Loop Optimizations in LLVM: The Good, The Bad, and The Ugly

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Acknowledgments

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Loop Transformations in the Compiler?

Approaches

- Compiler-based
    - Automatic (Polly, ...)
    - Language extensions (OpenMP, OpenACC, ...)
        - Prescriptive
        - Descriptive
    - New languages (Chapel, X10, Fortress, UPC, ...)
- Source-to-Source (PLuTo, ROSE, PPCG, ...)
- Library-based
    - Hand-optimized (MKL, OpenBLAS, ...)
    - Templates (RAJA, Kokkos, HPX, Halide, ...)
    - Embedded DSL (Tensor Comprehensions, ...)
- Domain-Specific Languages and Compilers (QIRAL, SPIRAL, LIFT, SQL, ...)

Partial Unrolling

```
#pragma unroll 4
for (int i = 0; i < n; i += 1)
  Stmt(i);
```

```
if (n > 0) {
  for (int i = 0; i+3 < n; i += 4) {
    Stmt(i);
    Stmt(i + 1);
    Stmt(i + 2);
    Stmt(i + 3);
  }
  switch (n % 4) {
  case 3:
    Stmt(n - 3);
  case 2:
    Stmt(n - 2);
  case 1:
    Stmt(n - 1);
  }
}
```

- Why?
  - Compiler pragmas
    https://arxiv.org/abs/1805.03374
  - Optimization heuristics
  - Loop Autotuning
    https://github.com/kavon/atJIT

Compiler-Supported Pragmas

Compiler Loop Transformations are Here to Stay

Clang

```
#pragma unroll
#pragma clang loop unroll(enable)
#pragma unroll_and_jam
#pragma clang loop distribute(enable)
#pragma clang loop vectorize(enable)
#pragma clang loop interleave(enable)
```

gcc

```
#pragma GCC unroll
#pragma GCC ivdep
```

msvc

```
#pragma loop(hint_parallel(0))
#pragma loop(no_vector)
#pragma loop(ivdep)
```

Cray

```
#pragma _CRI unroll
#pragma _CRI fusion
#pragma _CRI nofission
#pragma _CRI blockingsize
#pragma _CRI interchange
#pragma _CRI collapse
```

OpenMP

```
#pragma omp simd
#pragma omp for
#pragma omp target
```

PGI

```
#pragma concur
#pragma vector
#pragma ivdep
#pragma nodepchk
```

xlc

```
#pragma unrollandfuse
#pragma stream_unroll
#pragma block_loop
#pragma loopid
```

SGI/Open64

```
#pragma fuse
#pragma fission
#pragma blocking size
#pragma altcode
#pragma noinvarif
#pragma mem prefetch
#pragma interchange
#pragma ivdep
```

OpenACC

```
#pragma acc kernels
```

icc

```
#pragma parallel
#pragma offload
#pragma unroll_and_jam
#pragma nofusion
#pragma distribute_point
#pragma simd
#pragma vector
#pragma swp
#pragma ivdep
#pragma loop_count(n)
```

Oracle Developer Studio

```
#pragma pipeloop
#pragma nomemorydepend
```

HP

```
#pragma UNROLL_FACTOR
#pragma IF_CONVERT
#pragma IVDEP
#pragma NODEPCHK
```

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Supported Loop Transformations

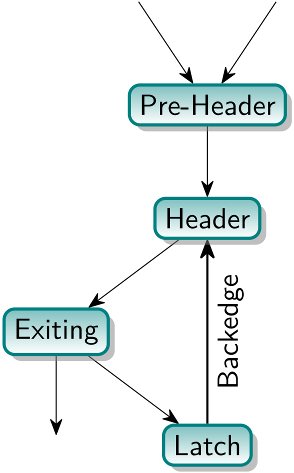
- Available passes:
    - Loop Unroll (-and-Jam)
    - Loop Unswitching
    - Loop Interchange
    - Detection of `memcpy`, `memset` idioms
    - Delete side-effect free loops
    - Loop Distribution
    - Loop Vectorization
- Modular: Can switch passes on and off independently

Supported Pragmas

- `#pragma clang loop unroll` / `#pragma unroll`
- `#pragma unrollandjam`
- `#pragma clang loop vectorize(enable)` / `#pragma omp simd`
- `#pragma clang loop interleave(enable)`
- `#pragma clang loop distribute(enable)`

Canonical Loop Form

- Loop-rotated form (at least one iteration)
  - Can hoist invariant loads
- Loop-Closed SSA



Available Infrastructure

Analysis passes:

- LoopInfo
- ScalarEvolution / PredicatedScalarEvolution

Preparation passes:

- LoopRotate
- LoopSimplify
- IndVarSimplify

Transformations:

- LoopVersioning

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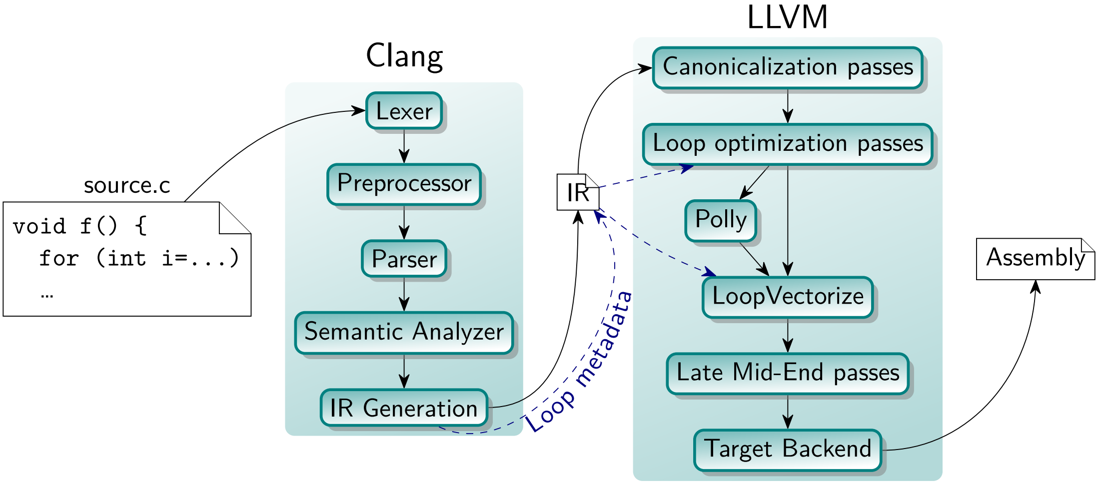
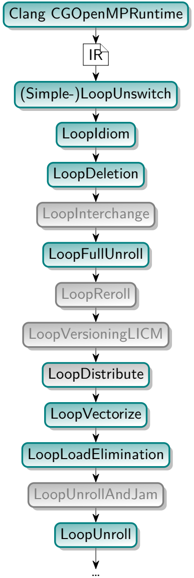
Clang/LLVM/Polly Compiler Pipeline



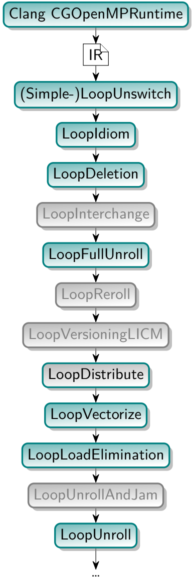
Unavailable Loop Passes



Clang CGOpenMPRuntime
IR
(Simple-)LoopUnswitch
LoopIdiom
LoopDeletion
LoopInterchange
LoopFullUnroll
LoopReroll
LoopVersioningLICM
LoopDistribute
LoopVectorize
LoopLoadElimination
LoopUnrollAndJam
LoopUnroll
...

