A whirlwind tour of the LLVM optimizer

Nikita Popov @ EuroLLVM 2023

Red Hat

Agenda

- High-level overview of the middle-end optimization pipeline
- Brief description of important optimization passes
  - Get basic idea about pass responsibilities
  - Learn about key restrictions/constraints

About Me

- Software Engineer on Platform Tools team at Red Hat
  - Packaging of LLVM for Fedora, CentOS and RHEL
  - Upstream work on LLVM and Clang

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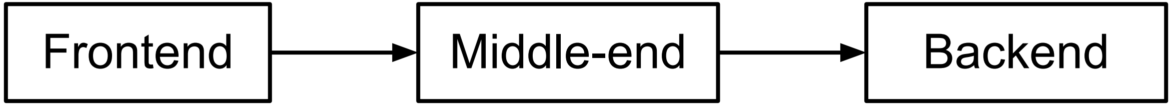
- Software Engineer on Platform Tools team at Red Hat
  - Packaging of LLVM for Fedora, CentOS and RHEL
  - Upstream work on LLVM and Clang
- I work on:
  - The LLVM middle-end
  - LLVM / Rust integration
  - Compilation time improvements (LLVM Compile-Time Tracker)

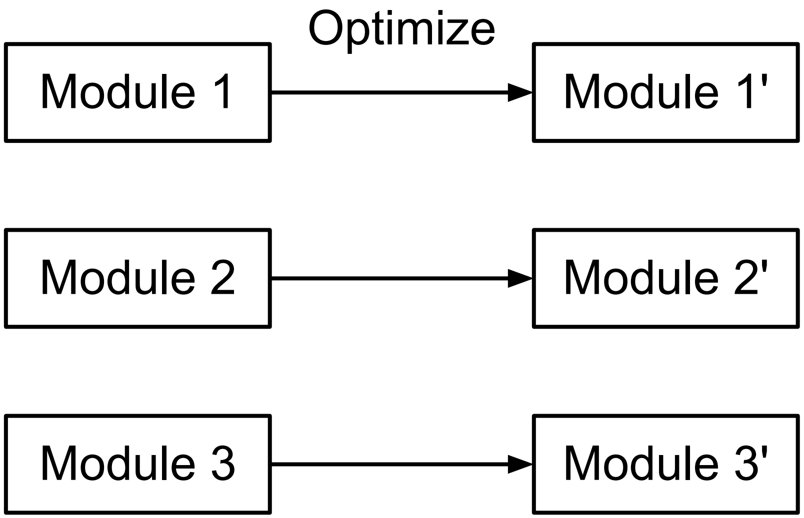
...ends



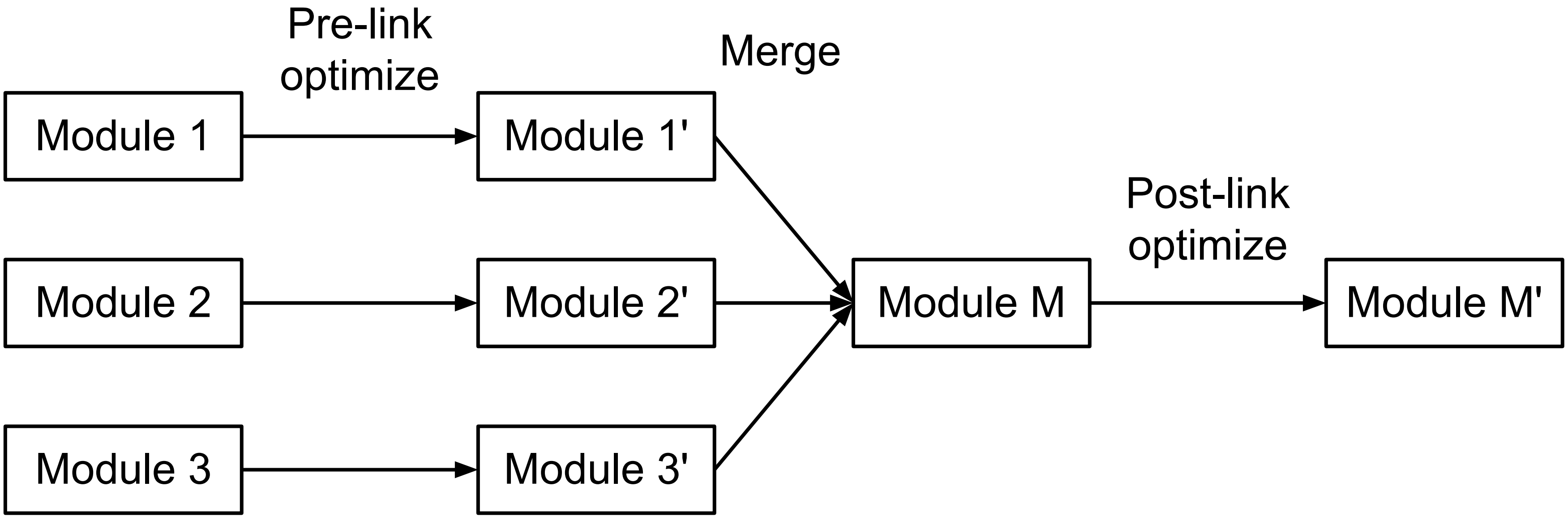
Clang
Rust
Swift
Julia
...

X86
AArch64
ARM
RISCV
...

Default (non-LTO) pipeline



Full LTO pipeline



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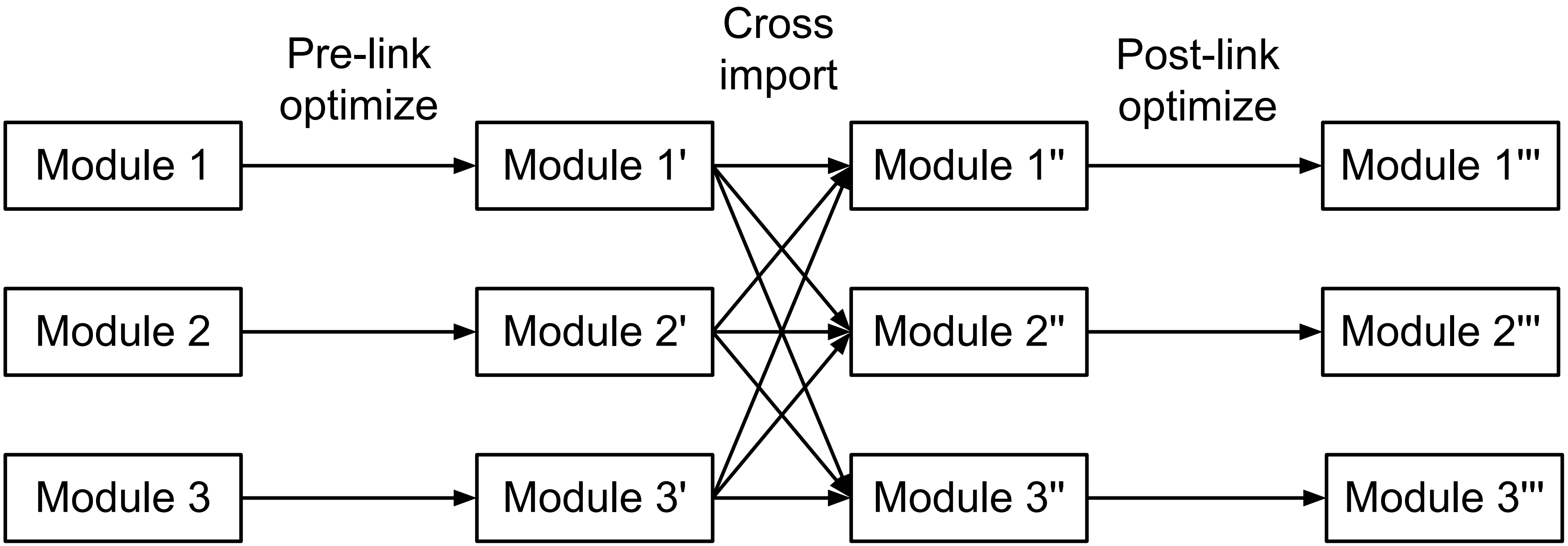
Thin LTO pipeline



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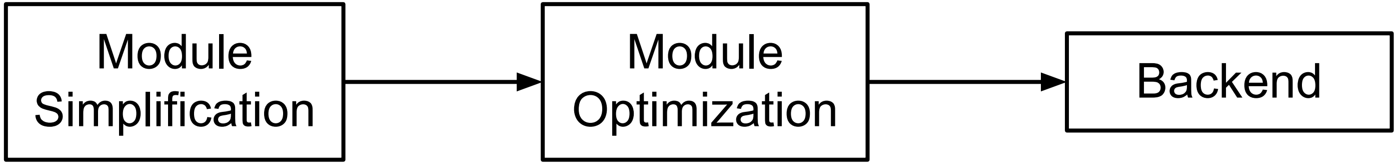
Default pipeline



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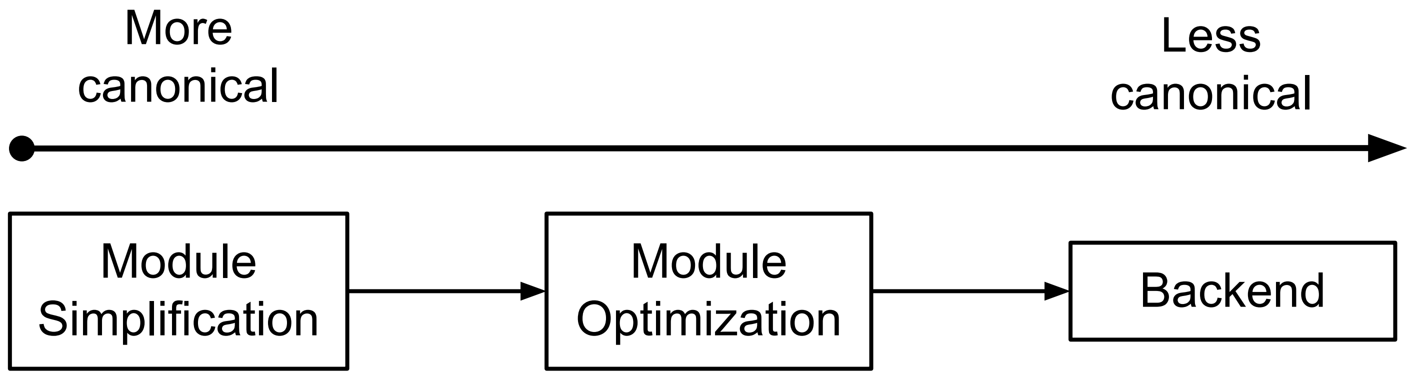

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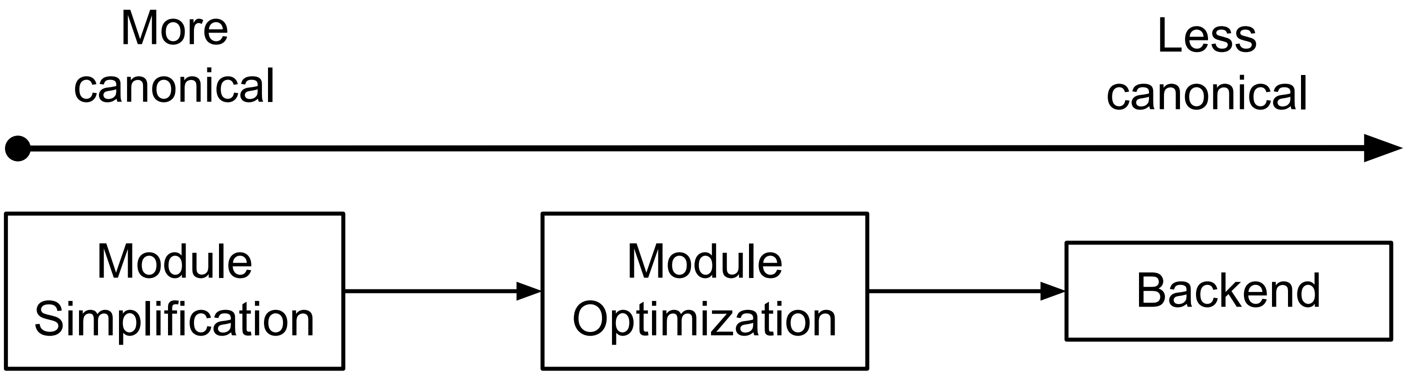

