Scalable, Robust, and “Regression-Free” Loop Optimizations for Scientific Fortran and Modern C++

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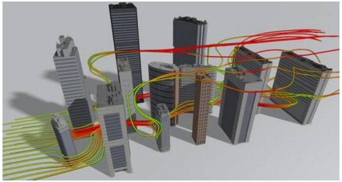
Xilinx

Swiss Universities / PASC
Qualcomm, ARM, Xilinx

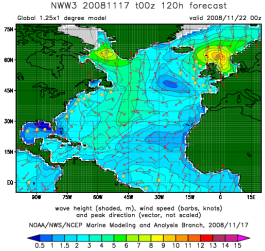
… many others

polly labs ARM ETH Zürich

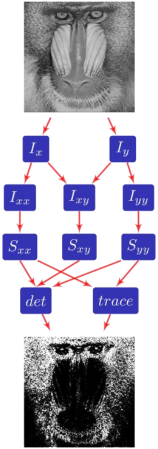
Physics Simulations



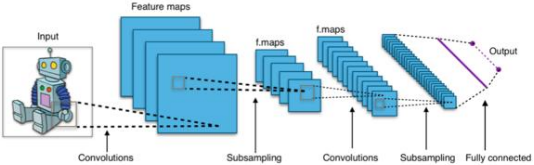
Weather



Graphics



Machine Learning



COSMO: Weather and Climate Model

- 500.000 Lines of Fortran
- 18.000 Loops
- 19 Years of Knowledge

- Used in Switzerland, Russia, Germany, Poland, Italy, Israel, Greece, Romania, …

COSMO – Climate Modeling

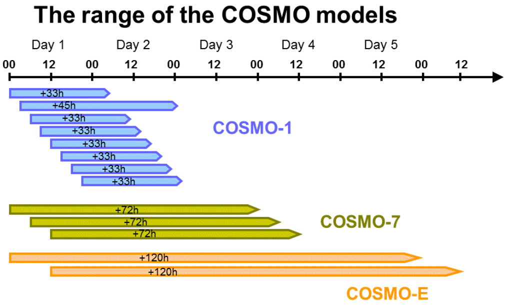
Piz Daint, Lugano, Switzerland

TOP 500 The List.

Rank	System	Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	**Sunway TaihuLight** - Sunway MPP, Sunway SW26010 260C 1.45GHz, Sunway , NRCPC National Supercomputing Center in Wuxi China	10,649,600	93,014.6	125,435.9	15,371
2	**Tianhe-2 (MilkyWay-2)** - TH-IVB-FEP Cluster, Intel Xeon E5-2692 12C 2.200GHz, TH Express-2, Intel Xeon Phi 31S1P , NUDT National Super Computer Center in Guangzhou China	3,120,000	33,862.7	54,902.4	17,808
3	**Piz Daint** - Cray XC50, Xeon E5-2690v3 12C 2.6GHz, Aries interconnect , NVIDIA Tesla P100 , Cray Inc. Swiss National Supercomputing Centre (CSCS) Switzerland	361,760	19,590.0	25,326.3	2,272
4	**Titan** - Cray XK7, Opteron 6274 16C 2.200GHz, Cray Gemini	560,640	17,590.0	27,112.5	8,209

- Global (low-resolution Model)
- Up to 5000 Nodes
- Run ~monthly

COSMO – Weather Forecast



- Regional model
- High-resolution
- Runs hourly
  (20 instances in parallel)

- Today: 40 Nodes * 8 GPU
- Manual Translation to GPUs
- 3 year multi-person project

Can LLVM do
this automatically?

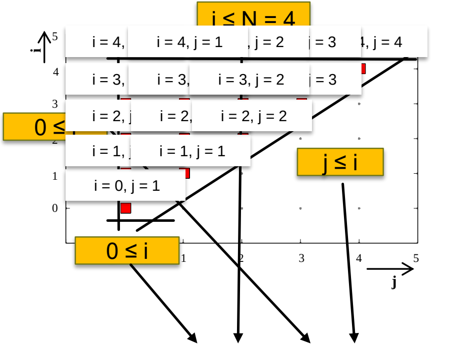
Polyhedral Model – In a nutshell

Program Code

```
for (i = 0; i <= N; i++)
  for (j = 0; j <= i; j++)
    S(i,j);
```

N = 4

Iteration Space



D = { (i,j) | 0 ≤ i ≤ N ∧ 0 ≤ j ≤ i }

Polly – Performing Polyhedral Optimizations on a Low-Level Intermediate Representation
Tobias Grosser, Armin Groesslinger, and Christian Lengauer in Parallel Processing Letters (PPL), April, 2012

Statistics - COSMO

Siddharth Bhat

- **Number of Loops**
  - 18,093 Total
  - 9,760 Static Control Loops (Modeled precisely by Polly)
  - 15,245 Non-Affine Memory Accesses (Approximated by Polly)
  - 11.154 Loops after precise modeling, less e.g. due to:
    - *Infeasible assumptions taken, or modeling timeouts*
- **Largest set of loops:** 72 loops
- **Reasons why loops cannot be modeled**
  - Function calls with side-effects
  - Uncomputable loops bounds (data-dependent loop bounds?)

Interprocedural Loop Interchange for GPU Execution

Pulled out parallel loop for OpenACC Annotations

```
#ifdef _OPENACC
  !$acc parallel
  !$acc loop gang vector
  DO j1 = ki1sc, ki1ec
    CALL coe_th_gpu(pduh2oc (j1, ki3sc), pduh2of(j1, ki3sc), pduco2(j1, ki3sc),
                    pduo3(j1, ki3sc), …, pa2f(j1), pa3c(j1), pa3f(j1))
  ENDDO
  !$acc end parallel
#else
  CALL coe_th (pduh2oc, pduh2of, pduco2, pduo3, palogp, palogt, podsc, podsf, podac, podaf,
               …, pa3c, pa3f)
#endif
```

Optical Effect on Solar Layer

Outer loop is sequential

Inner loop is parallel

```
DO j3 = ki3sc+1, ki3ec
   CALL coe_th (j3) {    ! Determine effect of the layer in *coe_th*
   ! Optical depth of gases
     DO j1 = ki1sc, ki1ec
       …
       IF (kco2 /= 0) THEN
         zodgf = zodgf + pduco2(j1   ,j3)* (cobi(kco2,kspec,2)* EXP ( coali(kco2,kspec,2) *
               palogp(j1   ,j3) -cobti(kco2,kspec,2) * palogt(j1   ,j3)))
       ENDIF
     …
     zeps=SQRT(zodgf*zodgf)
    …
    ENDDO
   }

   DO j1 = ki1sc, ki1ec   ! Set RHS
         …
   ENDDO
   DO j1 = ki1sc, ki1ec   ! Elimination and storage of utility variables
         …
   ENDDO
 ENDDO     ! End of vertical loop over layers
```