- Many transformations disabled by default
    - Experimental / not yet matured

Static Loop Pipeline



- Fixed transformation order
  - OpenMP outlining happens first
    - Difficult to optimize afterwards
  - May conflict with source directives:

```
#pragma distribute
#pragma interchange
for (int i = 1; i < n; i+=1)
  for (int j = 0; j < m; j+=1) {
    A[i][j] = i + j;
    B[i][j] = A[i-1][j];
  }
```

  - OpenMP proposal: `https://arxiv.org/abs/1805.03374`

Composition of Transformations

```
#pragma unroll 2
#pragma reverse
for (int i = 0; i < 128; i+=1)
  Stmt(i);
```

```
#pragma unroll 2
for (int i = 127; i >= 0; i-=1)
  Stmt(i);
```

```
for (int i = 127; i >= 0; i-=1) {
  Stmt(i);
  Stmt(i-1);
}
```

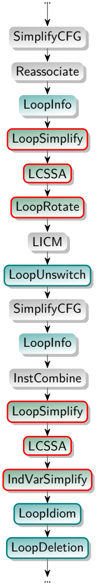
```
#pragma reverse
#pragma unroll 2
for (int i = 0; i < 128; i+=1)
  Stmt(i);
```

```
#pragma reverse
for (int i = 0; i < 128; i+=2) {
  Stmt(i);
  Stmt(i+1);
}
```

```
for (int i = 126; i >= 0; i-=2) {
  Stmt(i);
  Stmt(i+1);
}
```

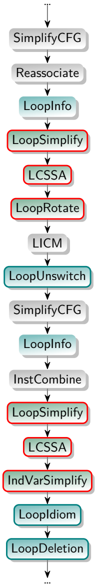
`https://reviews.llvm.org/D49281`

Non-Loop Passes Between Loop Passes



- Non-loop passes may destroy canonical loop structure
  - SimplifyCFG removes empty loop headers
    - keeps a list of loop headers
    - LoopSimplifyCFG only merges blocks within loop
    - Fixed in r343816
  - JumpThreading skips exiting blocks
    - has an integrated loop header detection
    - makes ScalarEvolution not recognize the loop
    - Fixed in r312664(?)
  - Bit-operations created by InstCombine must be understood by ScalarEvolution
- Analysis invalidation / Extra work in non-loop passes

Instruction Movement vs. Loop Transformations



- Scalar transformations making loop optimizations harder
  - Loop-Invariant Code Motion
  - Global Value Numbering
  - Loop-Closed SSA

Scalar/Loop Pass Interaction

Loop Nest Bakin-In

```
for (int i=0; i<n; i+=1)
  for (int j=0; j<m; j+=1)
    A[i] += i*B[j];
```

LICM
(Register Promotion)

```
for (int i=0; i<n; i+=1) {
  tmp = A[i];
  for (int j=0; j<m; j+=1)
    tmp += i*B[j];
  A[i] = tmp;
}
```

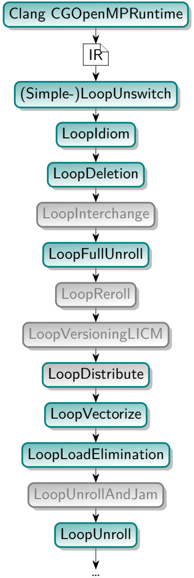
Loop
Interchange

```
for (int j=0; j<m; j+=1)
  for (int i=0; i<n; i+=1)
    A[i] += i*B[j];
```

GVN
(LoadPRE)

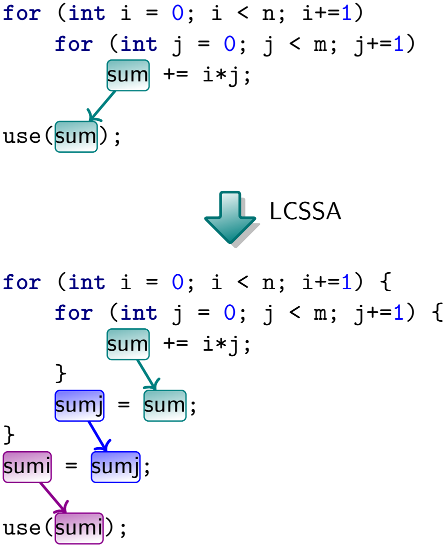
```
for (int j=0; j<m; j+=1) {
  tmp = B[j];
  for (int i=0; i<n; i+=1)
    A[i] += i*tmp;
}
```

Non-Shared Infrastructure



- Dependence analysis (not passes that can be preserved!):
  - LoopAccessInfo (LoopDistribute, LoopVectorize, LoopLoadElimination)
  - LoopInterchangeLegality (LoopInterchange)
  - MemoryDependenceAnalysis (LoopIdiom)
  - MemorySSA (LICM, LoopInstSimplify)
  - PolyhedralInfo
- Profitability:
  - LoopInterchangeProfitability
  - LoopVectorizationCostModel
  - UnrolledInstAnalyzer
- Code transformation

Loop-Closed SSA Form



```
for (int i = 0; i < n; i+=1)
    for (int j = 0; j < m; j+=1)
        sum += i*j;

use(sum);
```

LCSSA

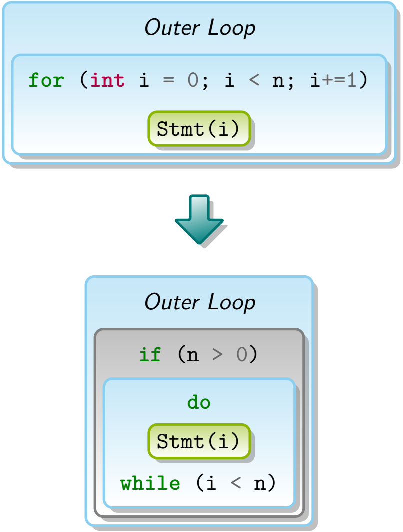
```
for (int i = 0; i < n; i+=1) {
    for (int j = 0; j < m; j+=1) {
        sum += i*j;
    }
    sumj = sum;
}
sumi = sumj;

use(sumi);
```

- Allows referencing the loop's exit value
    - Otherwise need to pass the loop every time
- Adds spurious dependencies
- Makes some (non-innermost) loop transformations more complicated

Loop-Rotated Normal Form in Tree Hierarchies

```
for (int i = 0; i < n; i+=1)
  Stmt(i);
```

```
int i = 0;
if (n > 0) {
   do {
     Stmt(i);
     i+=1;
   } while (i < n);
}
```



Loop Pass Boilerplate

- LoopDistribute: 1063 lines
- LoopInterchange: 1529 lines
- LoopUnroll: 2025 lines
- LoopIdiom: 1794 lines

Low-level complexity:

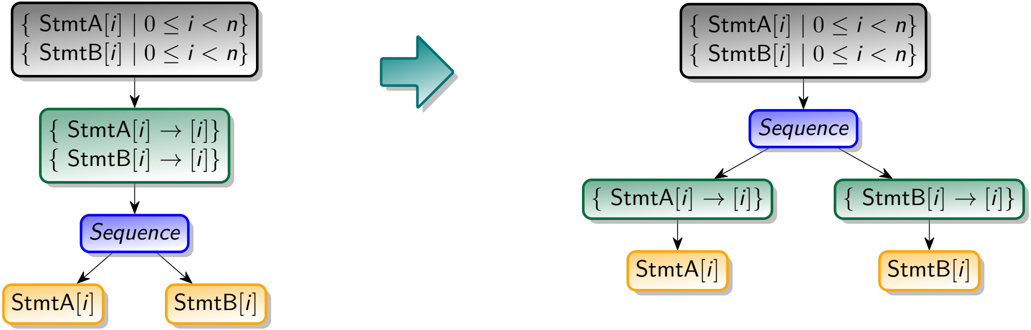
- Repair control flow
- Repair (LC-)SSA
- Preserve passes (LoopInfo, DominatorTree, ScalarEvolution, ...)