Inlining
Mem2Reg
LICM (Loop Invariant Code Motion)
...
Make further opts
easier

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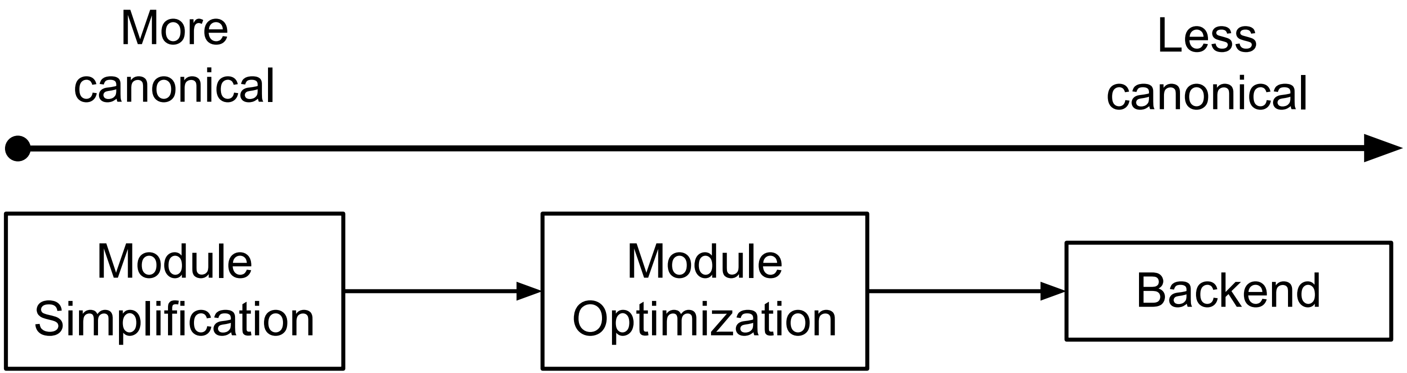
Default pipeline



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Mem2Reg
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...
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Vectorization
Runtime unrolling
...
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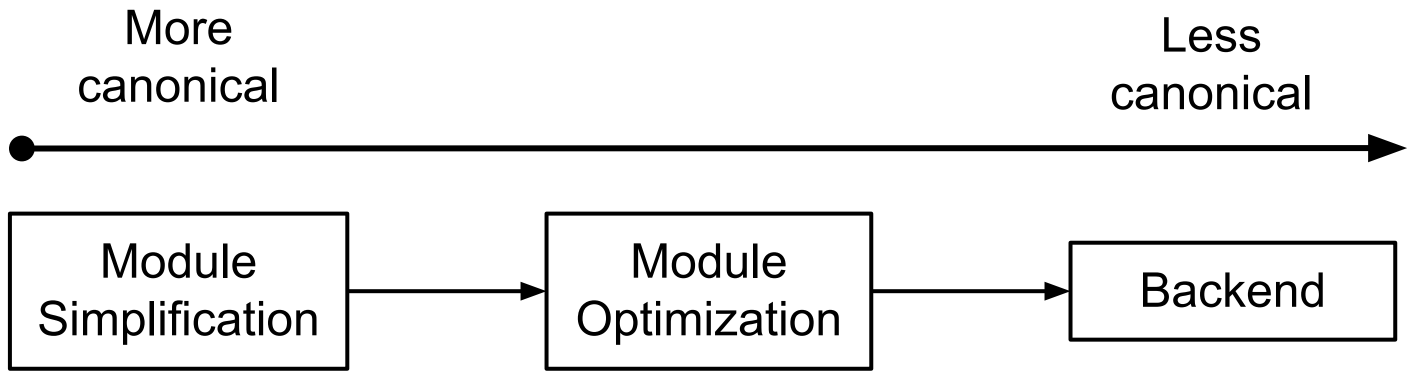
Default pipeline



Inlining
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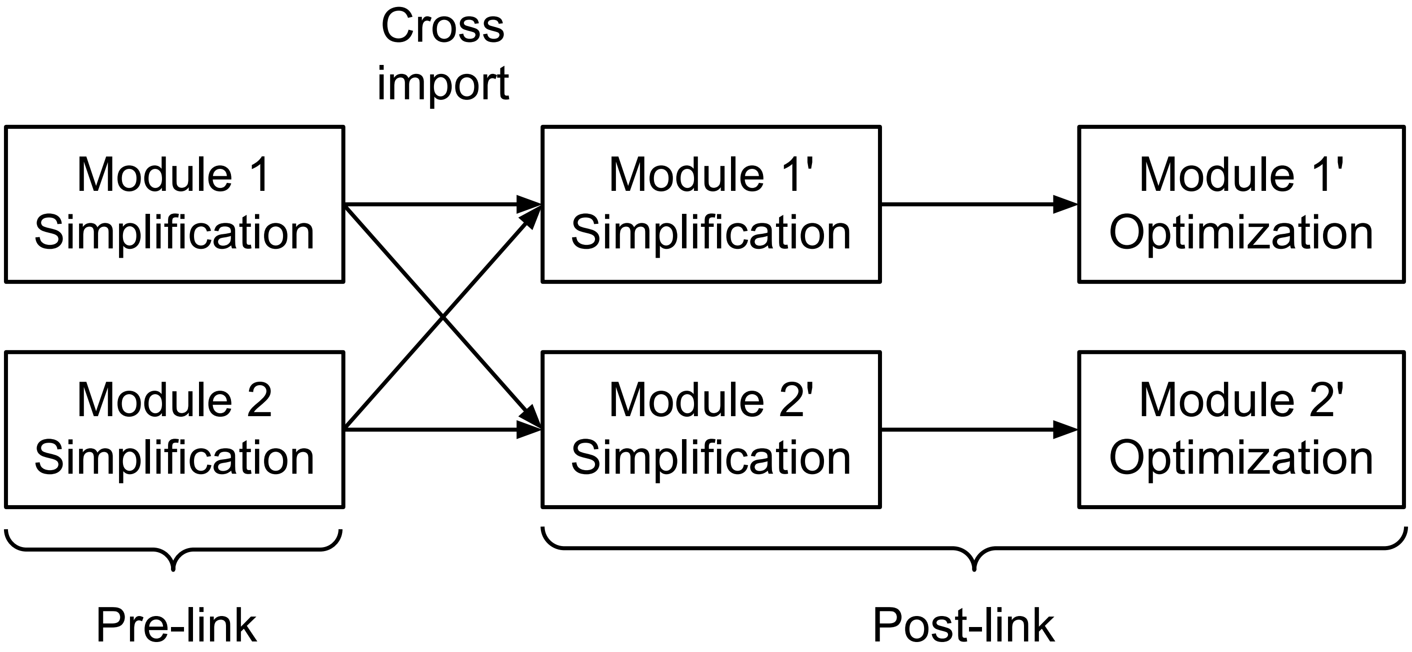
...
Make further opts easier