Sequential Dependences

Inner loop is parallel

Inner loop is parallel

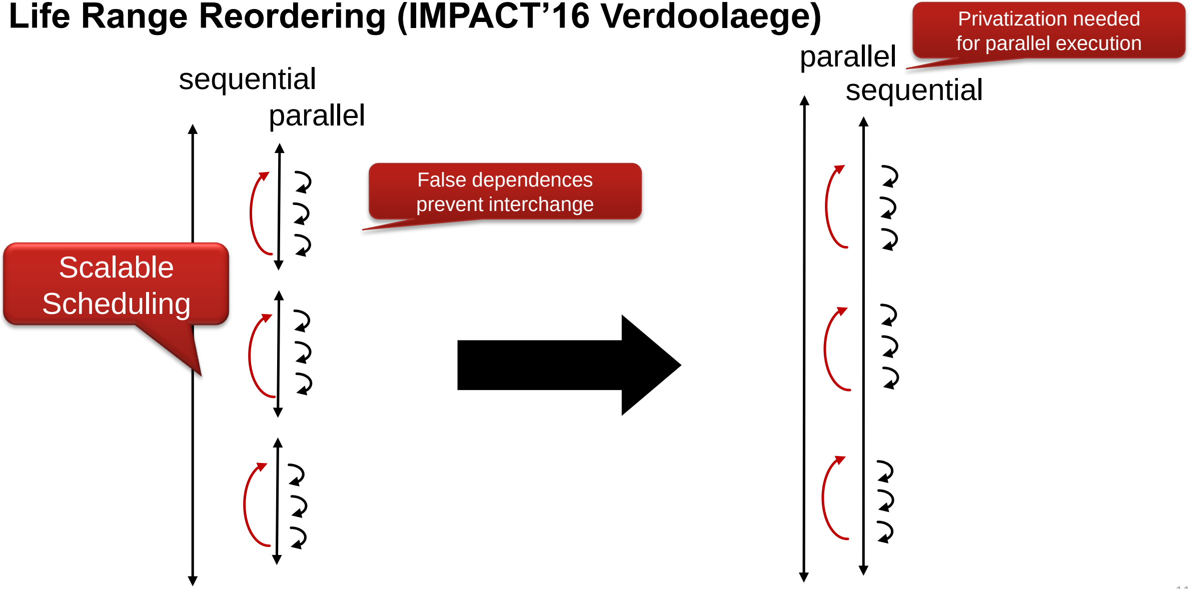
Optical Effect on Solar Layer – After interchange

```
!> Turn loop structure with multiple ip loops inside a
!> single k loop into perfectly nested k-in loop on GPU
#ifdef _OPENACC
  !$acc parallel
  !$acc loop gang vector
  DO j1 = ki1sc, ki1ec
    !$acc loop seq
    DO j3 = ki3sc+1, ki3ec         ! Loop over vertical

    ! Determine effects of layer in *coe_so*
      CALL coe_so_gpu(pduh2oc (j1,j3)   , pduh2of (j1,j3)   , …, pa4c(j1), pa4f(j1), pa5c(j1), pa5f(j1))

    ! Elimination
     …
      ztd1 = 1.0_dp/(1.0_dp-pa5f(j1)*(pca2(j1,j3)*ztu6(j1,j3-1)+pcc2(j1,j3)*ztu8(j1,j3-1)))
             ztu9(j1,j3) = pa5c(j1)*pcd1(j1,j3)+ztd6*ztu3(j1,j3) + ztd7*ztu5(j1,j3)
    ENDDO
END DO       ! Vertical loop
  !$acc end parallel
```

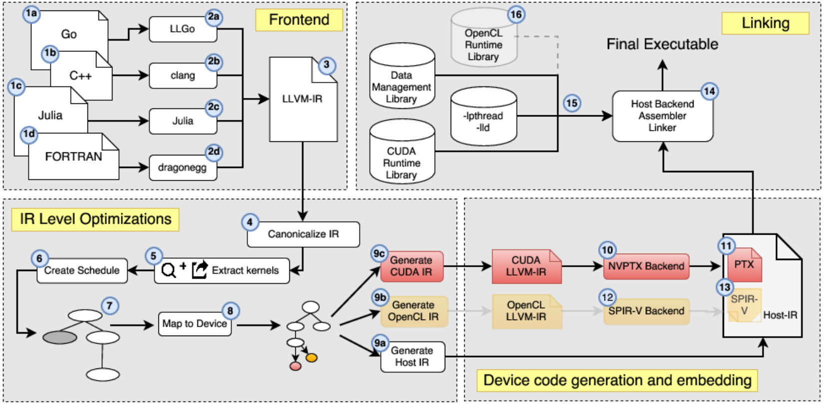
Outer loop is parallel

Inner loop is sequential

Life Range Reordering (IMPACT'16 Verdoolaege)



Polly-ACC: Architecture



Polly-ACC: Transparent Compilation to Heterogeneous Hardware
Tobias Grosser, Torsten Hoefler at International Conference of Supercomputing (ICS), June 2016, Istanbul

Polly-ACC: Architecture

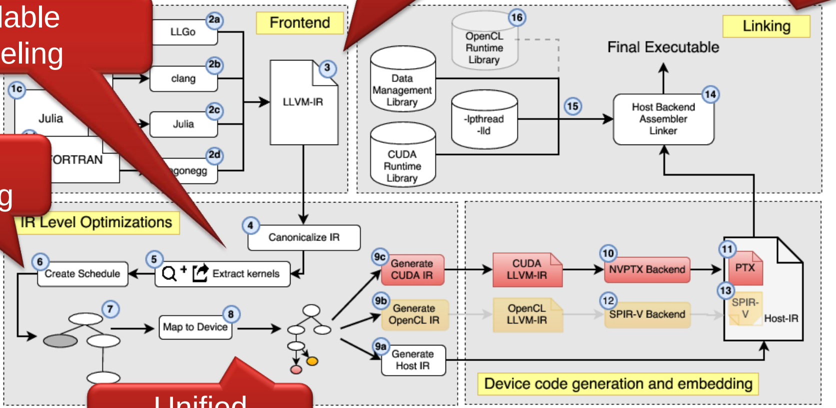
Intrinsics to model Multi-dimensional strided arrays

Better ways to link with NVIDIA libdevice

Scalable Modeling

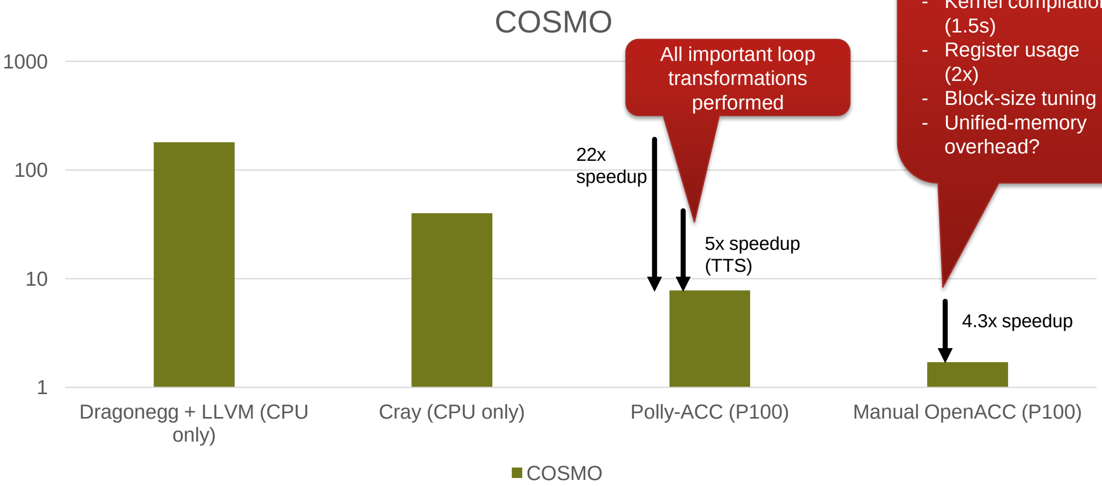
Scalable Scheduling

Unified Memory



Polly-ACC: Tr… …ous Hardware
Tobias Grosser, Torsten Hoefler at International Conference of Supercomputing (ICS), June 2016, Istanbul

Performance



Headroom:

- Kernel compilation (1.5s)
- Register usage (2x)
- Block-size tuning
- Unified-memory overhead?