ISL Schedule Tree Transformation

Loop Distribution

```
for (int i = 0; i < n; i+=1) {
  StmtA(i);
  StmtB(i);
}
```

```
for (int i = 0; i < n; i+=1)
  StmtA(i);
for (int i = 0; i < n; i+=1)
  StmtB(i);
```



$\{\ \text{StmtA}[i] \mid 0 \leq i < n\}$
$\{\ \text{StmtB}[i] \mid 0 \leq i < n\}$

$\{\ \text{StmtA}[i] \to [i]\}$
$\{\ \text{StmtB}[i] \to [i]\}$

Sequence

StmtA[i]

StmtB[i]

$\{\ \text{StmtA}[i] \mid 0 \leq i < n\}$
$\{\ \text{StmtB}[i] \mid 0 \leq i < n\}$

Sequence

$\{\ \text{StmtA}[i] \to [i]\}$

$\{\ \text{StmtB}[i] \to [i]\}$

StmtA[i]

StmtB[i]

Polly Code for Loop Distribution

Transformation-Specific Code

```
isl::schedule_node distributeBand(isl::schedule_node Band, const Dependences &D) {
  auto Partial = isl::manage(isl_schedule_node_band_get_partial_schedule(Band.get()));
  auto n = Seq.n_children();

  // Transformation
  auto Seq = isl::manage(isl_schedule_node_delete(Band.release()));
  for (int i = 0; i < n; i+=1)
      Seq = Seq.get_child(i).insert_partial_schedule(Partial).parent();

  // Legality check
  if (!D.isValidSchedule(Seq.get_schedule()))
    return {};

  return Seq;
}
```

- Dependences *unchanged*
- LLVM LoopDistribute: 1529 lines

Miscellaneous

- Forced promotion of induction variable to 64 bits
  - Multiple induction variables not coalesced
- SCEVExpander strength-reduces everything
- LoopIDs are not identifying loops (`https://reviews.llvm.org/D52116`)
- No equivalent for LoopIDs
- Difference between PHI and `select` irrelevant for high-level purposes

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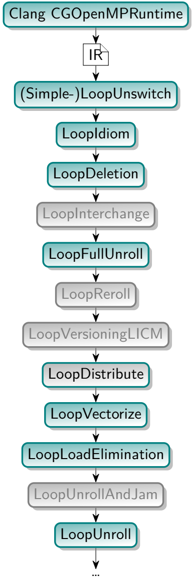
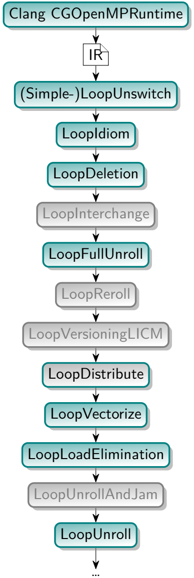
Loop Profitability



- Profitability determined independently
- Transformations might only be profitable in combination
  - Strip-mining alone only adds overhead
  - Loop distribution/fusion vs. loop vectorizer
    - Loop distribute targets vectorizability, but does not know whether vectorization is profitable
    - Inverse problem for loop fusion
  - Loop Unroll vs. Unroll-And-Jam
    - If unroll is “forced”, then unroll, do not unroll-and-jam
    - If unroll-and-jam is “forced”, then unroll-and-jam
    - If unroll-and-jam is profitable, then unroll-and-jam
    - If unroll is profitable, then unroll

Loop Versioning



Clang CGOpenMPRuntime

IR

(Simple-)LoopUnswitch

LoopIdiom

LoopDeletion

LoopInterchange

LoopFullUnroll

LoopReroll

LoopVersioningLICM

LoopDistribute

LoopVectorize

LoopLoadElimination

LoopUnrollAndJam

LoopUnroll

...

- Multiple passes do code versioning
    - LoopVersioningLICM
    - LoopDistribute
    - LoopVectorize
    - LoopLoadElimination
- → up to $2^4 = 16$ copies of the same (innermost) loop
- Outer loop transformation fallbacks include inner loops

Loop Version Explosion

Original Source

```
for (int i = 0; i < n; i+=1)
  for (int j = 0; j < m; j+=1)
    Stmt(i,j);
```

Loop Version Explosion

Optimize Outer Loop (1 transformation so far)

```
if (rtc1) {
  for (int i = 0; i < n; i+=1) /* 1x transformed */
    for (int j = 0; j < m; j+=1)
      Stmt(i,j);
} else {
  for (int i = 0; i < n; i+=1) /* fallback */
    for (int j = 0; j < m; j+=1)
      Stmt(i,j);
}
```

Loop Version Explosion

Strip-Mine Outer Loop (2 transformations so far)

```
if (rtc1) {
  if (rtc2) {
    for (int i1 = 0; i1 < n; i1+=4) /* 2x transformed */
      for (int j = 0; j < m; j+=1)
        for (int i2 = 0; i2 < 4; i2+=1) /* new loop */
          Stmt(i1+i2,j);
  } else {
    for (int i = 0; i < n; i+=1) /* 1x transformed */
      for (int j = 0; j < m; j+=1)
        Stmt(i,j);
  }
} else {
  if (rtc3) {
    for (int i1 = 0; i1 < n; i1+=4) /* 1x transformed */
      for (int j = 0; j < m; j+=1)
        for (int i2 = 0; i2 < 4; i2+=1) /* new loop */
          Stmt(i1+i2,j);
  } else {
    for (int i = 0; i < n; i+=1) /* fallback-fallback */
      for (int j = 0; j < m; j+=1)
        Stmt(i,j);
  }
}
```

Loop Version Explosion

Optimize Inner Loop (3 transformations so far)

```
if (rtc1) {
  if (rtc2) {
    for (int i1 = 0; i1 < n; i1+=4)
      for (int j = 0; j < m; j+=1) {
        if (rtc4) {
          for (int i2 = 0; i2 < 4; i2+=1)
            Stmt(i1+i2,j);
        } else {
          for (int i2 = 0; i2 < 4; i2+=1) /* fallback */
            Stmt(i1+i2,j);
        }
      }
  } else {
    for (int i = 0; i < n; i+=1) {
      if (rtc5) {
        for (int j = 0; j < m; j+=1)
          Stmt(i,j);
      } else {
        for (int j = 0; j < m; j+=1) /* fallback-fallback */
          Stmt(i,j);
      }
    }
  }
} else {
  if (rtc3) {
    for (int i1 = 0; i1 < n; i1+=4)
      for (int j = 0; j < m; j+=1) {
        if (rtc6)
          for (int i2 = 0; i2 < 4; i2+=1)
            Stmt(i1+i2,j);
        } else {
          for (int i2 = 0; i2 < 4; i2+=1) /* fallback-fallback */
            Stmt(i1+i2,j);
        }
      }
  } else {
    for (int i = 0; i < n; i+=1) {
      if (rtc7) {
        for (int j = 0; j < m; j+=1)
          Stmt(i,j);
      } else {
        for (int j = 0; j < m; j+=1) /* fallback-fallback-fallback */
          Stmt(i,j);
      }
    }
  }
}
```

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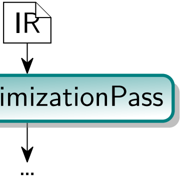
Single Integrated Loop Pass



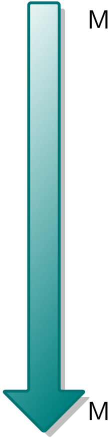
- Single pass in the pass pipeline
    - No interaction with scalar passes
    - No loop analysis invalidation
- Similar "passes" in LLVM:
    - VPlan
    - Machine pass manager

---

https://lists.llvm.org/pipermail/llvm-dev/2017-October/118125.html

Straightforward Optimization Heuristic

```
RedLoop optimizeLoop(RedLoop L) {
  if (L.hasPragma())
    return applyPragmas(L);

  if (L.isGEMM())
    return createCallToLibBLAS(L);

  if (L.canUnrollAndJam())
    L = L.unrollAndJam(TTI.getUnrollFactor());
  else
    L = L.unroll(TTI.getUnrollFactor());

  if (L.isParallelizable() && L.isProfitable())
    L = L.parallelize();

  return L;
}
```