Vectorization
Runtime unrolling
...
Make further opts harder

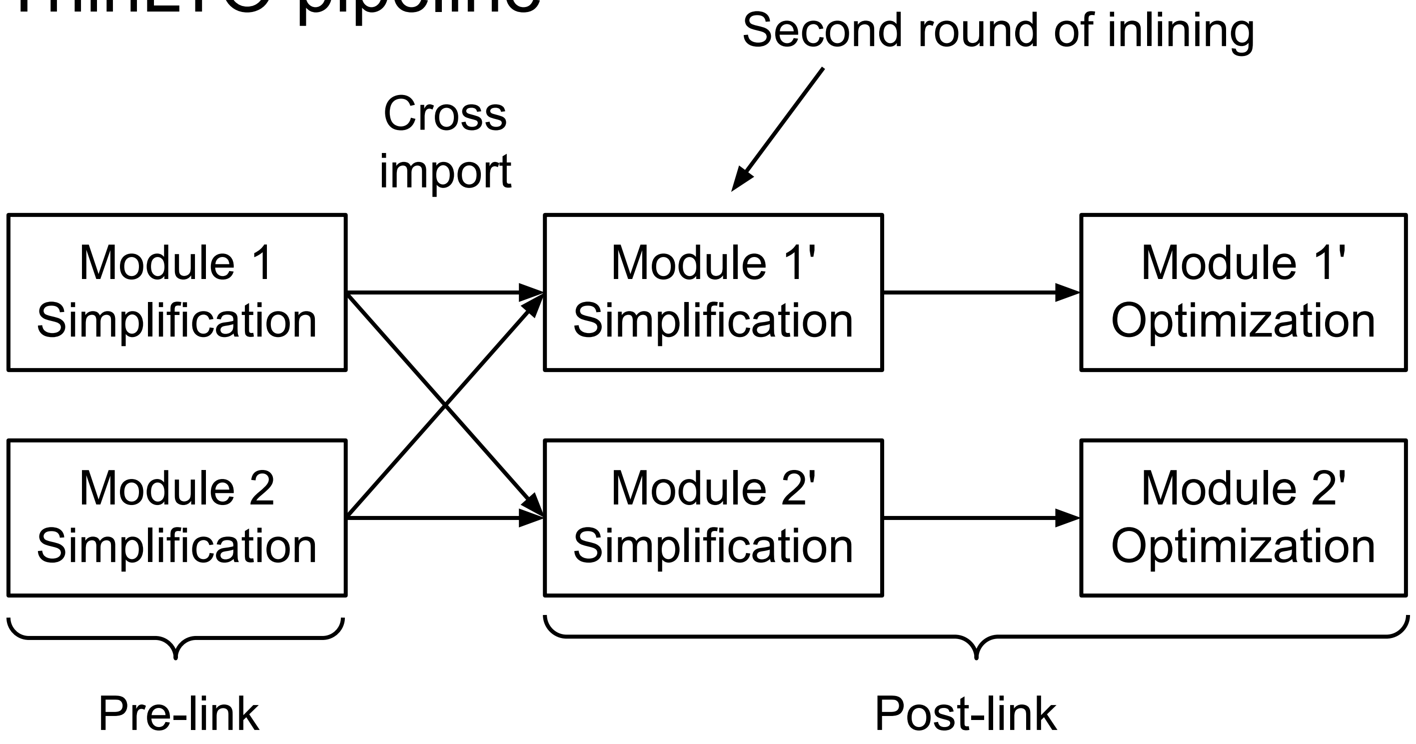
Target-specific optimization

Lowering to machine code

ThinLTO pipeline



ThinLTO pipeline



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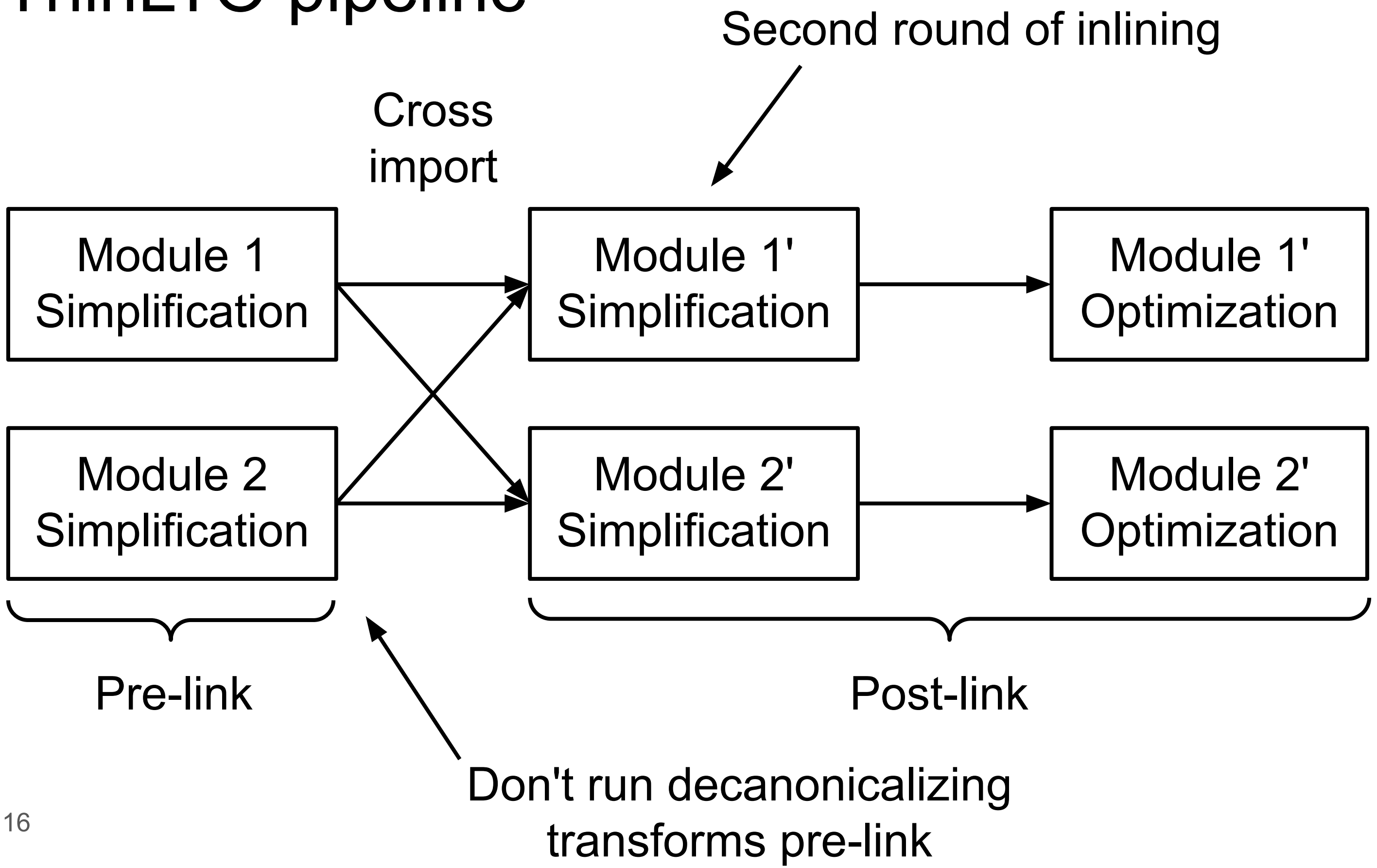
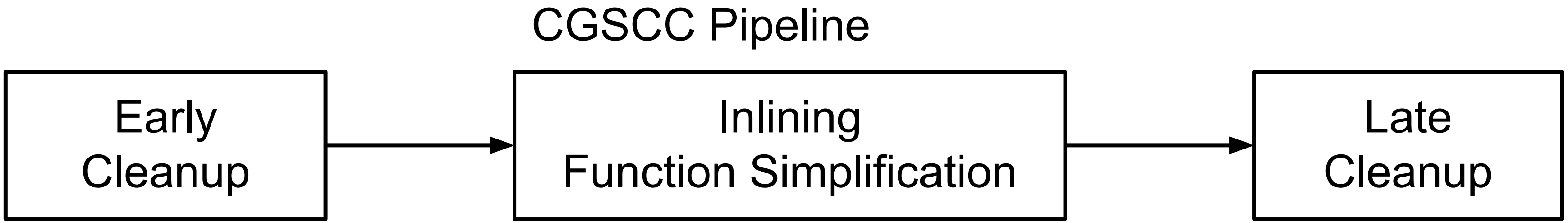
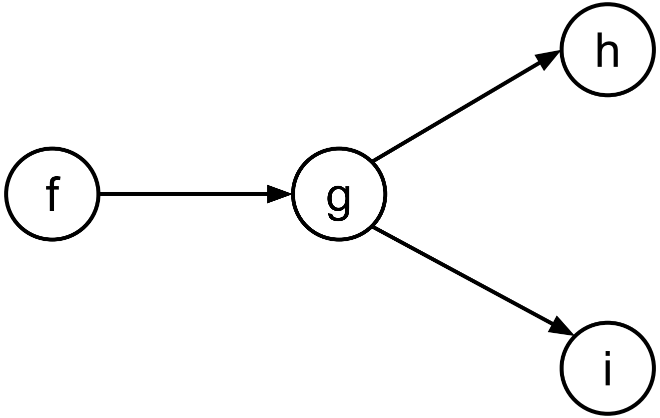


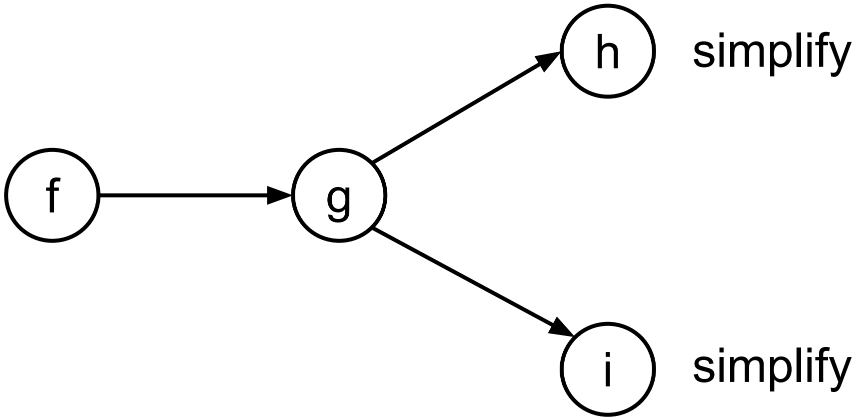
Module Simplification



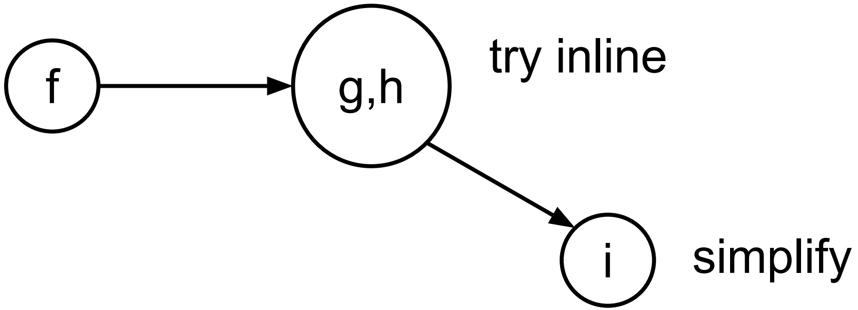
CGSCC Pipeline



CGSCC Pipeline



CGSCC Pipeline



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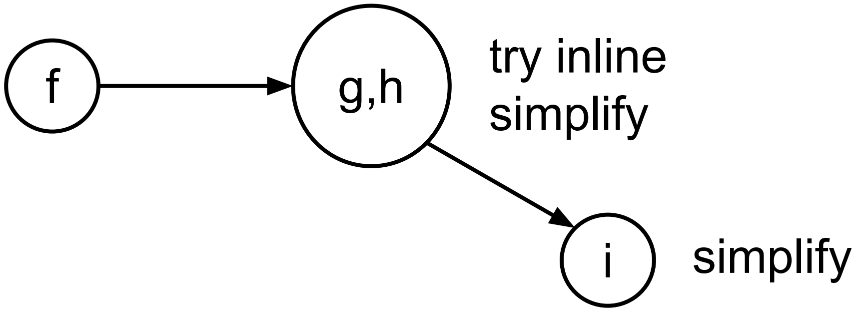
CGSCC Pipeline



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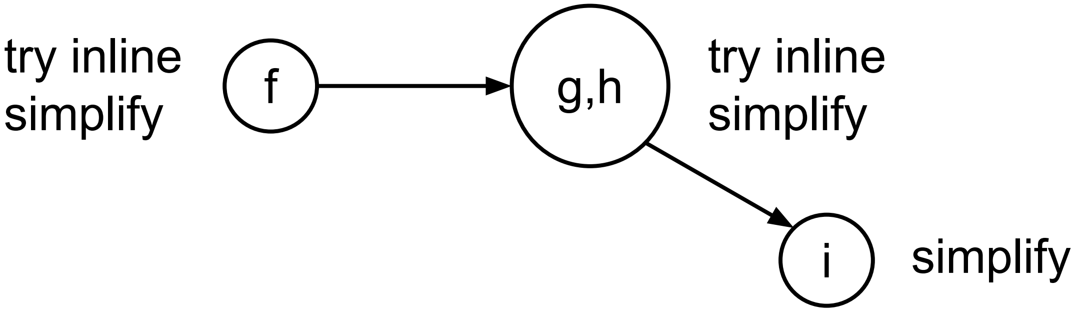

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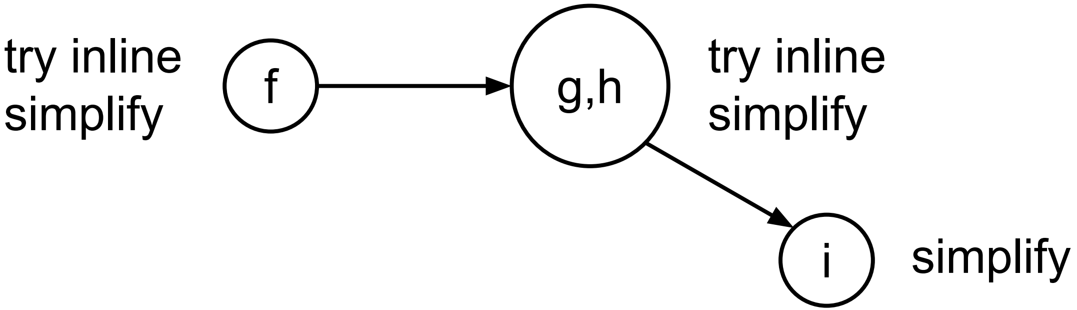
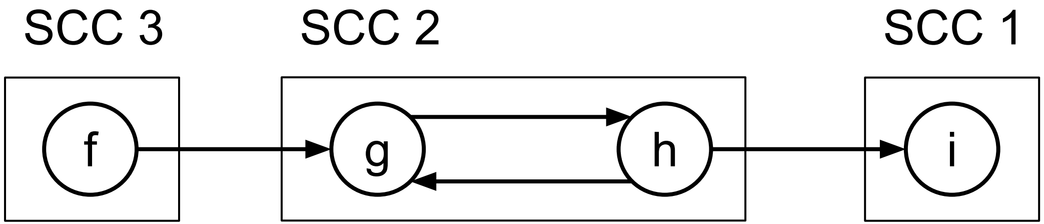


Inlining sees already simplified functions!