Expression Templates (in a nutshell)

```
class Vec : public VecExpression<Vec> {
    std::vector<double> elems;

  public:
    double operator[](size_t i) const { return elems[i]; }
    double &operator[](size_t i)      { return elems[i]; }
    size_t size() const               { return elems.size(); }

    Vec(size_t n) : elems(n) {}

    // A Vec can be constructed from any VecExpression, forcing its evaluation.
    template <typename E>
    Vec(VecExpression<E> const& vec) : elems(vec.size()) {
        for (size_t i = 0; i != vec.size(); ++i) {
            elems[i] = vec[i];
        }
    }
};
```

Expression Templates (in a nutshell)

```
class Vec : public VecExpression<Vec> {
    std::vector<double> elems;

  public:
    double operator[](size_t i) const { return elems[i]; }
    double &operator[](size_t i)      { return elems[i]; }
    size_t size() const               { return elems.size(); }

    Vec(size_t n) : elems(n) {}

    // A Vec can be constructed from any VecExpression, forcing its evaluation.
    template <typename E>
    Vec(VecExpression<E> const& vec) : elems(vec.size()) {
        for (size_t i = 0; i != vec.size(); ++i) {
            elems[i] = vec[i];
        }
    }
};
```

Expression Templates (in a nutshell) - II

```
template <typename E1, typename E2>
class VecSum : public VecExpression<VecSum<E1, E2> > {
    E1 const& _u;
    E2 const& _v;

 public:
    VecSum(E1 const& u, E2 const& v) : _u(u), _v(v) {
        assert(u.size() == v.size());
    }

    double operator[](size_t i) const { return _u[i] + _v[i]; }
    size_t size()              const { return _v.size(); }
};

 template <typename E1, typename E2>
 VecSum<E1,E2> const
 operator+(E1 const& u, E2 const& v) {
    return VecSum<E1, E2>(u, v);
 }
```

```
Vec a, b, c;

auto Sum = a + b + c;

assert(typeof(sum) ==
VecSum<VecSum<Vec, Vec>, Vec>)

// evaluation only happens on
// assignment to type Vec

Vec evaluate = Sum;
```

“Modern C++” -- boost::ublas and Expression Templates

Roman Gareev

1. Detect operations on tropical semi-rings
   - SGEMM/DGEMM (+, *)
   - Floyd-Warshall (min, +)

2. Apply GOTO Algorithm (1)
   - L2 Tiling
   - Cache Transposed Submatrices
   - Register Tiling

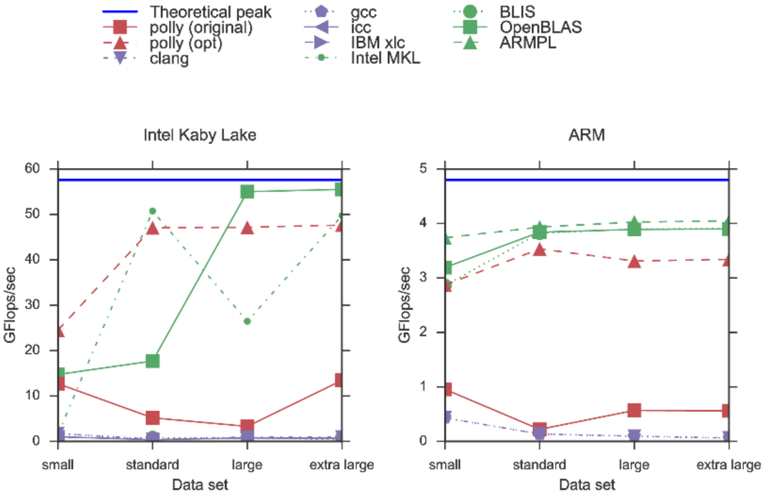
3. Chose optimal Cache and Register Tile Sizes (2)

Data-Layout Transformations in Polly

TargetData:
- L1/L2 Cache Sizes
- L2/L2 Cache Latencies

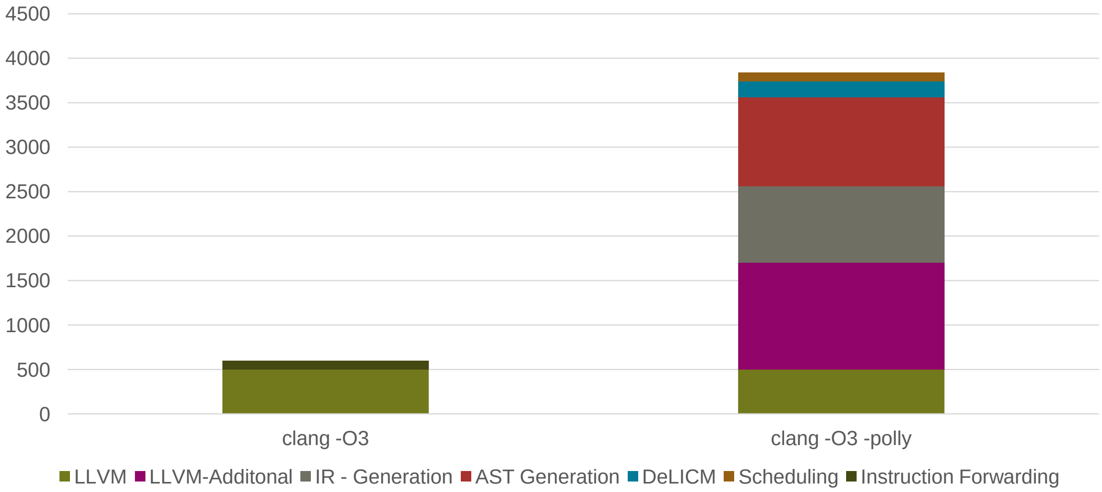
(1) High-performance implementation of the level-3 BLAS, Goto et al
(2) A Analytical Modeling is Enough for High Performance BLIS, Tzem Low et al

DGEMM Performance



Thanks @ARMHPC (Florian Hahn) for ARM codegen improvements!

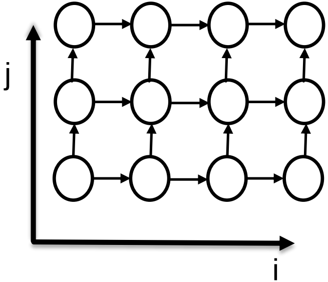
3MM Compile Time



"Provable" Correct Types for Loop Transformations

Maximilian Falkenstein

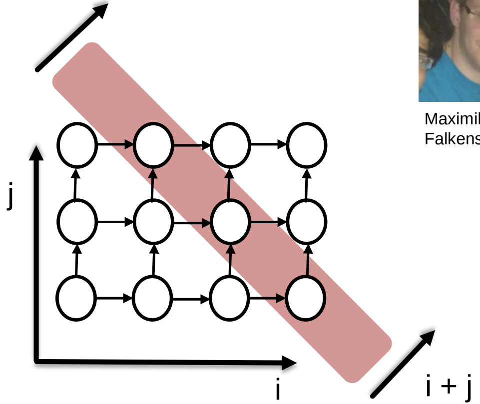
```
for (int32 i = 1; i < N; i++)
  for (int32 j = 1; j <= M; j++)
    A(i,j) = A(i-1,j) + A(i,j-1)
```



"Provable" Correct Types for Loop Transformations

```
for (int32 i = 1; i < N; i++)
  for (int32 j = 1; j <= M; j++)
    A(i,j) = A(i-1,j) + A(i,j-1)
```

```
for (intX c = 2; c < N+M; c++)
  #pragma simd
  for (intX i = max(1, c-M); i <= min(N, c-1); i++)
    A(i,c-i) = A(i-1,c-1) + A(i,c-i-1)
```

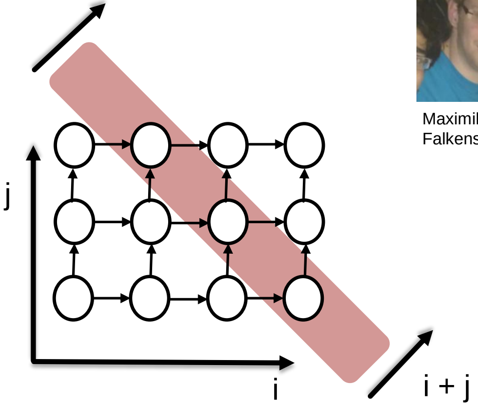


Maximilian Falkenstein

“Provable” Correct Types for Loop Transformations

Maximilian
Falkenstein

```
for (int32 i = 1; i < N; i++)
  for (int32 j = 1; j <= M; j++)
    A(i,j) = A(i-1,j) + A(i,j-1)
```



What is X?