More specific

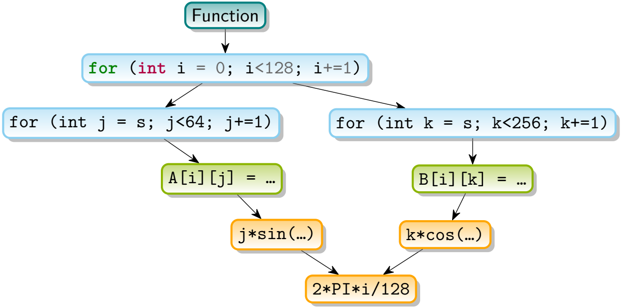
More general

Loop Structure DAG

- Use loop tree intermediate representation
  - Easily modifiable
  - Hierarchical
  - No bail-out (irreducible loops, exceptions, ...)
    - Irreducible loops can be converted to reducible loop by some code duplication
    - For other difficult constructs, loop can be marked as non-regular
- Three types of nodes
  - Loops (repeat something)
  - Statements (with side-effects)
  - Expressions (floating)

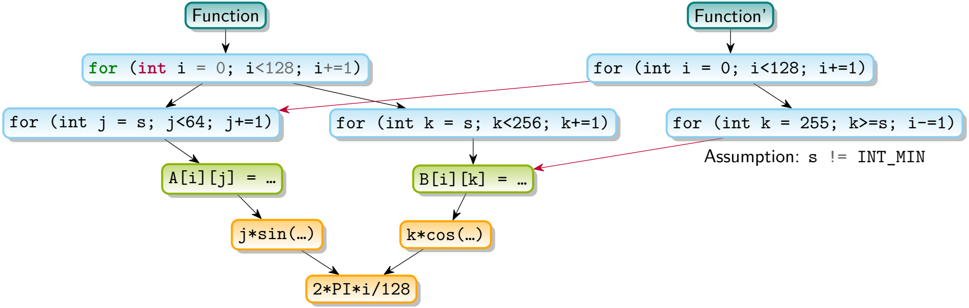
Loop Structure DAG

```
void Function(int s) {
    for (int i = 0; i < 128; i+=1) {
        for (int j = s; j <  64; j+=1) A[i][j] = j*sin(2*PI*i/128);
        for (int k = s; k < 256; k+=1) B[i][k] = k*cos(2*PI*i/128);
    }
}
```



Loop Structure DAG

```
void Function(int s) {
    for (int i = 0; i < 128; i+=1) {
        for (int j = s  ; j <  64; j+=1) A[i][j] = j*sin(2*PI*i/128);
        for (int k = 255; k >= s ; k-=1) B[i][k] = k*cos(2*PI*i/128);
    }
}
```



Red-Green Tree

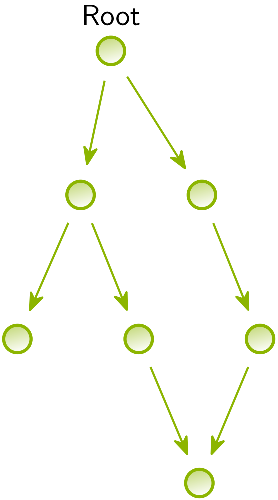
- Used by Roslyn's C# compiler
  - Immutable subtrees
  - Easy modification
  - Cheap copy
  - Create multiple variant, and chose most profitable

---

https://blogs.msdn.microsoft.com/ericlippert/2012/06/08/persistence-facades-and-roslyns-red-green-trees/
https://github.com/dotnet/roslyn/blob/master/src/Compilers/Core/Portable/Syntax/GreenNode.cs