Call-Graph Strongly Connected Components



No well-defined order within SCC

Running pipelines

- `opt -passes='default<O3>'` == `opt -O3`
- `opt -passes='thinlto-pre-link<O3>'`
- `opt -passes='thinlto<O3>'`
- `opt -passes='lto-pre-link<O3>'`
- `opt -passes='lto<O3>'`

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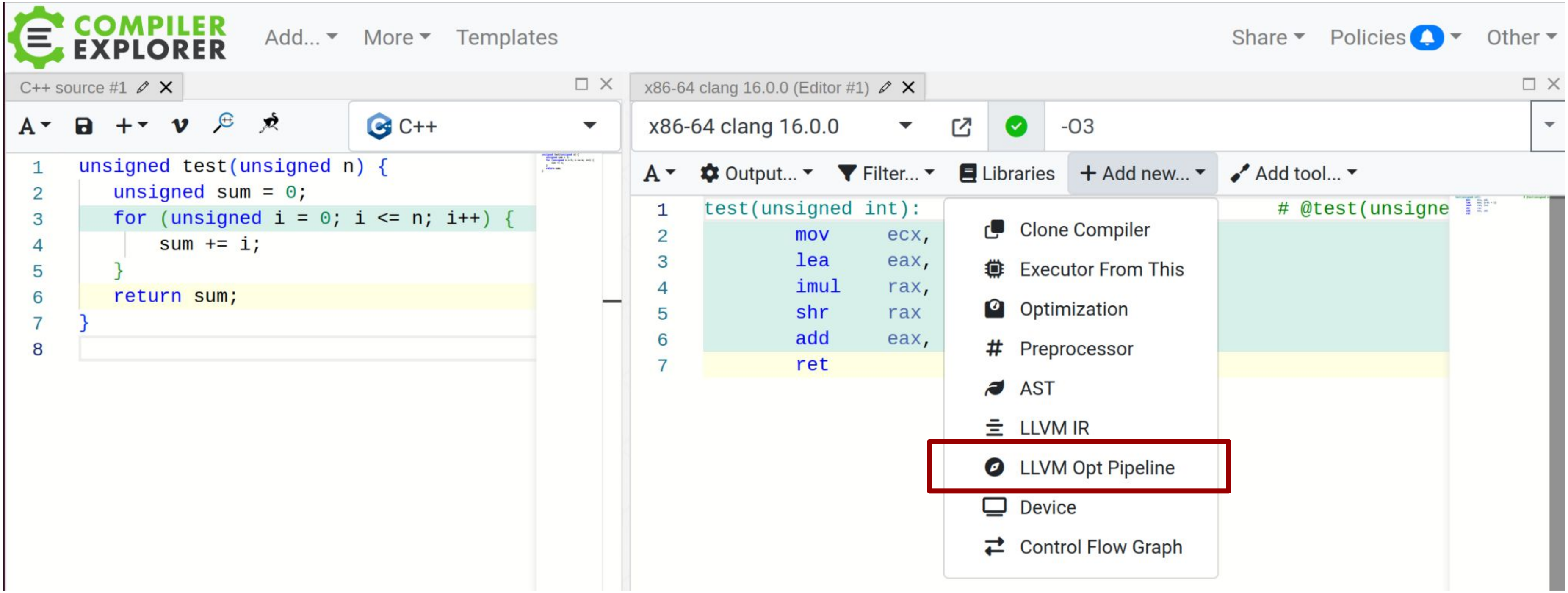
opt -passes='default<O3>' -print-pipeline-passes

```
annotation2metadata,forceattrs,inferattrs,coro-early,function<eager-inv>(lower-expect,simplifycfg<bonus-inst-threshold=1;no-forw
ard-switch-cond;no-switch-range-to-icmp;no-switch-to-lookup;keep-loops;no-hoist-common-insts;no-sink-common-insts>,sroa<modify-c
fg>,early-cse<>,callsite-splitting),openmp-opt,ipsccp,called-value-propagation,globalopt,function<eager-inv>(mem2reg,instcombine
<max-iterations=1000;no-use-loop-info>,simplifycfg<bonus-inst-threshold=1;no-forward-switch-cond;switch-range-to-icmp;no-switch-
to-lookup;keep-loops;no-hoist-common-insts;no-sink-common-insts>),require<globals-aa>,function(invalidate<aa>),require<profile-s
ummary>,cgscc(devirt<4>(inline<only-mandatory>,inline,function-attrs<skip-non-recursive>,argpromotion,openmp-opt-cgscc,function<
eager-inv;no-rerun>(sroa<modify-cfg>,early-cse<memssa>,speculative-execution,jump-threading,correlated-propagation,simplifycfg<b
onus-inst-threshold=1;no-forward-switch-cond;switch-range-to-icmp;no-switch-to-lookup;keep-loops;no-hoist-common-insts;no-sink-c
ommon-insts>,instcombine<max-iterations=1000;no-use-loop-info>,aggressive-instcombine,constraint-elimination,libcalls-shrinkwrap
,tailcallelim,simplifycfg<bonus-inst-threshold=1;no-forward-switch-cond;switch-range-to-icmp;no-switch-to-lookup;keep-loops;no-h
oist-common-insts;no-sink-common-insts>,reassociate,loop-mssa(loop-instsimplify,loop-simplifycfg,licm<no-allowspeculation>,loop-
rotate,licm<allowspeculation>,simple-loop-unswitch<nontrivial;trivial>),simplifycfg<bonus-inst-threshold=1;no-forward-switch-con
d;switch-range-to-icmp;no-switch-to-lookup;keep-loops;no-hoist-common-insts;no-sink-common-insts>,instcombine<max-iterations=100
0;no-use-loop-info>,loop(loop-idiom,indvars,loop-deletion,loop-unroll-full),sroa<modify-cfg>,vector-combine,mldst-motion<no-spli
t-footer-bb>,gvn<>,sccp,bdce,instcombine<max-iterations=1000;no-use-loop-info>,jump-threading,correlated-propagation,adce,memcpy
opt,dse,move-auto-init,loop-mssa(licm<allowspeculation>),coro-elide,simplifycfg<bonus-inst-threshold=1;no-forward-switch-cond;sw
itch-range-to-icmp;no-switch-to-lookup;keep-loops;hoist-common-insts;sink-common-insts>,instcombine<max-iterations=1000;no-use-l
oop-info>),function-attrs,function(require<should-not-run-function-passes>),coro-split)),deadargelim,coro-cleanup,globalopt,glob
aldce,elim-avail-extern,rpo-function-attrs,recompute-globalsaa,function<eager-inv>(float2int,lower-constant-intrinsics,chr,loop(
loop-rotate,loop-deletion),loop-distribute,inject-tli-mappings,loop-vectorize<no-interleave-forced-only;no-vectorize-forced-only
;>,loop-load-elim,instcombine<max-iterations=1000;no-use-loop-info>,simplifycfg<bonus-inst-threshold=1;forward-switch-cond;switc
h-range-to-icmp;switch-to-lookup;no-keep-loops;hoist-common-insts;sink-common-insts>,slp-vectorizer,vector-combine,instcombine<m
ax-iterations=1000;no-use-loop-info>,loop-unroll<O3>,transform-warning,sroa<preserve-cfg>,instcombine<max-iterations=1000;no-use
-loop-info>,loop-mssa(licm<allowspeculation>),alignment-from-assumptions,loop-sink,instsimplify,div-rem-pairs,tailcallelim,simpl
ifycfg<bonus-inst-threshold=1;no-forward-switch-cond;switch-range-to-icmp;no-switch-to-lookup;keep-loops;no-hoist-common-insts;n
o-sink-common-insts>),globaldce,constmerge,cg-profile,rel-lookup-table-converter,function(annotation-remarks),verify,print
```

Defined in `PassBuilderPipelines.cpp`

godbolt.org – LLVM Opt Pipeline



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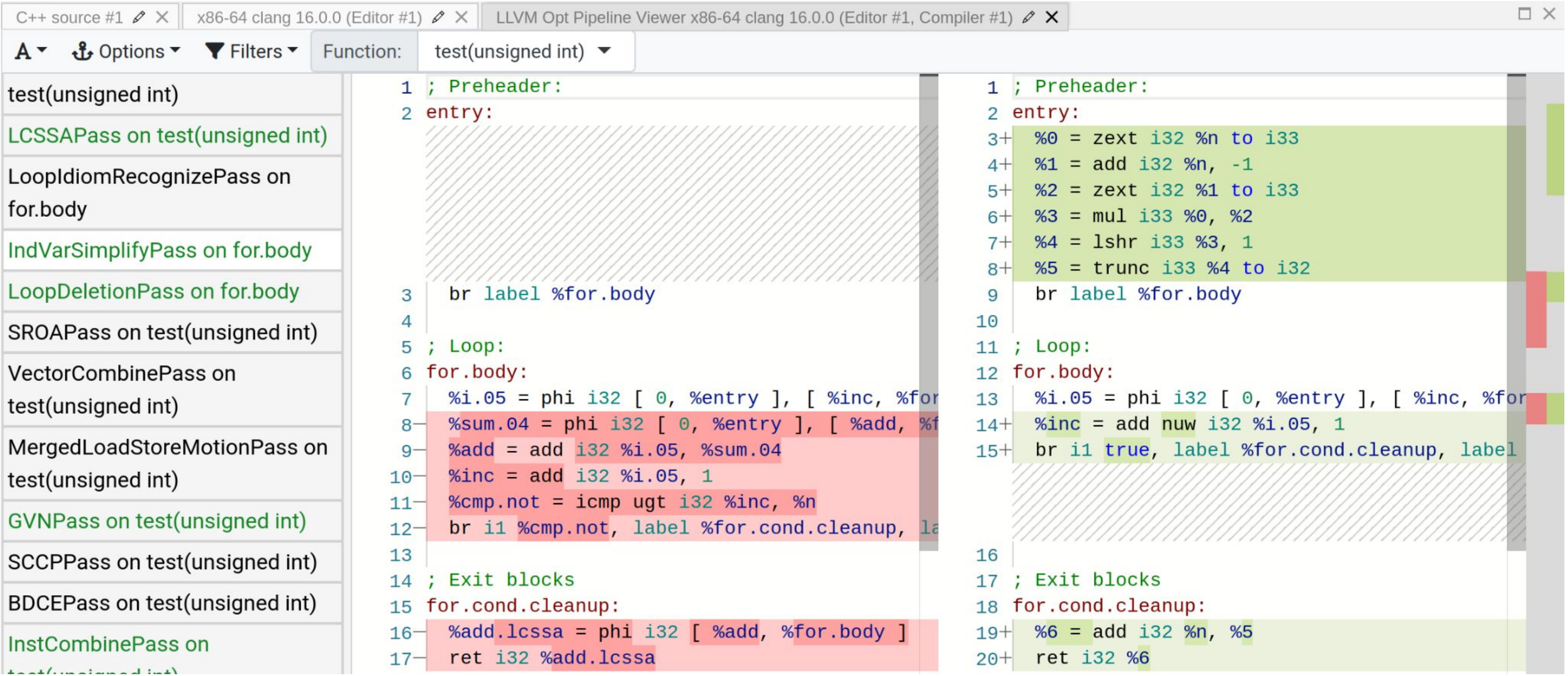

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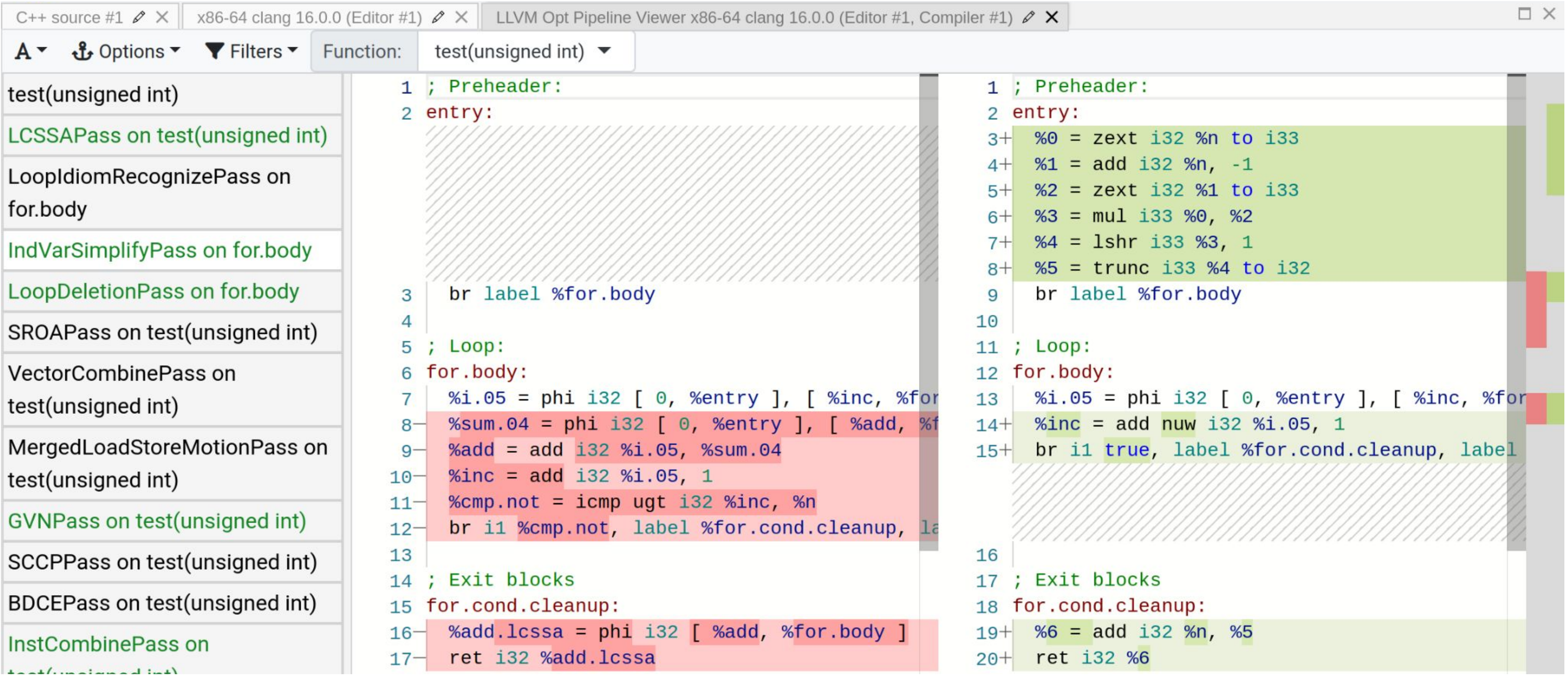
Or run `opt -print-after-all` locally