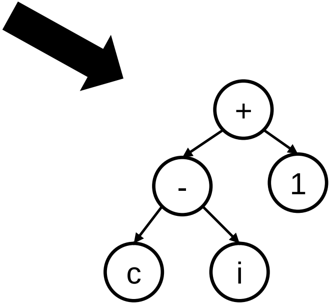
```
for (intX c = 2; c < N+M; c++)
  #pragma simd
  for (intX i = max(1, c-M); i <= min(N, c-1); i++)
    A(i,c-i) = A(i-1,c-1) + A(i,c-i-1)
```

Precise Solution

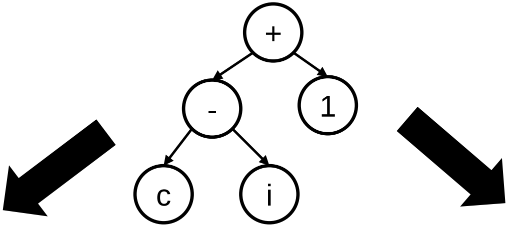
```
for (intX c = 2; c < N+M; c++)
  # simd
  for (intX i = max(1, c-M); i <= min(N, c-1); i++)
    A(i, c-i) = A(i-1, c-1) + A(i, c-i-1)
```

Domain: { [c] : 2 <= c < N + M
INT_MIN <= N, M <= INT_MAX }

f0() = c - i
f1() = c - i - 1



1) **calc:** min(fX()), max(fX()) under **Domain**
2) **choose type accordingly**



- Do you still target 32 bit?
- GPUs are faster in 32 bit
- FPGA?!

ILP Solver

- Minimal Types
- Potentially Costly

Approximations*

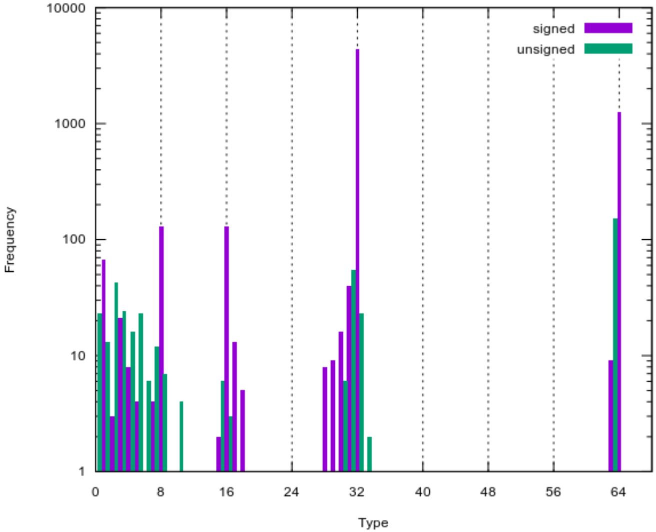
- $s(a+b) \leq \max(s(a), s(b)) + 1$
- Good, if smaller than native type

* Earlier uses in GCC and Polly

Preconditions

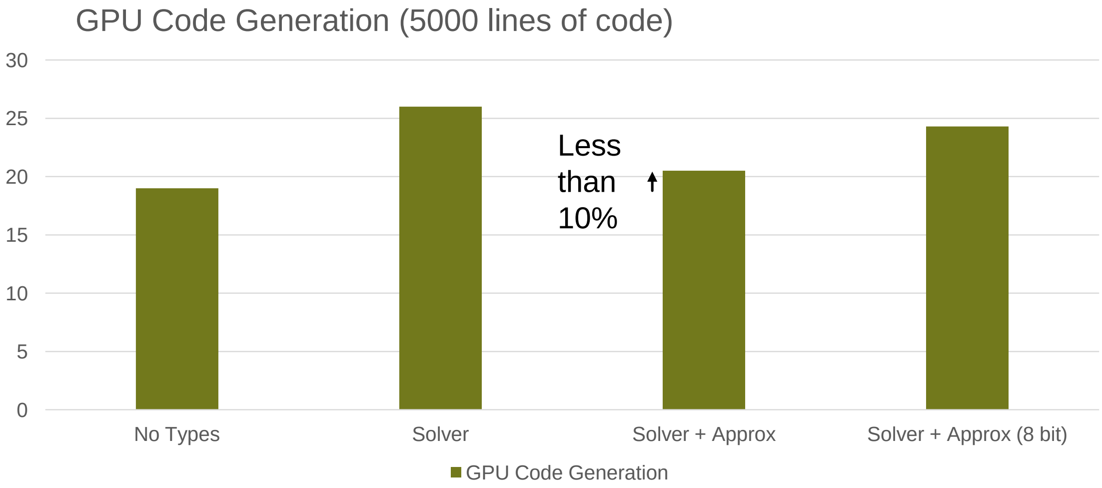
- Assume values fit into 32 bit
- Derive required pre-conditions

Type Distribution for LNT SCOPS



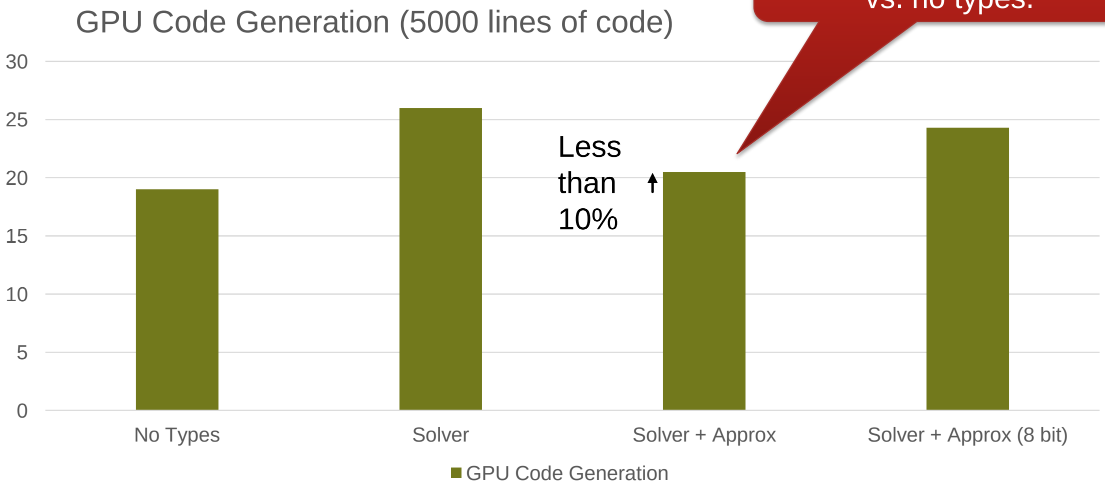
32 + epsilon is almost always enough!

Compile Time Overhead



Compile Time Overhead

Less than 10% overhead vs. no types.



Compile Time Overhead

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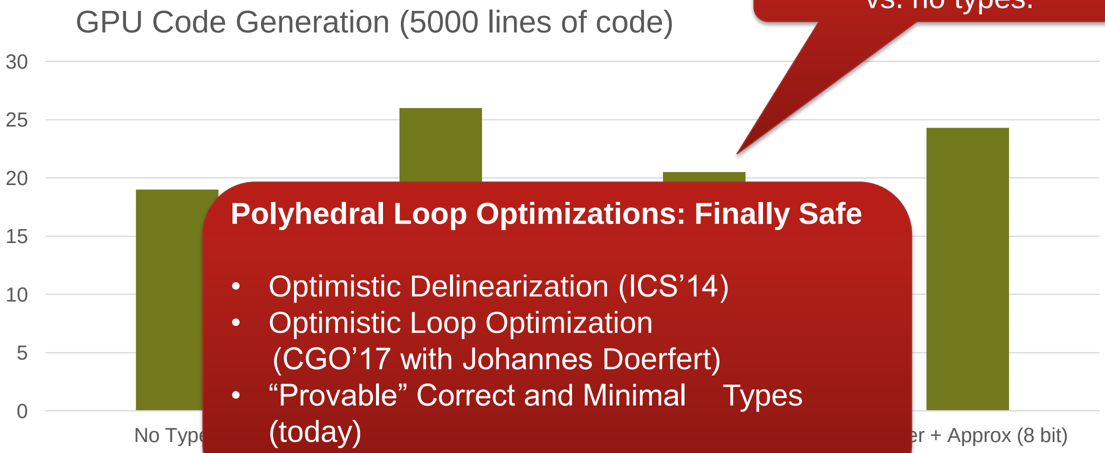


Polyhedral Loop Optimizations: Finally Safe

- Optimistic Delinearization (ICS'14)
- Optimistic Loop Optimization (CGO'17 with Johannes Doerfert)
- "Provable" Correct and Minimal Types (today)

Scalar Dependencies

Virtual Registers and PHI-Nodes

```
   for (int i=0; i<N; i++) {
S:   A[i] = ...;
T:   ... = A[i];
   }
```

- T(i) depends on S(i) — Read-After-Write/Flow-dependency
- S(0), S(1), …, S(N-1), T(0), T(1), … is a valid execution
- Parallel loop (OpenMP, OpenCL/PTX, tiling, vectorization, etc.)