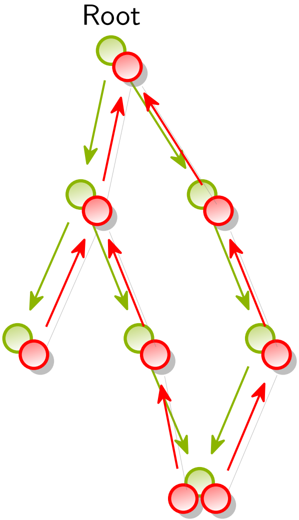
Red-Green Tree

The Green DAG



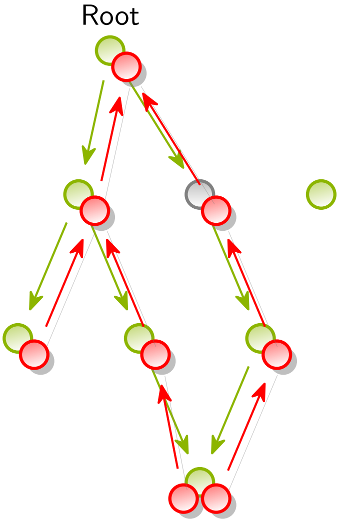
Red-Green Tree

The Red Tree



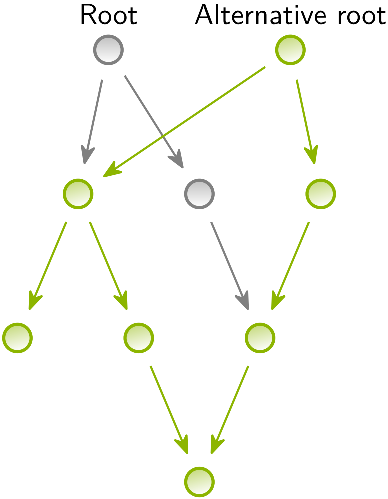
Red-Green Tree

Modify a Node



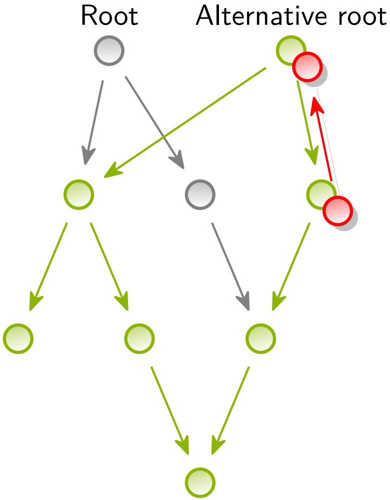
Red-Green Tree

Rebuild Green Tree Reusing Nodes



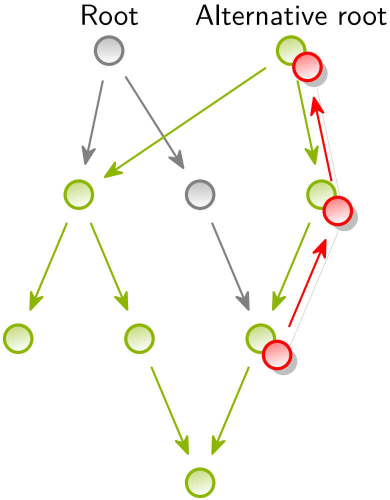
Red-Green Tree

Recreate Red Nodes on Demand



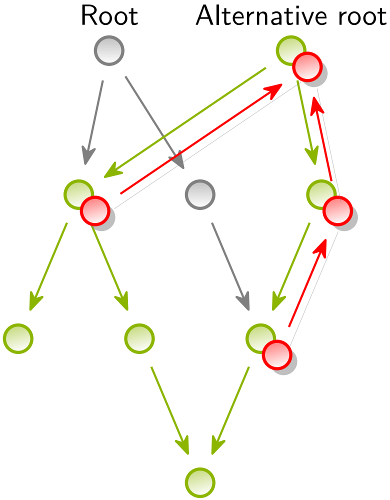
Red-Green Tree

Recreate Red Nodes on Demand

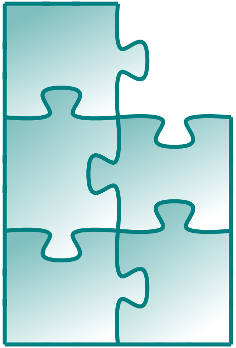


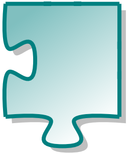
Red-Green Tree

Recreate Red Nodes on Demand

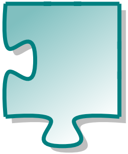


Closed-Form Expressions

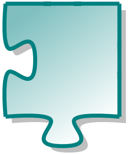




ScalarEvolution −01

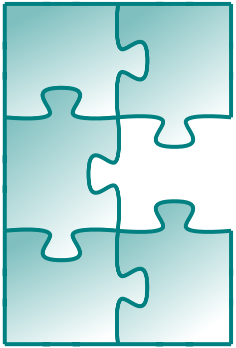


PredicatedScalarEvolution −02



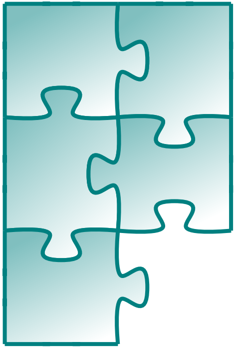
PolyhedralValueAnalysis −03

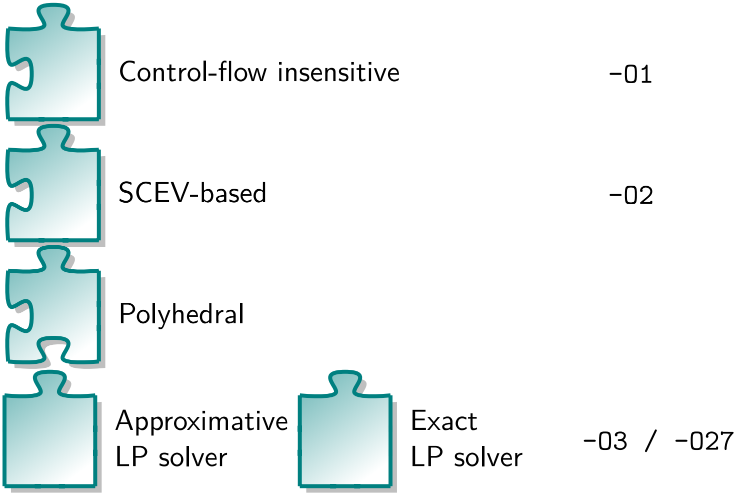
Access Analysis



One-dimensional	–01
One-dimensional, allow additional assumptions	–02
Multi-dimensional, allow additional assumptions	–03

Dependency Analysis





Control-flow insensitive `-O1`

SCEV-based `-O2`

Polyhedral

Approximative
LP solver

Exact
LP solver `-O3 / -O27`

Dependency Analysis

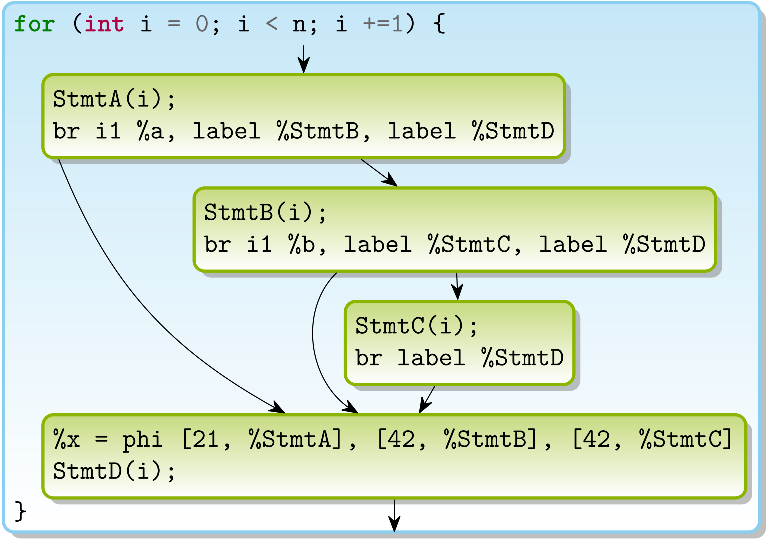
- Special purpose dependency types
  - Flow-, Anti-dependencies
    - No need for output-dependencies when anti-dependencies to a virtual return node
  - Memory clobber
  - Register dependencies (due to SSA)
  - Control dependencies (execute on if/on else flags)
- Register/Control dependencies may be backed by array storage if necessary
  - For instance, loop distribution crossing a def-use chain
  - Optimizer responsible for ensuring memory usage remains reasonable

Non-Cyclic Control Flow

- Predicated preferred
  - Simpler to handle: Sequential Root: →Loop→Sequential→Loop→Sequential→...
  - Corresponds SIMT model
  - Statements have execution conditions
    - Must execute conditions
    - May execute conditions (allow speculative execution)
  - Can be converted back to branching control flow
  - Makes PHI and `select` instructions the same
  - Difficulty: Branch out of loop to multiple targets (**`break`**, **`return`**)

Non-Cyclic Control Flow

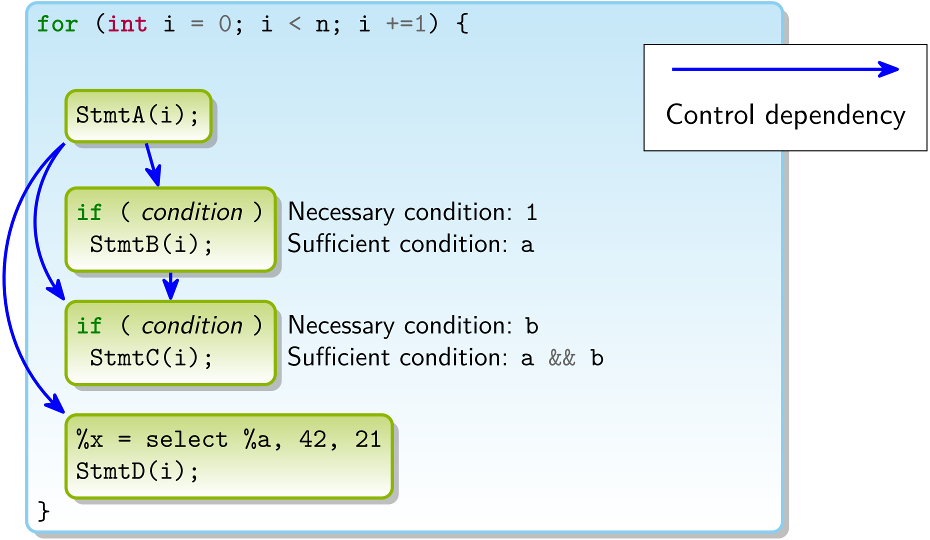
CFG Inside Loops



```
for (int i = 0; i < n; i +=1) {

StmtA(i);
br i1 %a, label %StmtB, label %StmtD

StmtB(i);
br i1 %b, label %StmtC, label %StmtD

StmtC(i);
br label %StmtD

%x = phi [21, %StmtA], [42, %StmtB], [42, %StmtC]
StmtD(i);
}
```

Non-Cyclic Control Flow

Sequential, but Conditional



```
for (int i = 0; i < n; i +=1) {

  StmtA(i);

  if ( condition )
   StmtB(i);

  if ( condition )
   StmtC(i);

  %x = select %a, 42, 21
  StmtD(i);
}
```