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SSA Construction

Mem2Reg

```
int test(int x, int y) {
    return x + y;
}
```

Mem2Reg

```
define i32 @test(i32 %x, i32 %y) {
entry:
 %x.addr = alloca i32
 %y.addr = alloca i32
 store i32 %x, ptr %x.addr
 store i32 %y, ptr %y.addr
 %0 = load i32, ptr %x.addr
 %1 = load i32, ptr %y.addr
 %add = add nsw i32 %0, %1
 ret i32 %add
}
```

Mem2Reg

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define i32 @test(i32 %x, i32 %y) {
entry:
 %add = add nsw i32 %x, %y
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```

SROA: Scalar Replacement of Aggregates

- Break up allocas into smaller allocas based on access pattern
  - `%vec = alloca { ptr, i64, i64 }`
  - `-> %vec.ptr = alloca ptr`
  - `-> %vec.size = alloca i64`
  - `-> %vec.capacity = alloca i64`

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- Then run Mem2Reg to convert alloca/load/store to SSA values
- Knows many tricks for overlapping accesses
  - For example inserting/extracting bits of a larger integer

Control-Flow Optimization

SimplifyCFG

- The kitchen sink of control-flow transforms
  - If it fits nowhere else, put it here!

SimplifyCFG: Hoist

```
if (cond) {
  foo();
  a();
} else {
  foo();
  b();
}
```

→

```
foo();
if (cond) {

  a();
} else {

  b();
}
```


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SimplifyCFG: Speculate

```
if (cond) {
  x = foo();
} else {
  x = 0;
}
```

→

```
tmp = foo();
x = cond ? tmp : 0;
```

SimplifyCFG: Switch to lookup table

```
switch (x) {
case 0:
  return 10;
case 1:
  return 42;
case 2:
  return 123;
case 3:
  return 7;
default:
  return 13;
}
```

→

```
int table[] = {10, 42, 123, 7};

if (x < 4) {
  return table[x];
} else {
  return 13;
}
```

SimplifyCFG

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- Invoked with many different options at different pipeline positions
  - Some transforms only run late in the pipeline

SimplifyCFG

- The kitchen sink of control-flow transforms
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- Invoked with many different options at different pipeline positions
  - Some transforms only run late in the pipeline
- Can use target-dependent cost model (via TargetTransformInfo)

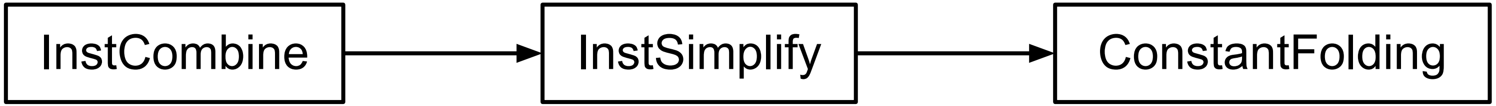
Instruction Combining

(Peephole Optimization)

InstCombine

- The kitchen sink of non-CFG transforms
  - If it fits nowhere else, put it here!

InstCombine: Analysis helpers



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  - 1 + 2 => 3

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  - `x + 0   =>   x`
  - `x - x   =>   0`

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- ConstantFolding
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- InstSimplify
  - Folds instructions to existing values or constants
  - `x + 0   =>   x`
  - `x - x   =>   0`
- InstCombine
  - Tries constant folding and instruction simplification first
  - Performs folds that create or modify instructions
  - `x * 4   =>   x << 2`

InstCombine

- The kitchen sink of non-CFG transforms
  - If it fits nowhere else, put it here!
  - Use InstSimplify / ConstantFolding for transforms that don't create/modify instructions.

InstCombine

- The kitchen sink of non-CFG transforms
    - If it fits nowhere else, put it here!
    - Use InstSimplify / ConstantFolding for transforms that don't create/modify instructions.
- Also used to paper over phase ordering issues
    - InstCombine re-implements weak versions of transforms from other passes
    - For example: Basic store-to-load forwarding (usually done by EarlyCSE/GVN)

…Combine

- InstCombine
  - Canonicalization pass: **Cannot** be target-dependent
  - Backend implements reverse/undo transform if necessary

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- AggressiveInstCombine
  - For expensive transforms, only runs once in pipeline
  - Target-dependence discouraged but sometimes allowed
- VectorCombine
  - For target-dependent, cost-model driven vector transforms

CVP: CorrelatedValuePropagation

- Optimizations based on value range information (from LazyValueInfo)
- Important for bounds check elimination
  - `icmp ult i32 %x, 10  =>  i1 true if %x in [0, 10)`

CVP: CorrelatedValuePropagation

- Optimizations based on value range information (from LazyValueInfo)
- Important for bounds check elimination
  - `icmp ult i32 %x, 10  =>  i1 true` if `%x` in `[0, 10)`
- Other range based optimizations
  - `sdiv i32 %x, %y  =>  udiv i32 %x, %y` if `%x`, `%y` non-negative

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Same transform, different analysis

- Some folds (e.g. sdiv -> udiv) are implemented in multiple passes
    - Folds are driven by different analyses, which are good at different things

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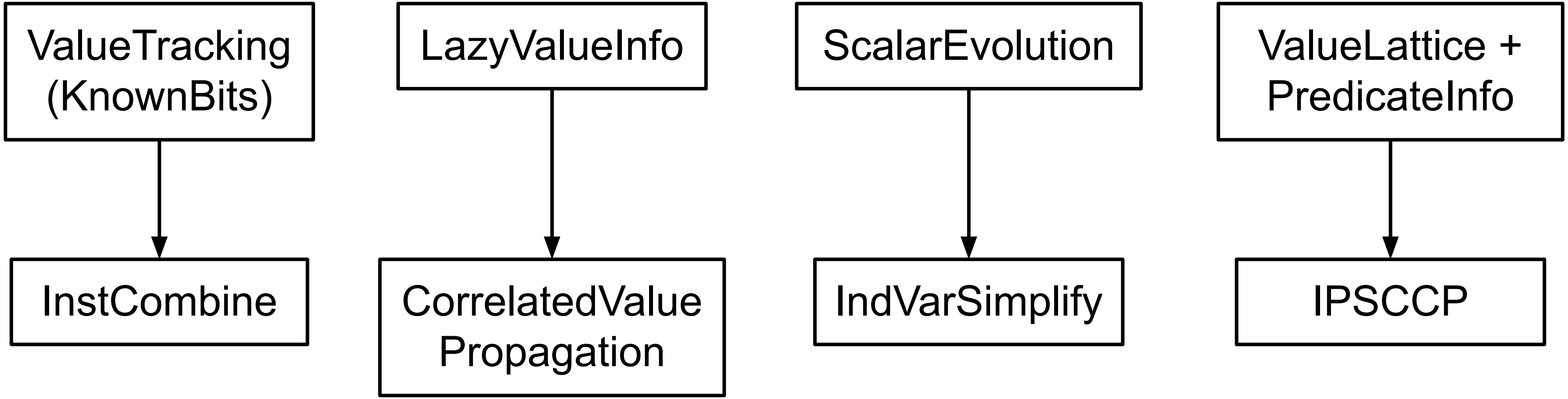

Redundancy Elimination

EarlyCSE: Common Subexpression Elimination

```
add1 = x + y;
// ...
add2 = x + y;

use(add1);
use(add2);
```

→

```
add1 = x + y;
// ...


use(add1);
use(add1);
```


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EarlyCSE: Common Subexpression Elimination

- Basic CSE based on scoped hash table
- Load CSE and store-to-load forwarding using MemorySSA

EarlyCSE: Store to load forwarding

```
*p = v1;
// p not written here
v2 = *p;

use(v1);
use(v2);
```

→

```
*p = v1;



use(v1);
use(v1);
```


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GVN: Global Value Numbering

- More general (and much more expensive!) than EarlyCSE
- Uses MemoryDependenceAnalysis
- Non-local load CSE
- Partial redundancy elimination (PRE)

GVN: Non-local load CSE

```
if (...) {
   v1 = *p;
} else {
   *p = v2;
}

v3 = *p;
use(v3);
```

→

```
if (...) {
   v1 = *p;
} else {
   *p = v2;
}

v3 = phi(v1, v2);
use(v3);
```

GVN: Load PRE

```
if (...) {

} else {
    *p = v1;
}

v2 = *p;
use(v2);
```

→

```
if (...) {
    v2_pre = *p;
} else {
    *p = v1;
}

v2 = phi(v2_pre, v1);
use(v2);
```


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Memory Optimizations

MemCpyOpt

- Optimize memcpy and memset using MemorySSA

MemCpyOpt: Memcpy forwarding

```
memcpy(y, x, 16);
// y not written here
memcpy(z, y, 16);
```

→

```
memcpy(y, x, 16);
// y not written here
memcpy(z, x, 16);
```

MemCpyOpt: Call Slot Optimization

```
Ty tmp;
foo(tmp);
memcpy(dst, tmp, sizeof(Ty));
```

→

```
foo(dst);
```

DSE: Dead Store Elimination

- Remove dead stores using MemorySSA

DSE: Dead Store Elimination

```
*p = v1;
// p not read here
*p = v2;
```

→

```
// p not read here
*p = v2;
```

DSE: Dead before return

```
%p = alloca i32
; ...
store i32 %v, ptr %p
; %p not read here
ret void
```

→

```
%p = alloca i32
; ...

; %p not read here
ret void
```


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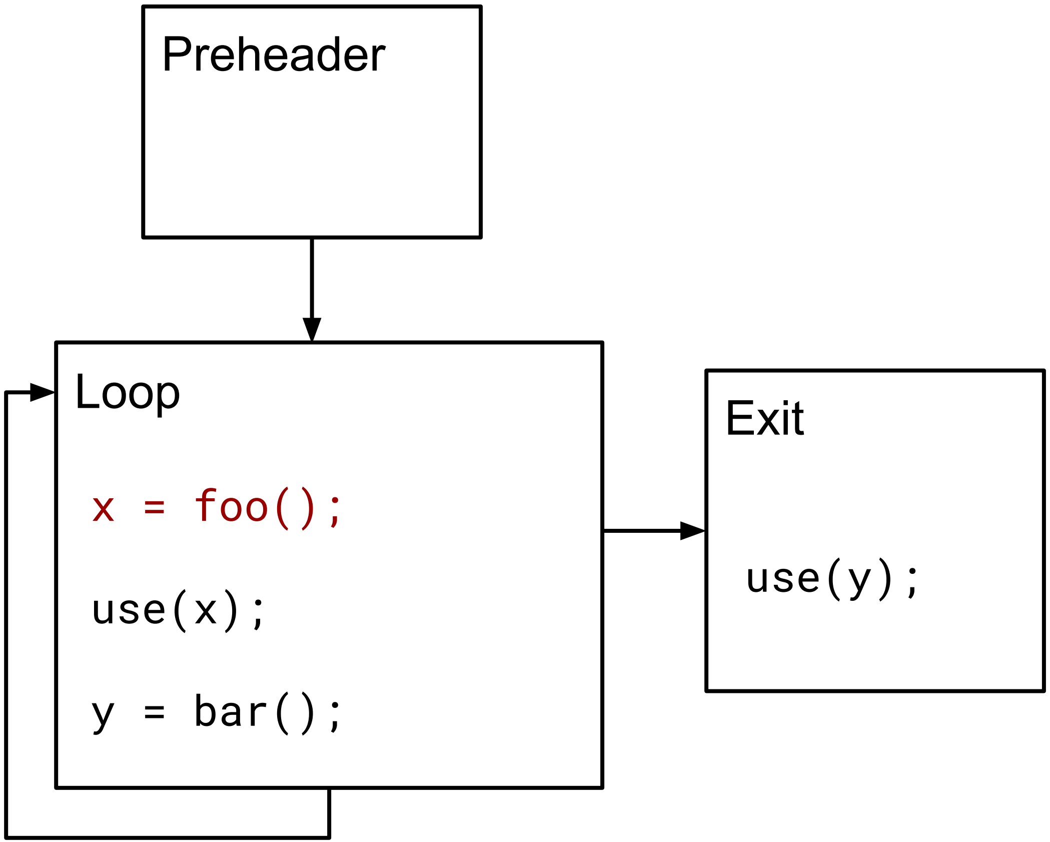
Loop Optimization