Scalar Dependencies

Virtual Registers and PHI-Nodes

```
   for (int i=0; i<N; i++) {
S:   A[i] = ...;
T:   ... = A[i];
   }
```

```
   for (int i=0; i<N; i++) {
S:   tmp = ...;
T:   ... = tmp;
   }
```

"0-dimensional array"

Scalar Dependencies

Virtual Registers and PHI-Nodes

```
   for (int i=0; i<N; i++) {
S:   A[i] = ...;
T:   ... = A[i];
   }
```

```
   for (int i=0; i<N; i++) {
S:   tmp = ...;
T:   ... = tmp;
   }
```

"0-dimensional array"

- S(i) "depends" on S(i-1) — Write-After-Write/Output-dependency
- S(i) "depends" on T(i-1) — Write-After-Read/Anti-dependency
- S(0), S(1), …, T(0), … is **no** valid execution

Scalar Dependencies

Virtual Registers and PHI-Nodes

```
   for (int i=0; i<N; i++) {
S:   A[i] = ...;
T:   ... = A[i];
   }
```

mem2reg/SROA

```
   for (int i=0; i<N; i++) {
S:   tmp = ...;
T:   ... = tmp;
   }
```

"0-dimensional array"

- S(i) "depends" on S(i-1) — Write-After-Write/Output-dependency
- S(i) "depends" on T(i-1) — Write-After-Read/Anti-dependency
- S(0), S(1), …, T(0), … is **no** valid execution

Loop-Invariant Code Motion

```
   for (int i = 0; i < N; i += 1)
     for (int k = 0; k < K; k += 1)
S:     C[i] += A[i] * B[k];
```

Loop-Invariant Code Motion

```
   for (int i = 0; i < N; i += 1)
     for (int k = 0; k < K; k += 1)
S:     C[i] += A[i] * B[k];
```

⇓

```
   for (int i = 0; i < N; i += 1) {
T:   double tmp = A[i];
     for (int k = 0; k < K; k += 1)
S:     C[i] += tmp * B[k];
   }
```

Loop-Invariant Code Motion

```
    for (int i = 0; i < N; i += 1)
      for (int k = 0; k < K; k += 1)
S:      C[i] += A[i] * B[k];
```

GVN/LICM

```
    for (int i = 0; i < N; i += 1) {
T:    double tmp = A[i];
      for (int k = 0; k < K; k += 1)
S:      C[i] += tmp * B[k];
    }
```

Scalar Promotion in Loops

```
    for (int i = 0; i < N; i += 1) {
T:    C[i] = 0;
      for (int k = 0; k < K; k += 1)
S:      C[i] += A[i][k];
    }
```

Scalar Promotion in Loops

```
   for (int i = 0; i < N; i += 1) {
T:   C[i] = 0;
     for (int k = 0; k < K; k += 1)
S:     C[i] += A[i][k];
   }
```

```
   for (int i = 0; i < N; i += 1) {
T:   double tmp = 0;
     for (int k = 0; k < K; k += 1)
S:     tmp += A[i][k];
U:   C[i] = tmp;
   }
```

Scalar Promotion in Loops

```
   for (int i = 0; i < N; i += 1) {
T:   C[i] = 0;
     for (int k = 0; k < K; k += 1)
S:     C[i] += A[i][k];
   }
```

LICM

```
   for (int i = 0; i < N; i += 1) {
T:   double tmp = 0;
     for (int k = 0; k < K; k += 1)
S:     tmp += A[i][k];
U:   C[i] = tmp;
   }
```

Speculative Execution

```
   for (int i = 0; i < N; i += 1) {
     if (i > 5)
S1:    C[i] = 5 + 2*x;
     else
S2:    C[i] = 7 + 2*x;
   }
```

Speculative Execution

```
    for (int i = 0; i < N; i += 1) {
      if (i > 5)
S1:     C[i] = 5 + 2*x;
      else
S2:     C[i] = 7 + 2*x;
    }
```

EarlyCSE/GVN/NewGVN/GVNHoist

```
    for (int i = 0; i < N; i += 1) {
T:    double tmp = 2*x;
      if (i > 5)
S1:     C[i] = 5 + tmp;
      else
S2:     C[i] = 7 + tmp;
    }
```

(Partial) Redundancy Elimination

```
   for (int i = 0; i < N; i += 1) {
T:   C[i] = 0;
     for (int k = 0; k < K; k += 1)
S:     C[i] += A[i][k];
   }
```

(Partial) Redundancy Elimination

```
   for (int i = 0; i < N; i += 1) {
T:   C[i] = 0;
     for (int k = 0; k < K; k += 1)
S:     C[i] += A[i][k];
   }
```

GVN Load PRE

```
   for (int i = 0; i < N; i += 1) {
T:   double tmp = 0;
     for (int k = 0; k < K; k += 1)
S:     C[i] = (tmp += A[i][k]);
   }
```

Loop Idiom

“doitgen” – Multiresolution Kernel from MADNESS

```
for (int r = 0; r < R; r++)
  for (int q = 0; q < Q; q++) {
    for (int p = 0; p < P; p++) {
      sum[p] = 0;
      for (int s = 0; s < P; s++)
        sum[p] += A[r][q][s] * C4[s][p];
    }
    for (int p = 0; p < P; p++)
      A[r][q][p] = sum[p];
  }
```

Loop Idiom

“doitgen” – Multiresolution Kernel from MADNESS

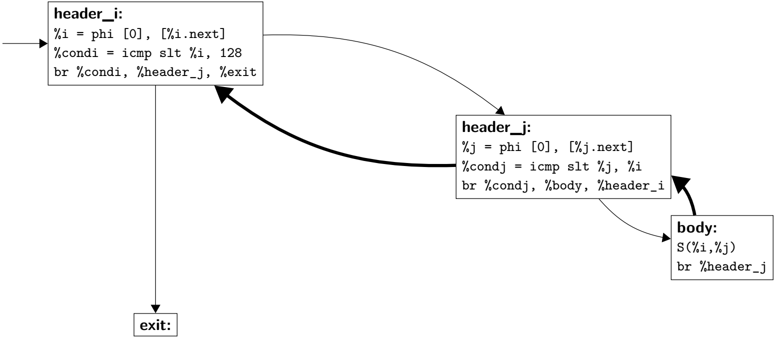
```
for (int r = 0; r < R; r++)
  for (int q = 0; q < Q; q++) {
    for (int p = 0; p < P; p++) {
      sum[p] = 0;
      for (int s = 0; s < P; s++)
        sum[p] += A[r][q][s] * C4[s][p];
    }
    for (int p = 0; p < P; p++)
      A[r][q][p] = sum[p];
  }
```

LoopIdiom

```
for (int r = 0; r < R; r++)
  for (int q = 0; q < Q; q++) {
    for (int p = 0; p < P; p++) {
      sum[p] = 0;
      for (int s = 0; s < P; s++)
        sum[p] += A[r][q][s] * C4[s][p];
    }
    memcpy(A[r][q], sum, sizeof(sum[i]) * P);
  }
```