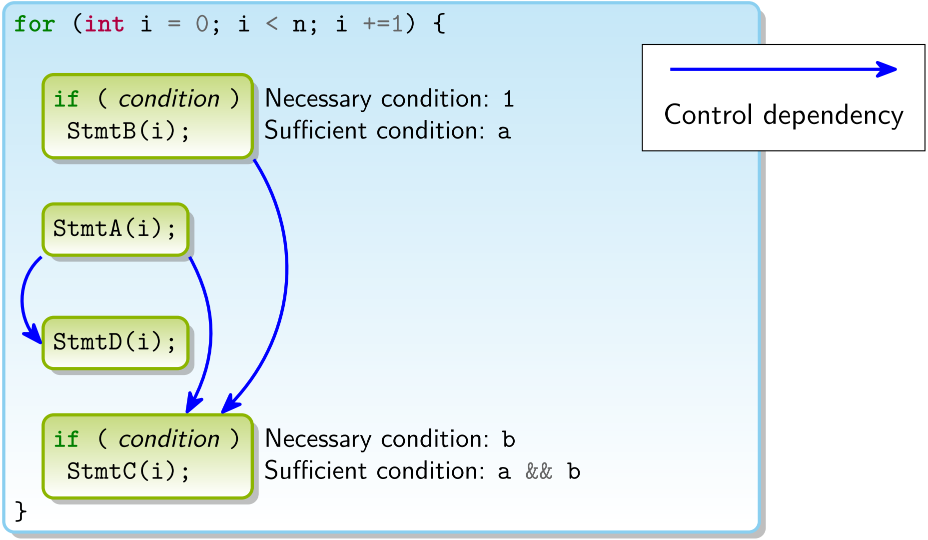
Necessary condition: 1
Sufficient condition: a

Necessary condition: b
Sufficient condition: a && b

Control dependency

Non-Cyclic Control Flow

Statement Reordering



```
for (int i = 0; i < n; i +=1) {

    if ( condition )
     StmtB(i);

    StmtA(i);

    StmtD(i);

    if ( condition )
     StmtC(i);
}
```

Necessary condition: 1
Sufficient condition: a

Necessary condition: b
Sufficient condition: a && b

Control dependency

Non-Cyclic Control Flow

Loop Distribution

```
for (int i = 0; i < n; i +=1) {

    if ( condition )
     StmtB(i);


    StmtA(i);
}
```

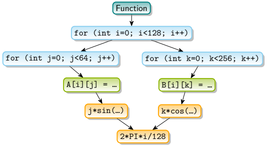
Necessary condition: 1
Sufficient condition: a

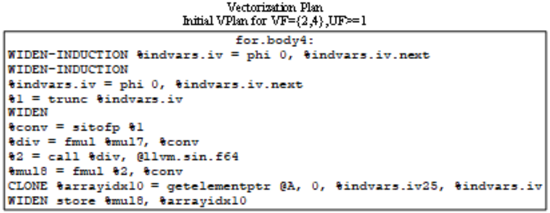
```
for (int i = 0; i < n; i +=1) {
    StmtD(i);


    if ( condition )
     StmtC(i);
}
```

Necessary condition: b
Sufficient condition: a && b

Code Generation

- Only emit modified subtrees
- Collect assumptions for runtime checks
- Recover non-cyclic control flow





Vectorization Plan
Initial VPlan for VF={2,4},UF>=1

```
for.body4:
WIDEN-INDUCTION %indvars.iv = phi 0, %indvars.iv.next
WIDEN-INDUCTION
%indvars.iv = phi 0, %indvars.iv.next
%1 = trunc %indvars.iv
WIDEN
%conv = sitofp %1
%div = fmul %mul7, %conv
%2 = call %div, @llvm.sin.f64
%mul8 = fmul %2, %conv
CLONE %arrayidx10 = getelementptr @A, 0, %indvars.iv25, %indvars.iv
WIDEN store %mul8, %arrayidx10
```

```
for.body4:
  %indvars.iv = phi i64 [ 127, %for.cond1.preheader ], [ %indvars.iv.next, %for.body4 ]
  %1 = trunc i64 %indvars.iv to i32
  %conv = sitofp i32 %1 to double
  %div = fmul fast double %mul7, %conv
  %2 = tail call fast double @llvm.cos.f64(double %div)
  %mul8 = fmul fast double %2, %conv
  %arrayidx10 = getelementptr inbounds [128 x double]* @B, i64 0, i64 %indvars.iv24, i64 %indvars.iv
  store double %mul8, double* %arrayidx10, align 8, !tbaa !5
  %indvars.iv.next = add nsw i64 %indvars.iv, -1
  %cmp2 = icmp eq i64 %indvars.iv, 0
  br i1 %cmp2, label %for.cond.cleanup3, label %for.body4, !llvm.loop !9
```

Pipeline

1. Create DAG from IR (lazy expansion)
2. Canonicalization
3. Analysis
    - Closed-form expressions
    - Array accesses
    - Dependencies
    - Idiom recognition
4. Transform
    - User-directives `#pragma`
    - Optimization heuristics
    - Using MINLP solver (polyhedral)
5. Cost model: Choose green tree root
6. Code Generation
    - To LLVM-IR
    - To VPlan

Summary

- LLVM not designed with loop optimizations in mind
  - Pass pipeline design
  - Normalized IR form
  - Non-shared infrastructure
  - Separate profitability analysis
  - Code version explosion
- Proposed solution:
  - Single integrated pass
  - Shared infrastructure
  - Loop hierarchy DAG
  - Red-Green Tree
  - If-converted normal from
  - Generate to LLVM-IR or VPlan
- Similar work
  - Every optimizing compiler with loop transformations
  - Silicon Graphics: *Loop Nest Optimization* (LNO)
    - Source available as part of Open64
  - IBM: *ASTI* and *Loop Structure Graph* (LSG) for xlf `https://www.doi.org/10.1147/rd.413.0233`
  - Intel: *VPlan* for LLVM
  - isl's *Schedule Trees* `https://hal.inria.fr/hal-00911894`

- Kit Barton (IBM), 3pm: "Revisiting Loop Fusion, and its place in the loop transformation framework"

That's all Folks!

LLVM Loop Passes

Excluding Normalization Passes

LLVM Pass	Metadata
(Simple-)LoopUnswitch	*none*
LoopIdiom	*none*
LoopDeletion	*none*
LoopInterchange*	*none*
SimpleLoopUnroll	`llvm.loop.unroll.*`
LoopReroll*	*none*
LoopVersioningLICM^{+*}	`llvm.loop.licm_versioning.disable`
LoopDistribute^{+}	`llvm.loop.distribute.enable`

LoopVectorize^{+}	`llvm.loop.vectorize.*`
	`llvm.loop.interleave.count`
	`llvm.loop.isvectorized`

LoopLoadElimination^{+}	*none*
LoopUnrollAndJam*	`llvm.loop.unroll_and_jam.*`
LoopUnroll	`llvm.loop.unroll.*`

The Polyhedral Model

```
for (int i=1; i<5; i++)
  for (int j=1; i+j<6; j++)
    S(i,j);
```

The Polyhedral Model

$\{S(i,j) \mid 0 < i,j \wedge i + j < 6\}$

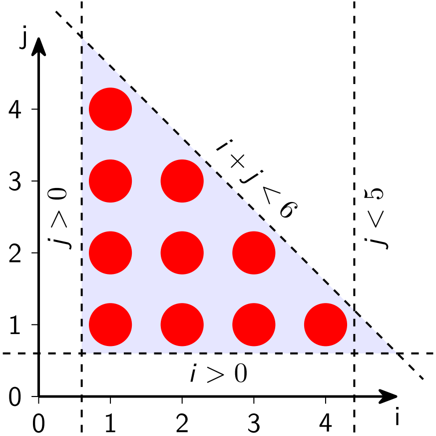
$S(1,1)$, $S(1,2)$, $S(1,3)$, $S(1,4)$, $S(2,1)$, $S(2,2)$, $S(2,3)$, $S(3,1)$, $S(3,2)$, $S(4,1)$

```
for (int i=1; i<5; i++)
  for (int j=1; i+j<6; j++)
    S(i,j);
```

