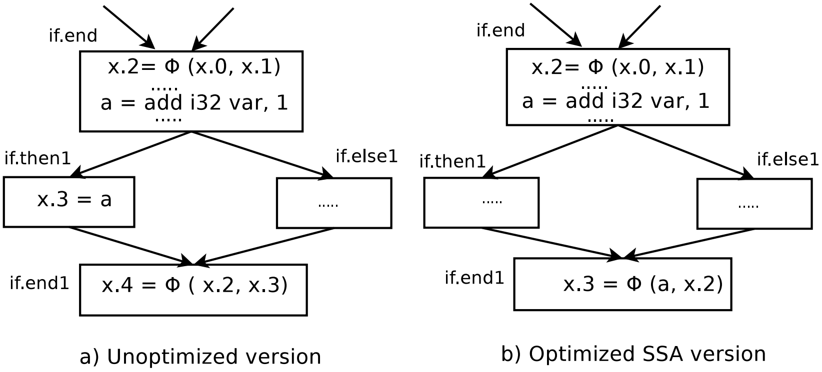

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in the above example, copy propagation breaks the *phi congruence property*...

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

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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.

```
+ //===----------- intrinsic for tau -------------------=====//
+ def int_tau : DefaultAttrsIntrinsic<[llvm_any_ty],
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```

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

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

HPSSAPass : Overview

- `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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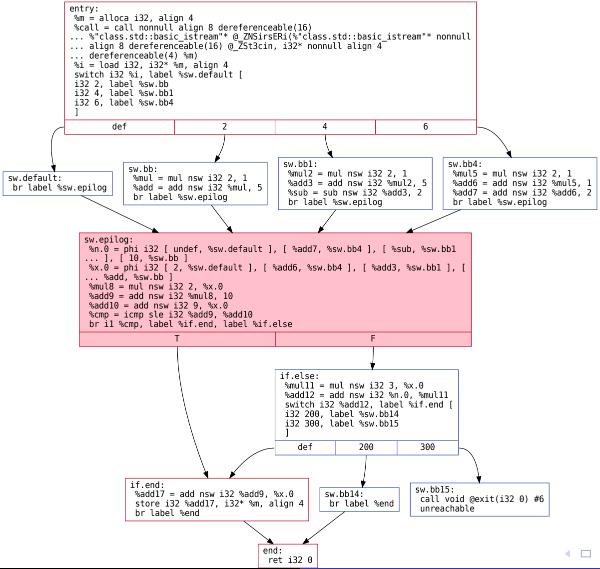
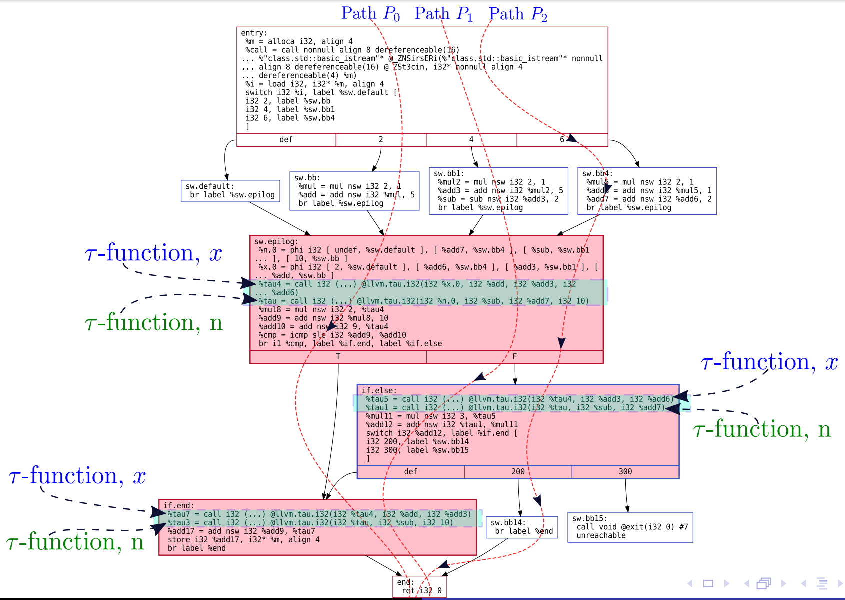
  - Definition Accumulator, `defAccumulator(op, currBB)` function. The argument "op" is a phi argument that reaches basic-block "currBB" via hot path .
  - A stack of map values `std::map<Value*,Value*>` to store the most "recent" tau definition encountered so far corresponding for a tau variable used later in variable renaming.

SSA Form


entry:
%m = alloca i32, align 4
%call = call nonnull align 8 dereferenceable(16)
... %"class.std::basic_istream"* @_ZNSirsERi(%"class.std::basic_istream"* nonnull
... align 8 dereferenceable(16) @_ZSt3cin, i32* nonnull align 4
... dereferenceable(4) %m)
%i = load i32, i32* %m, align 4
switch i32 %i, label %sw.default [
i32 2, label %sw.bb
i32 4, label %sw.bb1
i32 6, label %sw.bb4
]
def
2
4
6
sw.default:
br label %sw.epilog
sw.bb:
%mul = mul nsw i32 2, 1
%add = add nsw i32 %mul, 5
br label %sw.epilog
sw.bb1:
%mul2 = mul nsw i32 2, 1
%add3 = add nsw i32 %mul2, 5
%sub = sub nsw i32 %add3, 2
br label %sw.epilog
sw.bb4:
%mul5 = mul nsw i32 2, 1
%add6 = add nsw i32 %mul5, 1
%add7 = add nsw i32 %add6, 2
br label %sw.epilog
sw.epilog:
%n.0 = phi i32 [undef, %sw.default], [%add7, %sw.bb4], [%sub, %sw.bb1
...], [10, %sw.bb]
%x.0 = phi i32 [2, %sw.default], [%add6, %sw.bb4], [%add3, %sw.bb1], [
... %add, %sw.bb]
%mul8 = mul nsw i32 2, %x.0
%add9 = add nsw i32 %mul8, 10
%add10 = add nsw i32 9, %x.0
%cmp = icmp sle i32 %add9, %add10
br i1 %cmp, label %if.end, label %if.else
T
F
if.else:
%mul11 = mul nsw i32 3, %x.0
%add12 = add nsw i32 %n.0, %mul11
switch i32 %add12, label %if.end [
i32 200, label %sw.bb14
i32 300, label %sw.bb15
]
def
200
300
if.end:
%add17 = add nsw i32 %add9, %x.0
store i32 %add17, i32* %m, align 4
br label %end
sw.bb14:
br label %end
sw.bb15:
call void @exit(i32 0) #6
unreachable
end:
ret i32 0

Hot Path SSA Form



HPSSAPass : Main Pass

- `HPSSAPass::run(Function &F, FunctionAnalysisManager &AM)`
  - Invoke `HPSSAPass::getProfileInfo()` function to get a compact representation of all the profiled hot paths in the program and then call `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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- Out of HPSSA Form.
    - A seperate 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 calll 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.