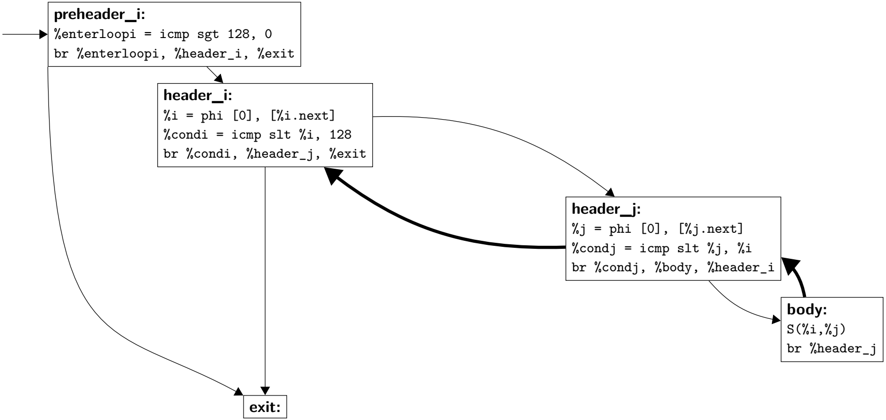
Loop Rotation

```
for (int i = 0; i < 128; i += 1)
  for (int j = 0; j < i; j += 1)
    S(i,j);
```



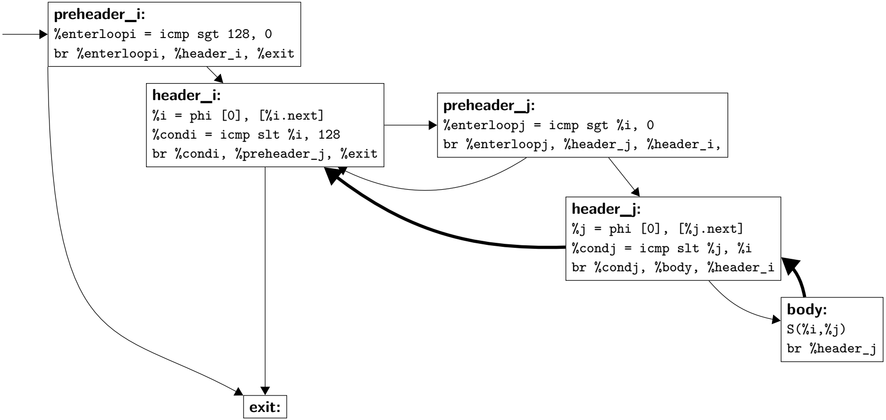
Loop Rotation

```
for (int i = 0; i < 128; i += 1)
  for (int j = 0; j < i; j += 1)
    S(i,j);
```



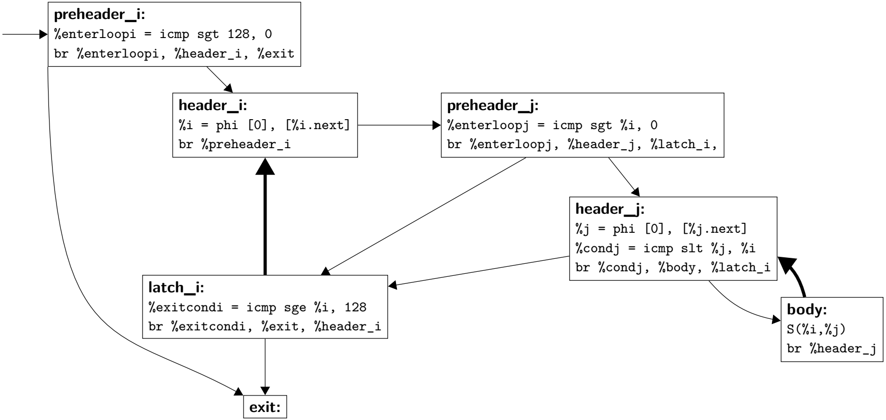
Loop Rotation

```
for (int i = 0; i < 128; i += 1)
  for (int j = 0; j < i; j += 1)
    S(i,j);
```



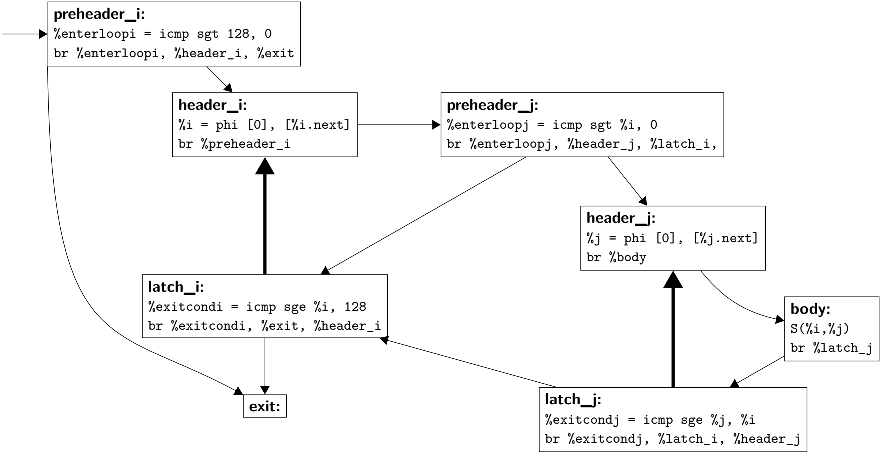
Loop Rotation

```
for (int i = 0; i < 128; i += 1)
  for (int j = 0; j < i; j += 1)
    S(i,j);
```



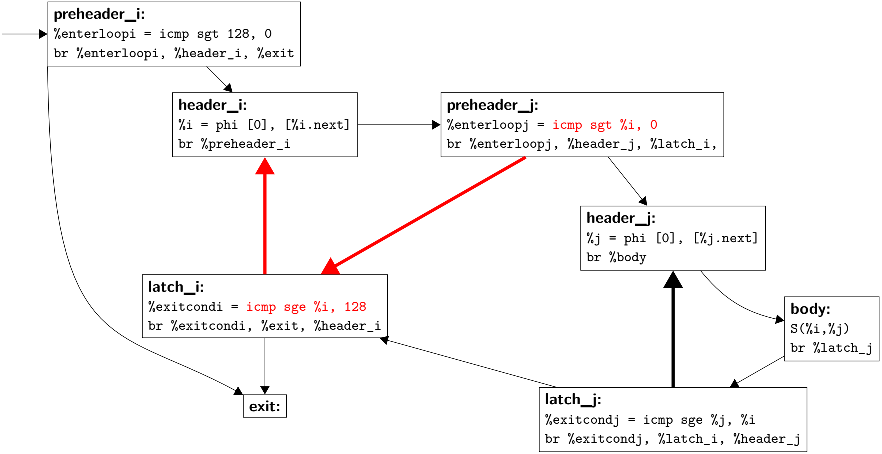
Loop Rotation

```
for (int i = 0; i < 128; i += 1)
  for (int j = 0; j < i; j += 1)
    S(i,j);
```



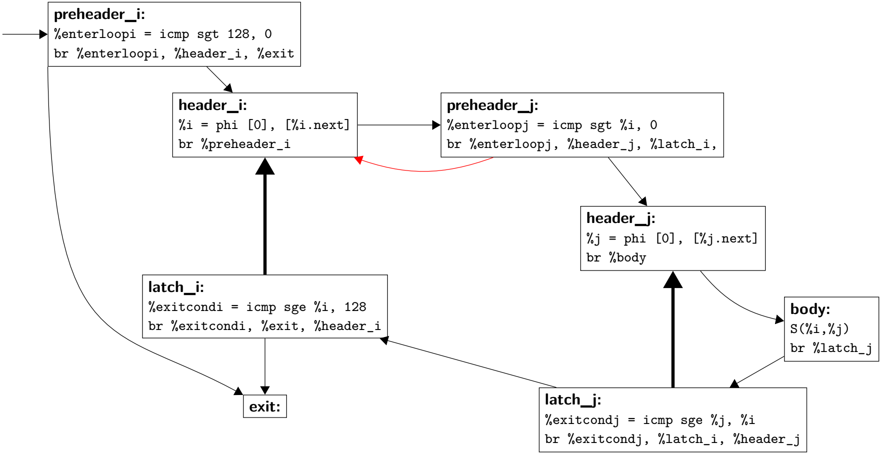
Jump Threading

```
for (int i = 0; i < 128; i += 1)
  for (int j = 0; j < i; j += 1)
    S(i,j);
```