The Polyhedral Model

$$\{S(i,j) \mid 0 < i,j \wedge i+j < 6\}$$

$S(1,1)$, $S(1,2)$, $S(1,3)$, $S(1,4)$, $S(2,1)$, $S(2,2)$, $S(2,3)$, $S(3,1)$, $S(3,2)$, $S(4,1)$

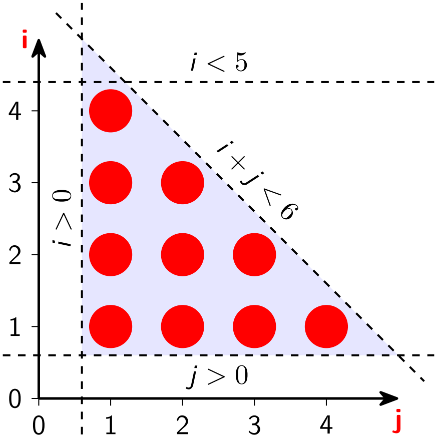


```
for (int i=1; i<5; i++)
  for (int j=1; i+j<6; j++)
    S(i,j);
```

The Polyhedral Model

Loop Interchange

$$S(i, j) \mapsto (j, i)$$



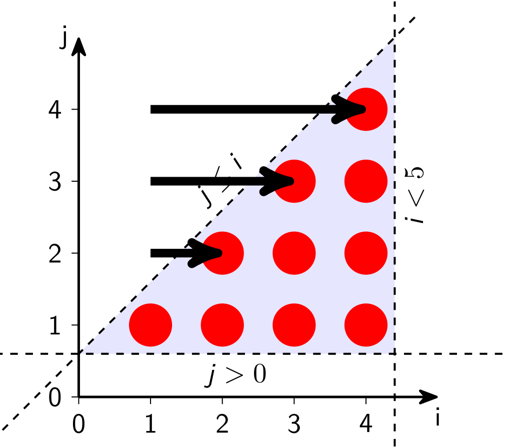
```
for (int j=1; j<5; j++)
  for (int i=1; i+j<6; i++)
    S(i,j);
```

Bonus

The Polyhedral Model

Skewing (Wavefronting)

$$S(i,j) \mapsto (i, i+j-1)$$

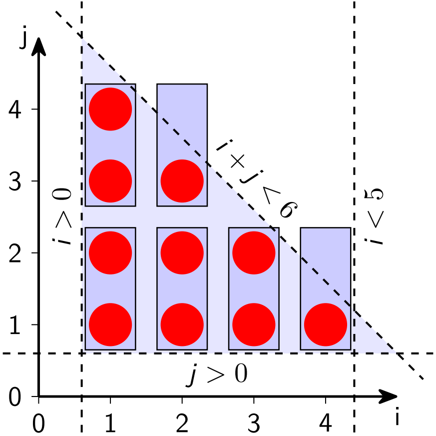


```
for (int i=1; i<5; i++)
  for (int j=i; j<5; j++)
    S(i,j-i+1);
```

The Polyhedral Model

Strip Mining (Vectorization)

$$S(i,j) \mapsto (i, j/2, j \textbf{ mod } 2)$$

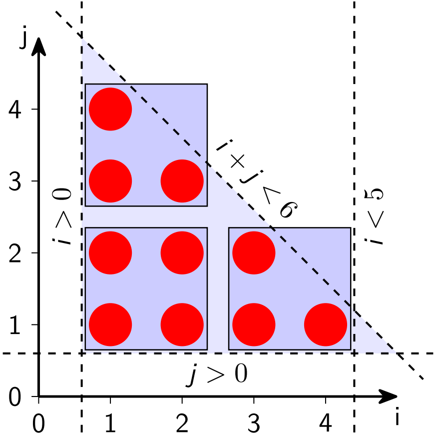


```
for (int i=1; i<5; i++)
  for (int t=1; i+t<6; t+=2)
    for (int j=t; j<t+2 && i+j<6; j++)
      S(i,j);
```

The Polyhedral Model

Tiling

$$S(i,j) \mapsto (i/2, j/2, i \ \mathbf{mod}\ 2, j \ \mathbf{mod}\ 2)$$

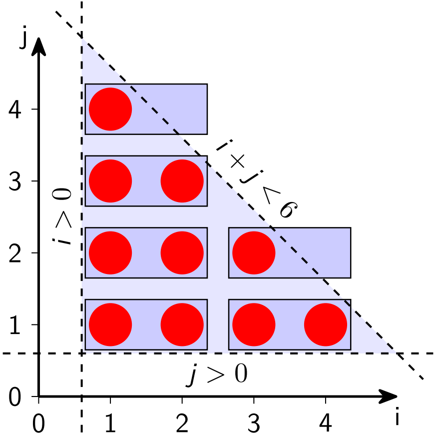


```
for (int s=1; s<5; s+=2)
  for (int t=1; s+t<6; t+=2)
    for (int i=s; i<s+2 && i<5; i++)
      for (int j=t; j<t+2 && i+j<6; j++)
        S(i,j);
```

The Polyhedral Model

Strip Mining (Outer Loop Vectorization)

$$S(i,j) \mapsto (i/2, j, i \textbf{ mod } 2)$$

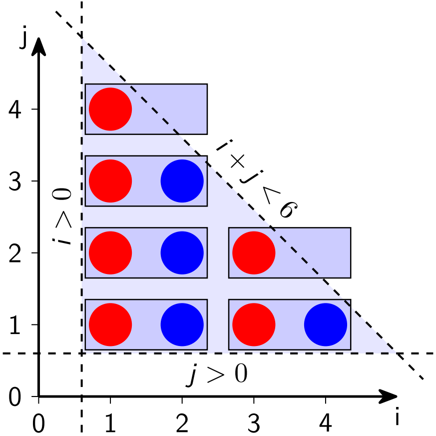


```
for (int t=1; t<5; t+=2)
  for (int j=1; i+t<6; j++)
    for (int i=t; i<t+2 && j+i<6; i++)
      S(i,j);
```

The Polyhedral Model

Unroll-and-Jam

$$S(i,j) \mapsto \begin{cases} (i/2,j,0) & \text{if } i \textbf{ mod } 2 = 0 \\ (i/2,j,1) & \text{if } i \textbf{ mod } 2 = 1 \end{cases}$$



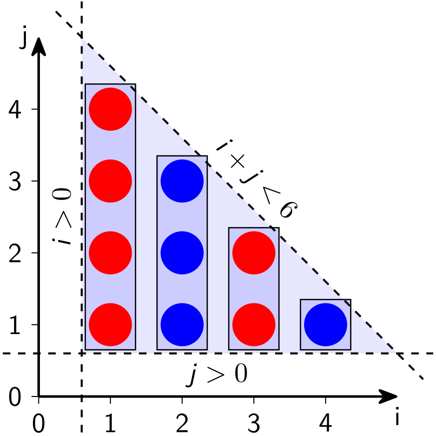
```
for (int i=1; i<5; i+=2)
  for (int j=1; i+j<6; j++) {
    S(i,j);
    if (i+j+1<6)
      S(i+1,j);
  }
```

Bonus

The Polyhedral Model

Loop Distribution

$$S(i,j) \mapsto \begin{cases} (i/2,0,j) & \text{if } i \bmod 2 = 0 \\ (i/2,1,j) & \text{if } i \bmod 2 = 1 \end{cases}$$

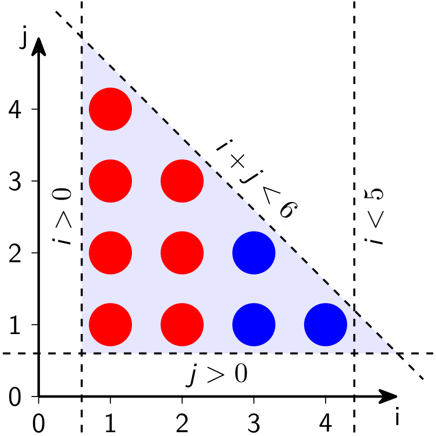


```
for (int i=1; i<5; i++) {
  for (int j=1; i+j<6; j+=2)
    S(i,j);
  for (int j=2; i+j<6; j+=2)
    S(i,j);
}
```

The Polyhedral Model

Index Set Splitting

$$S(i,j) \mapsto \begin{cases} (0, i, j) & \text{if } i < 3 \\ (1, i, j) & \text{if } i \geq 3 \end{cases}$$