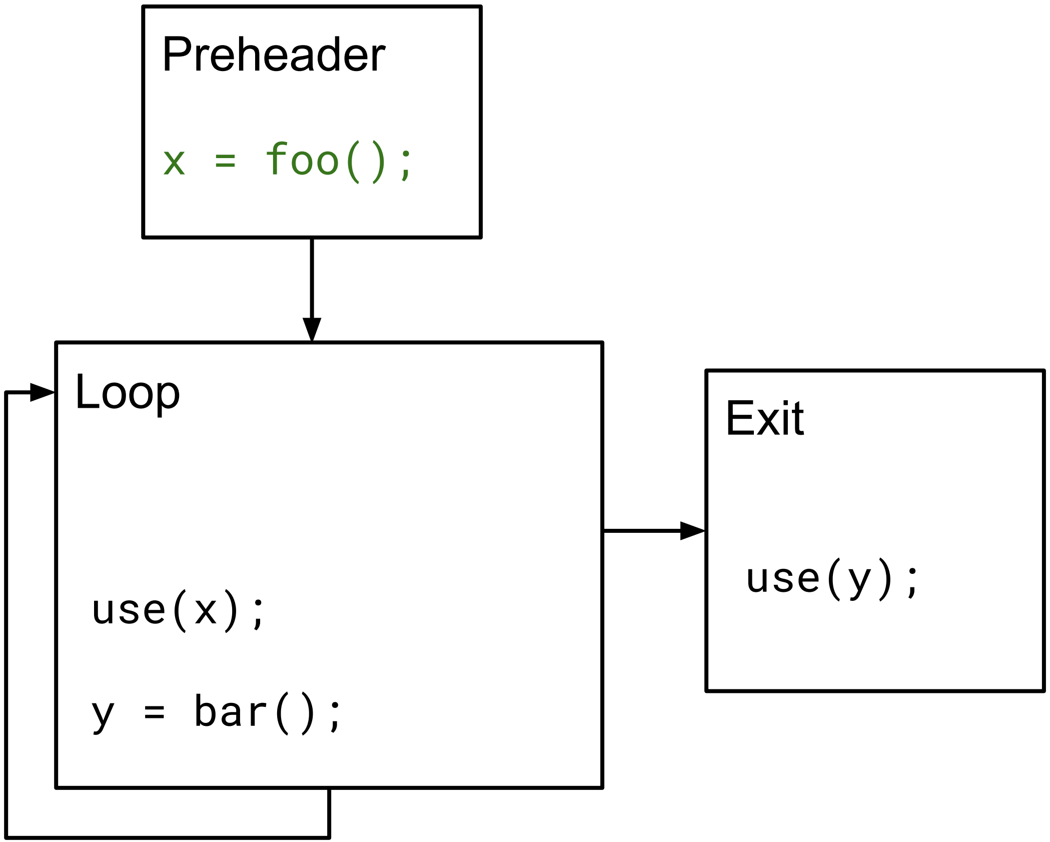
Loop pass manager

- Visit child loops first, then parent loops
- Constructs LoopSimplify and LCSSA (Loop-Closed SSA) form before running

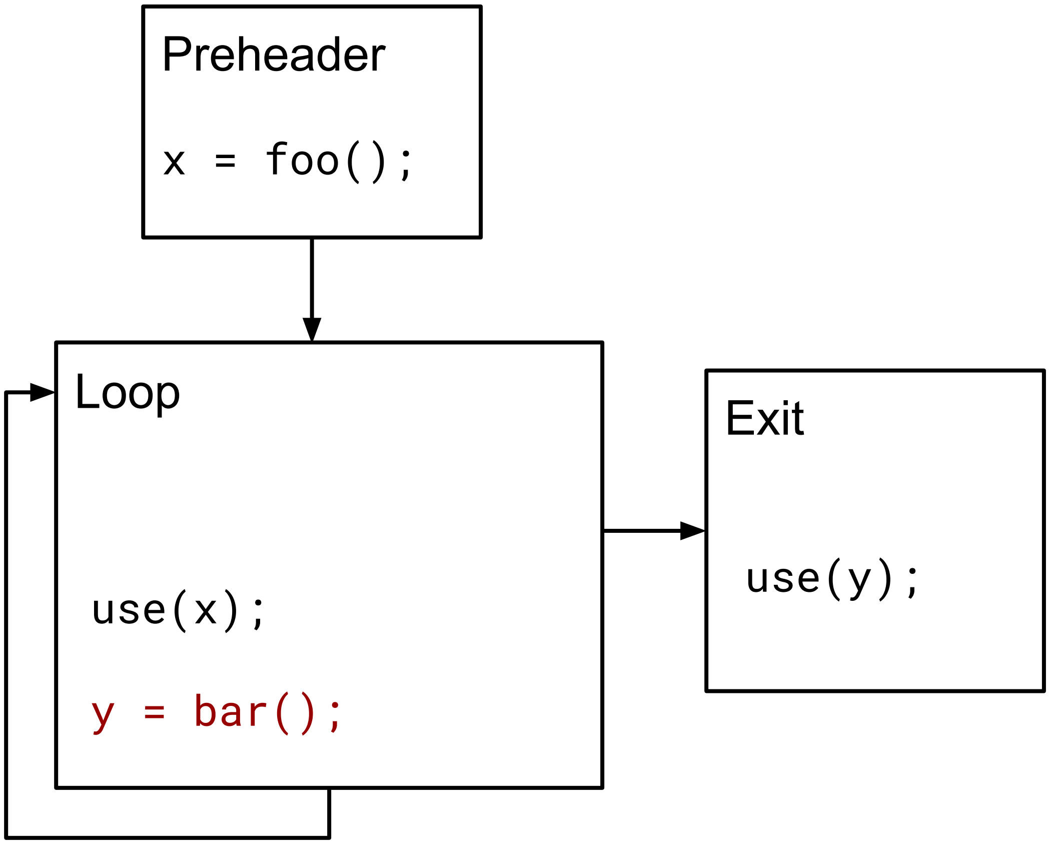
LICM: Hoist



LICM: Hoist



LICM: Sink



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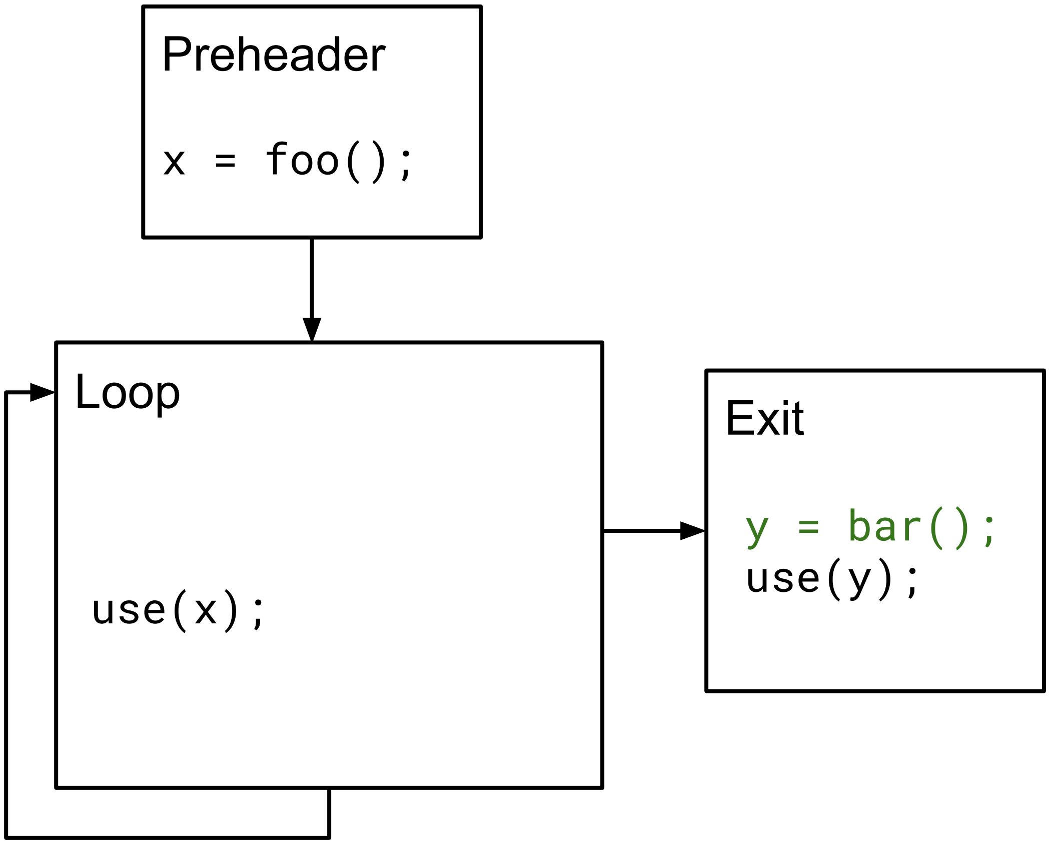