Jump Threading

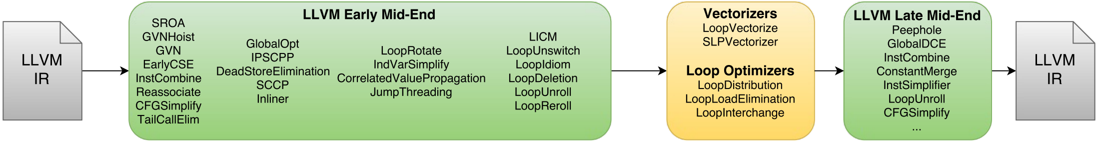
```
for (int i = 0; i < 128; i += 1)
  for (int j = 0; j < i; j += 1)
    S(i,j);
```



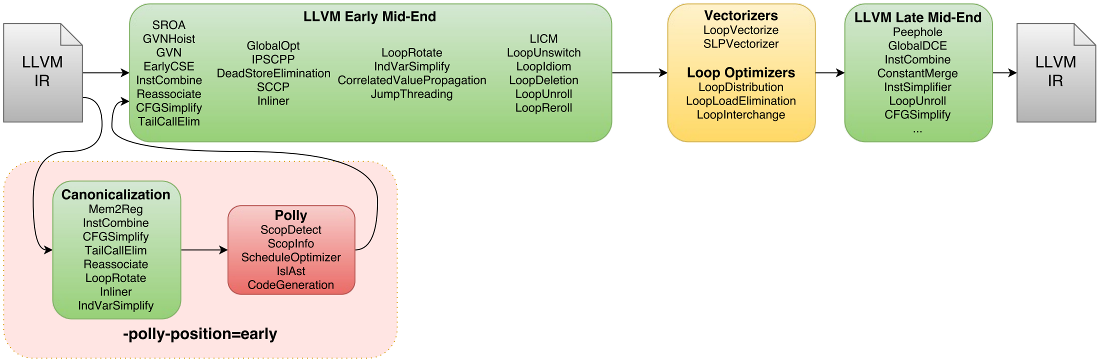
Chapter Summary

- Semantically identical IR can be harder to optimize
- Possible causes:
  - Static Single Assignment form (e.g. mem2reg)
  - Non-Polyhedral transformation passes (e.g. GVN, LICM)
  - C++ abstraction layers (e.g. Boost uBLAS)
  - Manual source optimizations (e.g. loop hoisting)
  - Code generators (e.g. TensorFlow XLA)

LLVM Pass Pipeline -O3

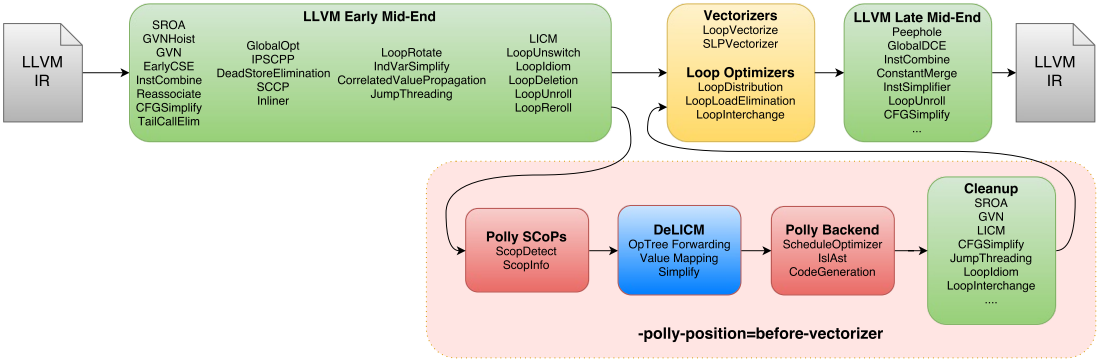


LLVM Pass Pipeline -O3 -polly -polly-position=early

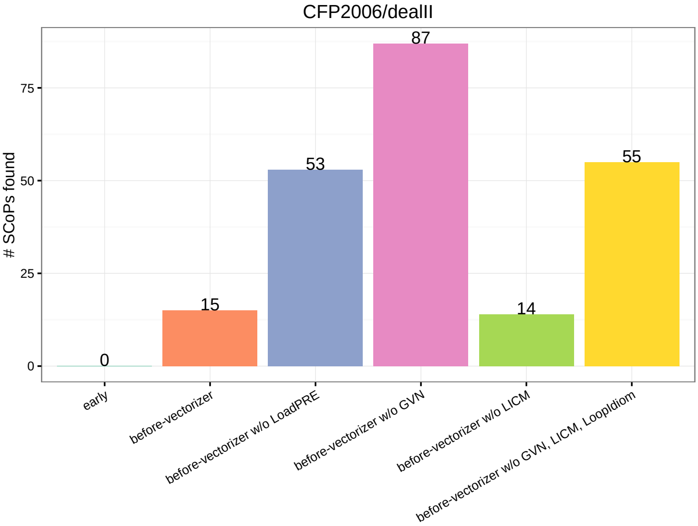


LLVM Pass Pipeline

-O3 -polly -polly-position=before-vectorizer



Effects of GVN, LICM, LoopIdiom



Value Mapping

"DeLICM"

```
   double c;
   for (int i = 0; i < 3; i += 1) {
T:   c = 0;
     for (int k = 0; k < 3; k += 1)
S:     c += A[i] * B[k];
U:   C[i] = c;
   }
```

Value Mapping

“DeLICM”

```
    double c;
    for (int i = 0; i < 3; i += 1) {
T:    c = 0;
      for (int k = 0; k < 3; k += 1)
S:      c += A[i] * B[k];
U:    C[i] = c;
    }
```

	$T(0)$	$S(0,0)$	$S(0,1)$	$S(0,2)$	$U(0)$	$T(1)$	$S(1,0)$	$S(1,1)$	$S(1,2)$	$U(1)$	$T(2)$	$S(2,0)$	$S(2,1)$	$S(2,2)$	$U(2)$	
c	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...

Value Mapping “DeLICM”

```
   double c;
   for (int i = 0; i < 3; i += 1) {
T:   c = 0;
     for (int k = 0; k < 3; k += 1)
S:     c += A[i] * B[k];
U:   C[i] = c;
   }
```

	$T(0)$	$S(0,0)$	$S(0,1)$	$S(0,2)$	$U(0)$	$T(1)$	$S(1,0)$	$S(1,1)$	$S(1,2)$	$U(1)$	$T(2)$	$S(2,0)$	$S(2,1)$	$S(2,2)$	$U(2)$	
c	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...

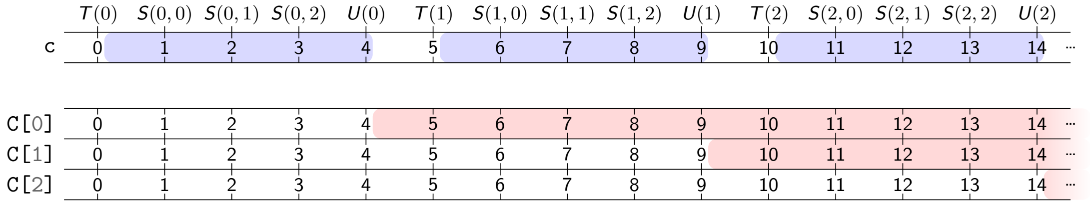
Value Mapping "DeLICM"

```
    double c;
    for (int i = 0; i < 3; i += 1) {
T:    c = 0;
      for (int k = 0; k < 3; k += 1)
S:      c += A[i] * B[k];
U:    C[i] = c;
    }
```

	$T(0)$	$S(0,0)$	$S(0,1)$	$S(0,2)$	$U(0)$	$T(1)$	$S(1,0)$	$S(1,1)$	$S(1,2)$	$U(1)$	$T(2)$	$S(2,0)$	$S(2,1)$	$S(2,2)$	$U(2)$	
c	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...
C[0]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...
C[1]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...
C[2]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...