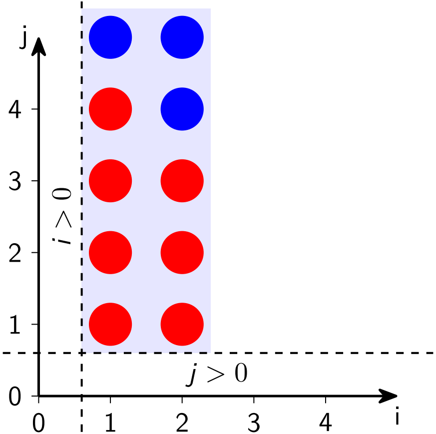


```
for (int i=1; i<3; i++)
  for (int j=1; i+j<6; j++)
    S(i,j);
for (int i=3; i<5; i++)
  for (int j=1; i+j<6; j++)
    S(i,j);
```

The Polyhedral Model

“Loop Fusion”

$$S(i,j) \mapsto \begin{cases} (i,j) & \text{if } i < 3 \\ (5-i, 6-j) & \text{if } i \geq 3 \end{cases}$$



```
for (int i=1; i<3; i++)
  for (int j=1; j<6; j++)
    if (i+j<6)
      S(i,j);
    else
      S(5-i,6-j);
```

Polly Solution to Everything?

- Scalar Dependencies
- Only Single-Entry-Single-Exit regions
- Non-affine loop bounds
- Non-affine control flow is atomic
- Statically infinite loops
- No exceptions (incl. mayThow and invoke)
- No VLAs inside loops
- Complexity limits
- Checkable aliasing
- Profitability heuristics always apply
- Always detect and codegen the max compatible regions
- Unpredictable loop bodies

When do Loop Optimization?

- After inlining
- Before parallel outlining (OpenMP)
- Before vectorization
- Before LICM, LoadPRE
- Before LoopRotate

Polly Code for Loop Reversal

From OpenMP Prototype Implementation

```
isl::schedule applyLoopReversal(isl::schedule_node BandToReverse) {
  auto PartialSched = isl::manage(
    isl_schedule_node_band_get_partial_schedule(BandToReverse.get()));
  auto MPA = PartialSched.get_union_pw_aff(0);
  auto Neg = MPA.neg();
  auto Node = isl::manage(isl_schedule_node_delete(BandToReverse.copy()));
  Node = Node.insert_partial_schedule(Neg);

  return Node;
}
```

From OpenMP Prototype Implementation

```
isl::schedule_node interchangeBands(isl::schedule_node Band, ArrayRef<LoopIdentification> NewOrder) {
  auto NumBands = NewOrder.size();
  Band = moveToBandMark(Band);
  SmallVector<isl::schedule_node, 4> OldBands;

  // Scan loops
  int NumRemoved = 0;
  int NodesToRemove = 0;
  auto BandIt = Band;
  while (true) {
    if (NumRemoved >= NumBands)
      break;

    if (isl_schedule_node_get_type(BandIt.get()) == isl_schedule_node_band) {
      OldBands.push_back(BandIt);
      NumRemoved += 1;
    }
    BandIt = BandIt.get_child(0);
    NodesToRemove += 1;
  }

  // Remove old order
  for (int i = 0; i < NodesToRemove; i += 1)
    Band = isl::manage(isl_schedule_node_delete(Band.release()));

  // Rebuild loop nest bottom-up according to new order.
  for (auto &NewBandId : reverse(NewOrder)) {
    auto OldBand = findBand(OldBands, NewBandId);
    auto OldMarker = LoopIdentification::createFromBand(OldBand);
    auto TheOldBand = ignoreMarkChild(OldBand);
    auto TheOldSchedule = isl::manage(
        isl_schedule_node_band_get_partial_schedule(TheOldBand.get()));

    Band = Band.insert_partial_schedule(TheOldSchedule);
    Band = Band.insert_mark(OldMarker.getIslId());
  }

  return Band;
}
```

Matrix-Multiplication

```
void matmul(int M, int N, int K,
            double C[const restrict static M][N],
            double A[const restrict static M][K],
            double B[const restrict static K][N]) {
  #pragma clang loop(j2) pack array(A)
  #pragma clang loop(i1) pack array(B)
  #pragma clang loop(i1,j1,k1,i2,j2) interchange \
                                     permutation(j1,k1,i1,j2,i2)
  #pragma clang loop(i,j,k) tile sizes(96,2048,256) \
                            pit_ids(i1,j1,k1) tile_ids(i2,j2,k2)
  #pragma clang loop id(i)
  for (int i = 0; i < M; i += 1)
    #pragma clang loop id(j)
    for (int j = 0; j < N; j += 1)
      #pragma clang loop id(k)
      for (int k = 0; k < K; k += 1)
        C[i][j] += A[i][k] * B[k][j];
}
```

Bonus

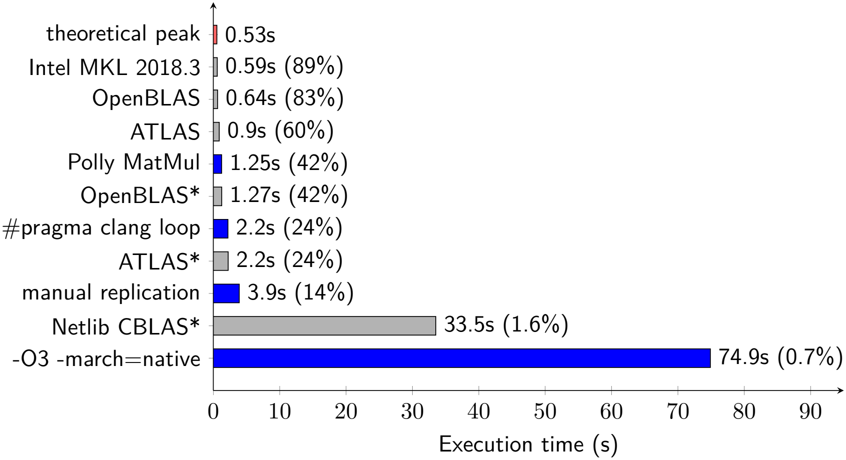
Matrix-Multiplication

After Transformation

```
double Packed_B[256][2048];
double Packed_A[96][256];
if (runtime check) {
  if (M >= 1)
    for (int c0 = 0; c0 <= floord(N - 1, 2048); c0 += 1)     // Loop j1
      for (int c1 = 0; c1 <= floord(K - 1, 256); c1 += 1) { // Loop k1

        // Copy-in: B -> Packed_B
        for (int c4 = 0; c4 <= min(2047, N - 2048 * c0 - 1); c4 += 1)
          for (int c5 = 0; c5 <= min(255, K - 256 * c1 - 1); c5 += 1)
            Packed_B[c4][c5] = B[256 * c1 + c5][2048 * c0 + c4];

        for (int c2 = 0; c2 <= floord(M - 1, 96); c2 += 1) { // Loop i1

          // Copy-in: A -> Packed_A
          for (int c6 = 0; c6 <= min(95, M - 96 * c2 - 1); c6 += 1)
            for (int c7 = 0; c7 <= min(255, K - 256 * c1 - 1); c7 += 1)
              Packed_A[c6][c7] = A[96 * c2 + c6][256 * c1 + c7];

          for (int c3 = 0; c3 <= min(2047, N - 2048 * c0 - 1); c3 += 1)   // Loop j2
            for (int c4 = 0; c4 <= min(95, M - 96 * c2 - 1); c4 += 1)      // Loop i2
              for (int c5 = 0; c5 <= min(255, K - 256 * c1 - 1); c5 += 1) // Loop k2
                C[96 * c2 + c4][2048 * c0 + c3] += Packed_A[c4][c5] * Packed_B[c3][c5];
        }
      }
} else {
  /* original code */
}
```

Matrix-Multiplication

Execution Speed



* Pre-compiled from Ubuntu repository