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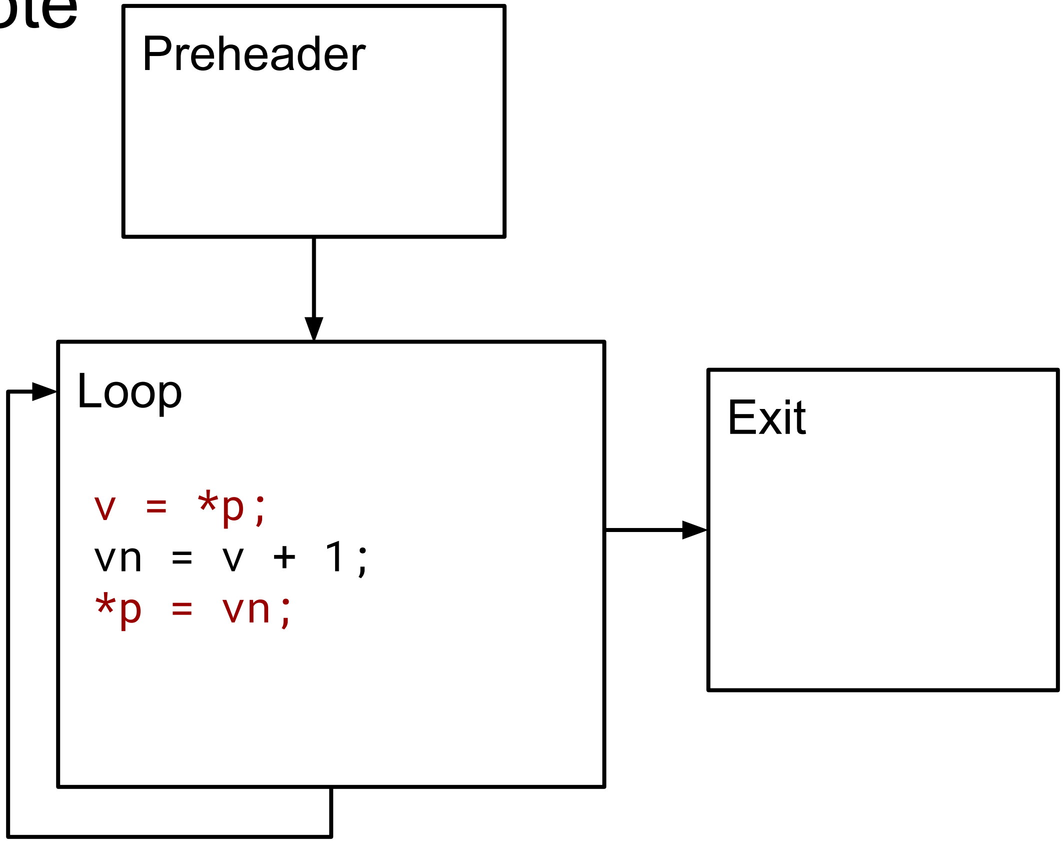
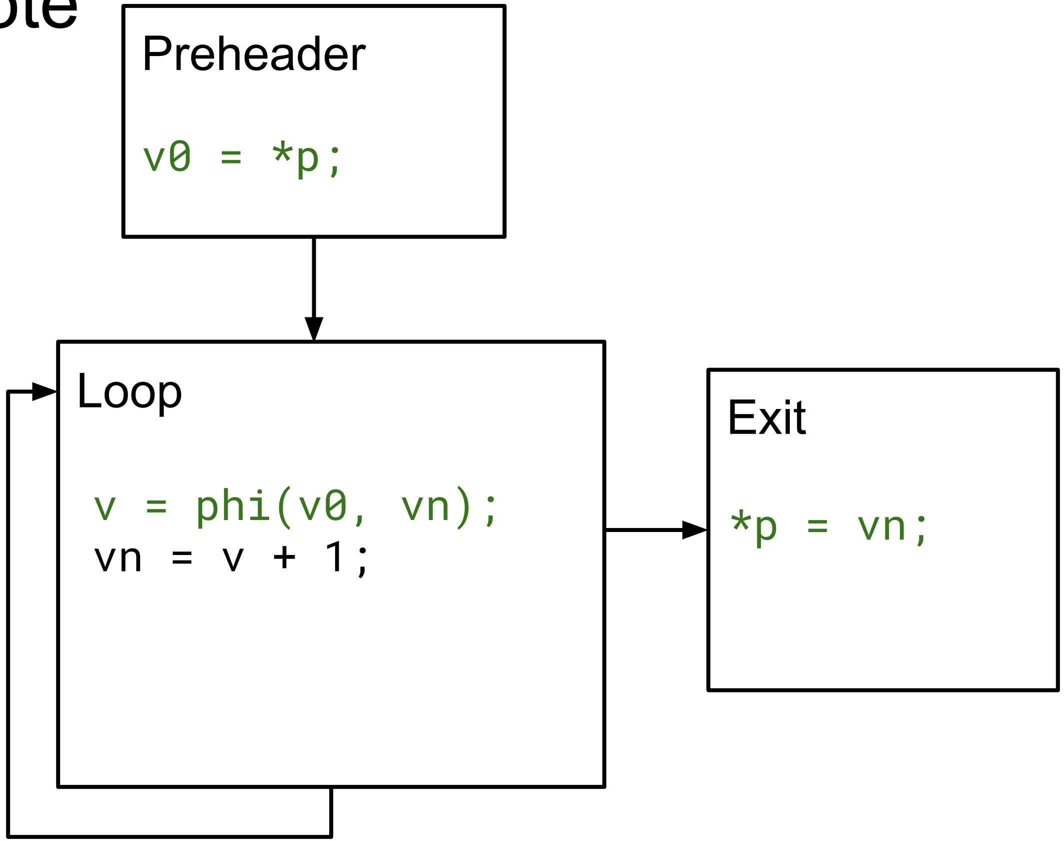
LICM: Promote



LICM: Promote



LICM: Loop Invariant Code Motion

- Transforms:
  - Hoist instructions into preheader
  - Sink instructions into exits
  - Promote scalars
- Uses MemorySSA
- Canonicalization pass: **Cannot** be target or PGO dependent
  - May be undone by LoopSink or MachineSink

IndVarSimplify

- Uses ScalarEvolution analysis
- Simplify induction variables (IVs) and their uses
- Simplify loop exit conditions

IndVarSimplify: Loop exit value replacement

```
unsigned test(unsigned n) {
   unsigned sum = 0;
   for (unsigned i = 0; i <= n; i++) {
       sum += i;
   }
   return sum;
}
```

IndVarSimplify: Loop exit value replacement

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↓

```
unsigned test(unsigned n) {
   for (unsigned i = 0; i <= n; i++) {}

   return (n * (n - 1))/2 + n;
}
```

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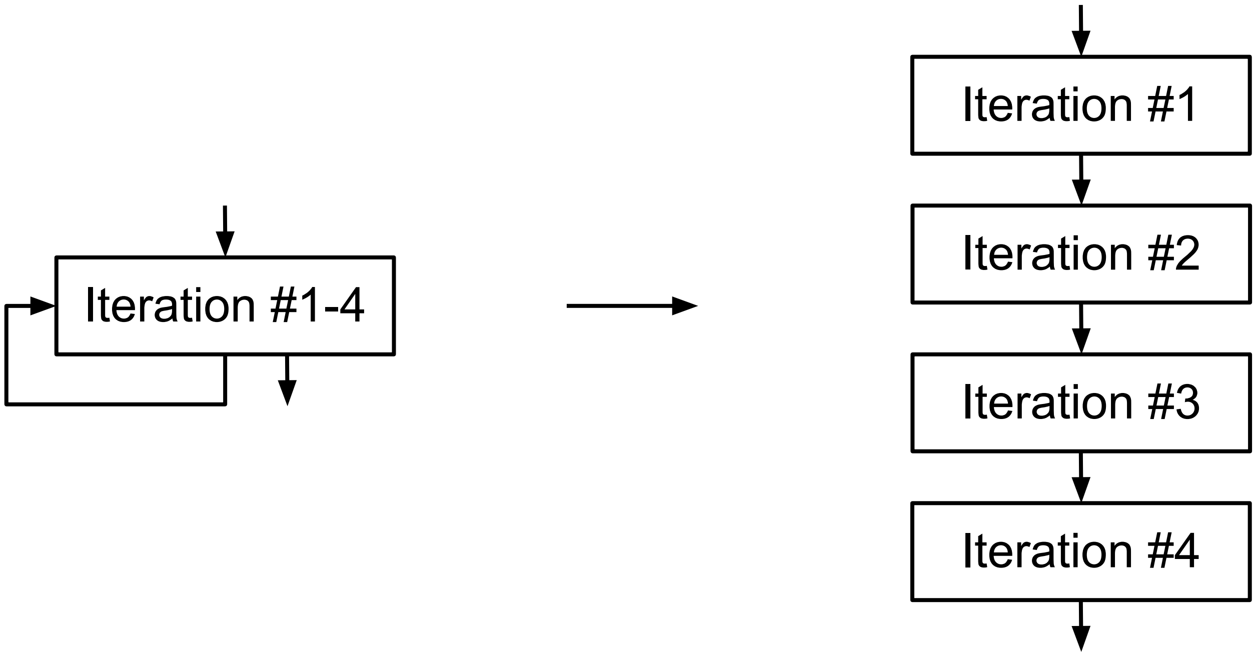
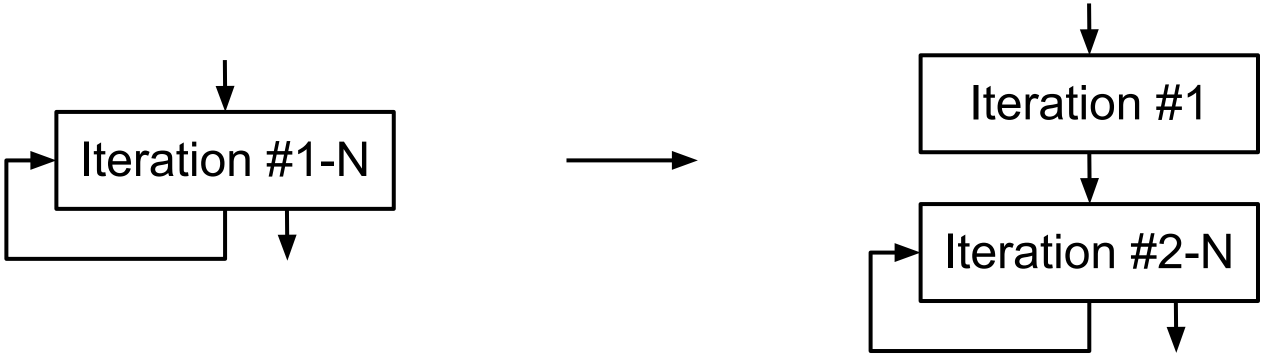
Later removed by LoopDeletion

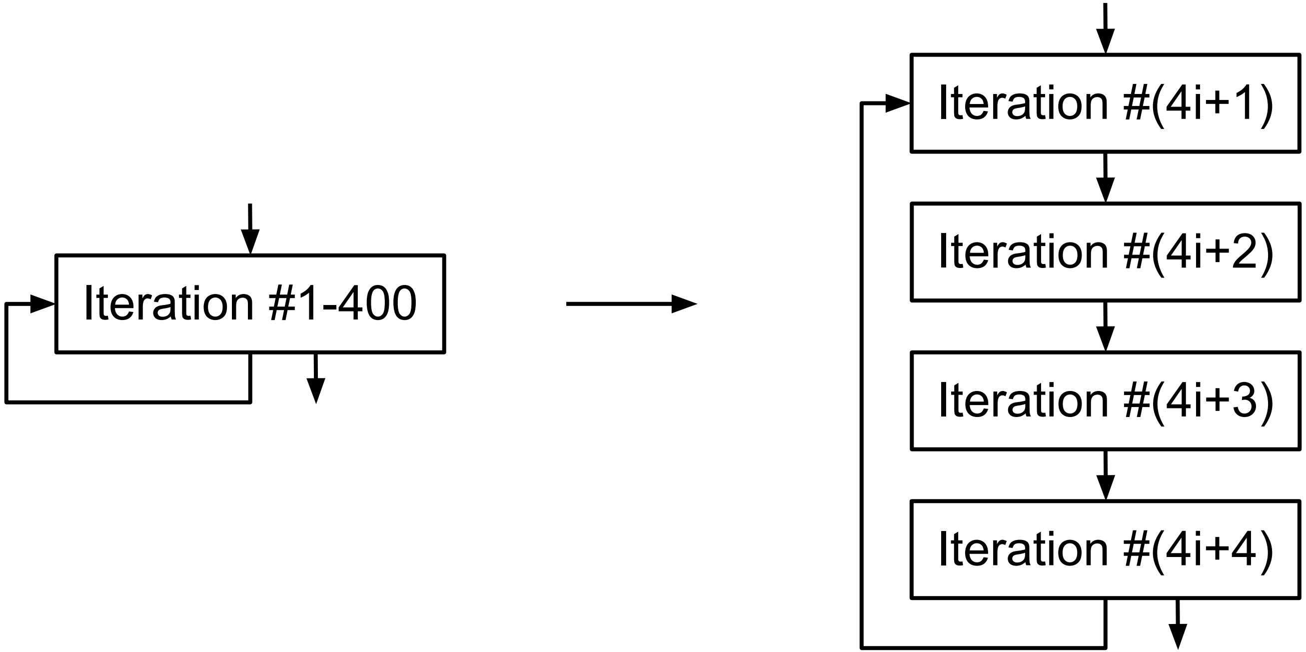
LoopUnroll: Full unrolling



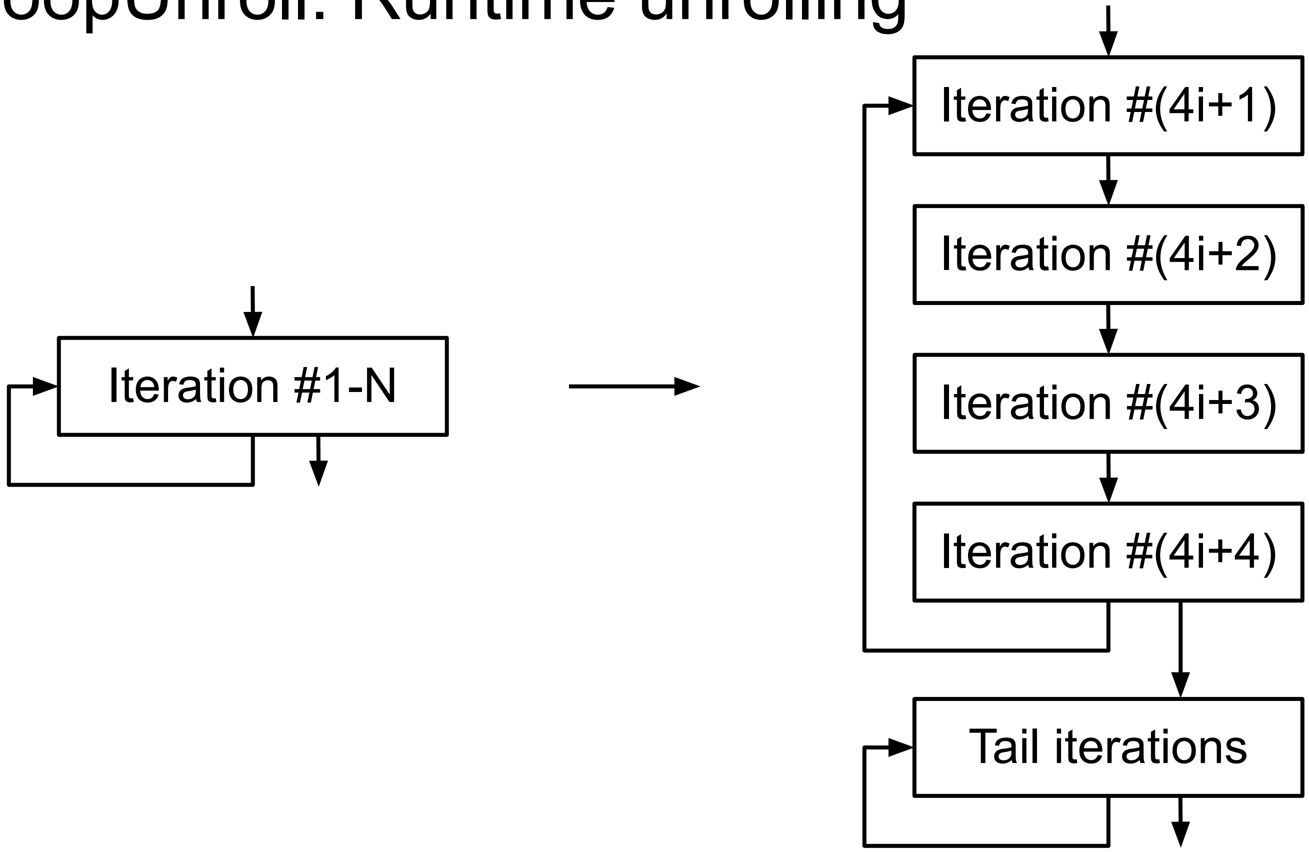
LoopUnroll: Loop peeling



LoopUnroll: Partial unrolling



LoopUnroll: Runtime unrolling



LoopUnroll

- Simplification:
  - Full unrolling (requires known constant trip count)
  - Loop peeling
- Optimization:
  - Partial unrolling (requires known constant trip count/multiple)
  - Runtime unrolling

Vectorization

LoopVectorize

- VPlan to model vectorization without IR changes
- LoopAccessAnalysis to ensure memory dependences are safe
- May require inserting runtime checks and LoopVersioning

SLPVectorize

- SLP = Superword-Level Parallelism
- Vectorizes straight-line code

Inter-Procedural Optimization (IPO)

FunctionAttrs

- Infer attributes on function, arguments and return values
    - nounwind, readonly, nonnull, etc.

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FunctionAttrs

- Infer attributes on function, arguments and return values
  - nounwind, readonly, nonnull, etc.
- General approach:
  - Optimistically all functions in the SCC are nounwind
  - Check whether there are any non-nounwind instructions
  - If not, mark all functions in the SCC nounwind
- New "Attributor" implements much stronger version of this, but not enabled by default (too slow)

IPSCCP: Inter-Procedural Sparse Conditional Constant Propagation

- Propagates constants and constant ranges across functions
- Uses PredicateInfo to take branch conditions into account

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- Uses PredicateInfo to take branch conditions into account
- Runs very early, before most simplification (which may lose information)
- Also does function specialization (since recently)

Thank You!
Questions?

The End

- Blog: https://www.npopov.com/
- Reach me at:
  - npopov@redhat.com
  - https://twitter.com/nikita_ppv

Bonus Slides

JumpThreading

```
if (x > 10) {
  greater10();
}
always();
if (x > 0) {
  greater0();
}
```

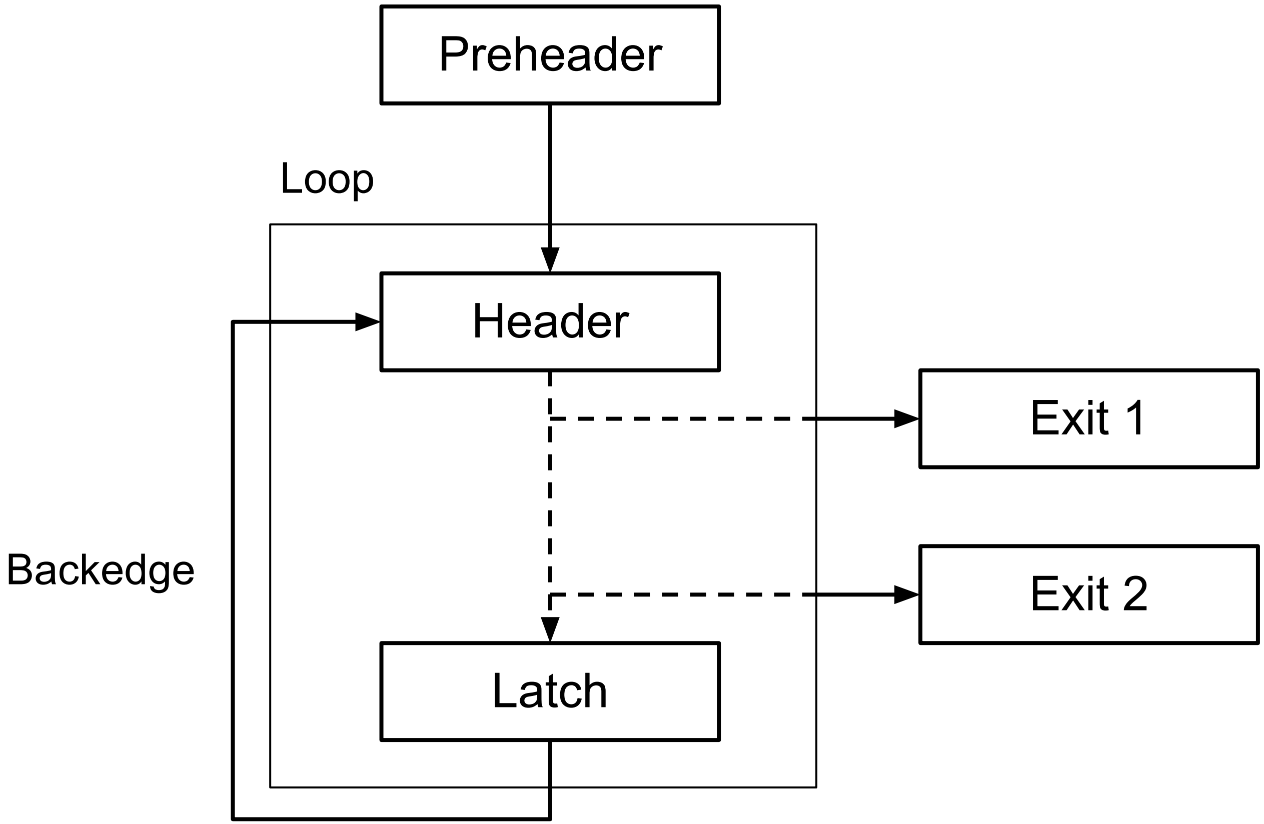
→

```
if (x > 10) {
  greater10();
  always();
  greater0();
} else {
  always();
}
```

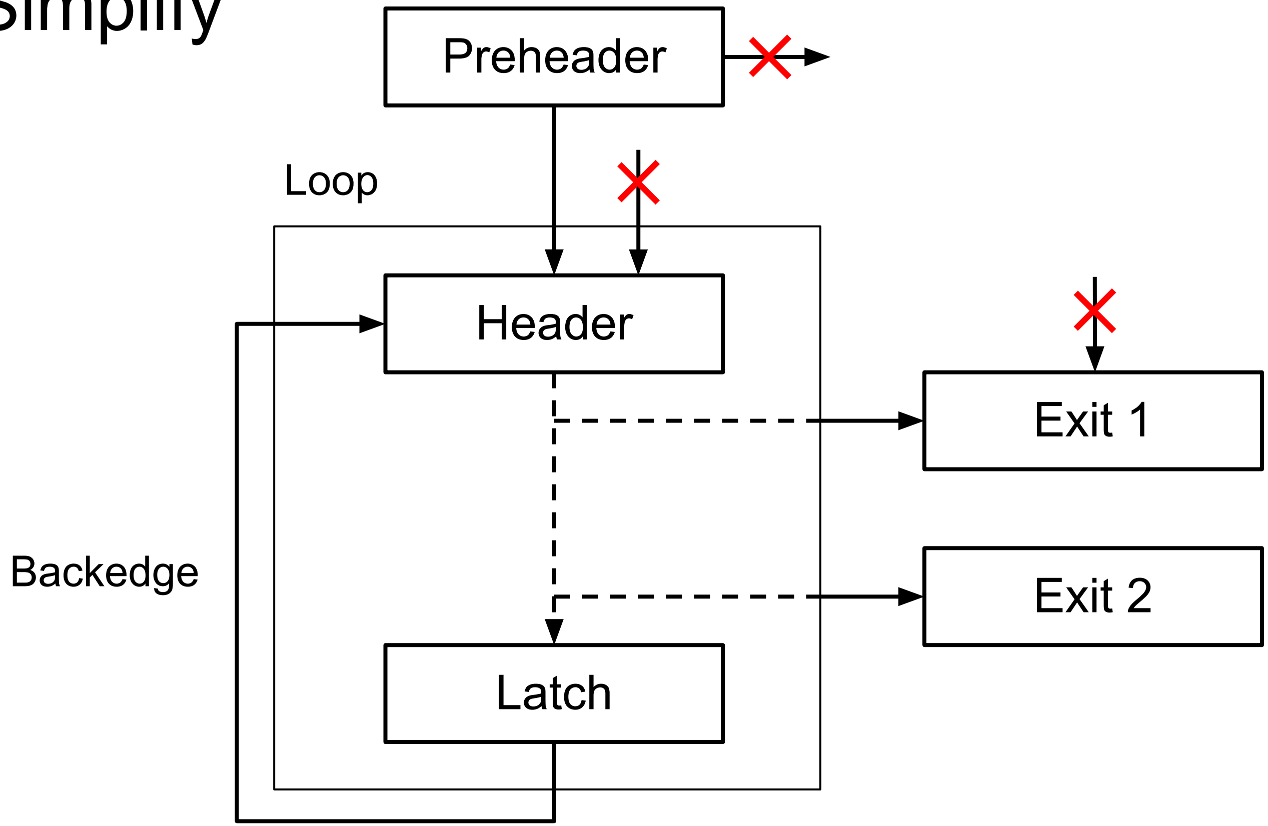
JumpThreading

- Optimizes conditional branches where one condition implies another
- Uses LazyValueInfo analysis, which provides value range information

Loop



LoopSimplify Form



Red Hat

SimpleLoopUnswitch

```
while (...) {
  if (c) {
    foo();
  } else {
    bar();
  }
}
```

→

```
if (c) {
  while (...) {
    foo();
  }
} else {
  while (...) {
    bar();
  }
}
```