Value Mapping "DeLICM"

```
    double c;
    for (int i = 0; i < 3; i += 1) {
T:    c = 0;
      for (int k = 0; k < 3; k += 1)
S:      c += A[i] * B[k];
U:    C[i] = c;
    }
```



Value Mapping "DeLICM"

```
   double c;
   for (int i = 0; i < 3; i += 1) {
T:   C[2] = 0;
     for (int k = 0; k < 3; k += 1)
S:     C[2] += A[i] * B[k];
U:   C[i] = C[2];
   }
```

	$T(0)$	$S(0,0)$	$S(0,1)$	$S(0,2)$	$U(0)$	$T(1)$	$S(1,0)$	$S(1,1)$	$S(1,2)$	$U(1)$	$T(2)$	$S(2,0)$	$S(2,1)$	$S(2,2)$	$U(2)$	
c	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...
C[0]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...
C[1]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...
C[2]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...

Value Mapping

“DeLICM”

```
   double c;
   for (int i = 0; i < 3; i += 1) {
T:   C[i] = 0;
     for (int k = 0; k < 3; k += 1)
S:     C[i] += A[i] * B[k];
U:   C[i] = C[i];
   }
```

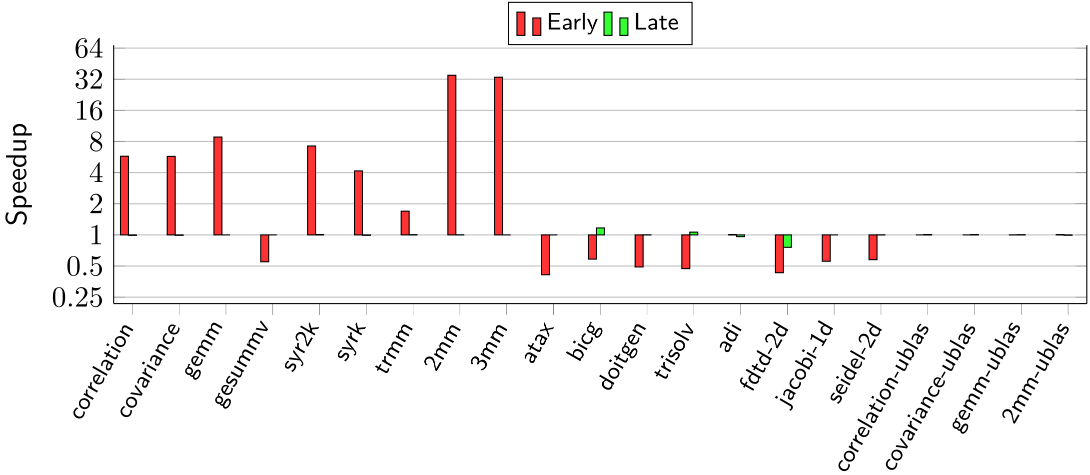
	$T(0)$	$S(0,0)$	$S(0,1)$	$S(0,2)$	$U(0)$	$T(1)$	$S(1,0)$	$S(1,1)$	$S(1,2)$	$U(1)$	$T(2)$	$S(2,0)$	$S(2,1)$	$S(2,2)$	$U(2)$	
c	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	…
C[0]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	…
C[1]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	…
C[2]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	…

Value Mapping “DeLICM”

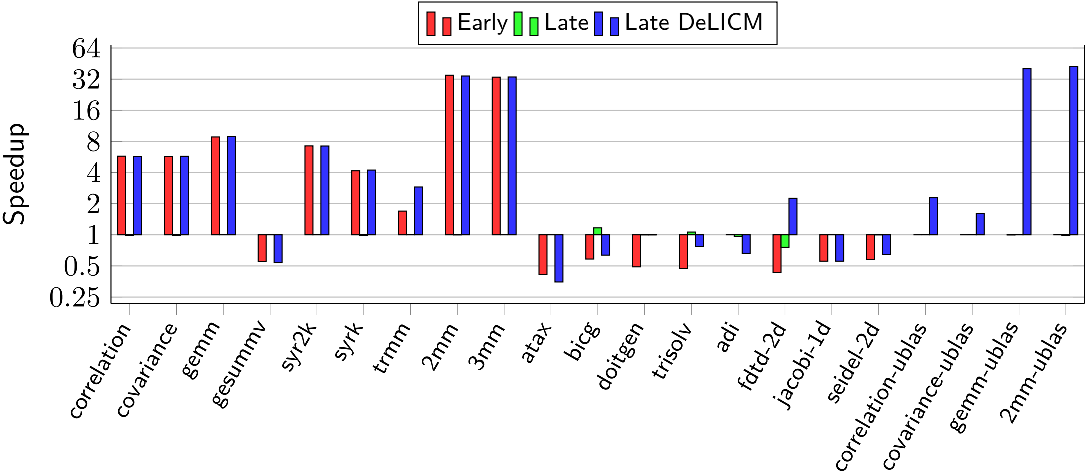
```
    double c;
    for (int i = 0; i < 3; i += 1) {
T:    C[i] = 0;
      for (int k = 0; k < 3; k += 1)
S:      C[i] += A[i] * B[k];
    }
```

	$T(0)$	$S(0,0)$	$S(0,1)$	$S(0,2)$		$T(1)$	$S(1,0)$	$S(1,1)$	$S(1,2)$		$T(2)$	$S(2,0)$	$S(2,1)$	$S(2,2)$		
c	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	…
C[0]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	…
C[1]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	…
C[2]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	…

Experiments



Experiments



Chapter Summary

- LLVM mid-end canonicalization inhibits polyhedral optimization
- Can undo scalar optimizations on the polyhedral representation ("DeLICM")
- Reasons to run Polly after canonicalization:
  - More optimizations, especially the inliner
  - More canonicalized, less dependent on input code
  - Avoid running canonicalization passes redundantly
  - No IR-modification when no polyhedral transformation was done

SPEC CPU 2006 456.hmmer

```
for (k = 1; k <= M; k++) {
  mc[k] = mpp[k-1]   + tpmm[k-1];
  if ((sc = ip[k-1]  + tpim[k-1]) > mc[k])  mc[k] = sc;
  if ((sc = dpp[k-1] + tpdm[k-1]) > mc[k])  mc[k] = sc;
  if ((sc = xmb  + bp[k])         > mc[k])  mc[k] = sc;
  mc[k] += ms[k];
  if (mc[k] < -INFTY) mc[k] = -INFTY;
  dc[k] = dc[k-1] + tpdd[k-1];
  if ((sc = mc[k-1] + tpmd[k-1]) > dc[k]) dc[k] = sc;
  if (dc[k] < -INFTY) dc[k] = -INFTY;
  if (k < M) {
    ic[k] = mpp[k] + tpmi[k];
    if ((sc = ip[k] + tpii[k]) > ic[k]) ic[k] = sc;
    ic[k] += is[k];
    if (ic[k] < -INFTY) ic[k] = -INFTY;
  }
}
```

SPEC CPU 2006 456.hmmer

```
for (k = 1; k <= M; k++) {
  mc[k] = mpp[k-1]   + tpmm[k-1];
  if ((sc = ip[k-1]  + tpim[k-1]) > mc[k])  mc[k] = sc;
  if ((sc = dpp[k-1] + tpdm[k-1]) > mc[k])  mc[k] = sc;
  if ((sc = xmb  + bp[k])         > mc[k])  mc[k] = sc;
  mc[k] += ms[k];
  if (mc[k] < -INFTY) mc[k] = -INFTY;
  dc[k] = dc[k-1] + tpdd[k-1];
  if ((sc = mc[k-1] + tpmd[k-1]) > dc[k]) dc[k] = sc;
  if (dc[k] < -INFTY) dc[k] = -INFTY;
  if (k < M) {
    ic[k] = mpp[k] + tpmi[k];
    if ((sc = ip[k] + tpii[k]) > ic[k]) ic[k] = sc;
    ic[k] += is[k];
    if (ic[k] < -INFTY) ic[k] = -INFTY;
  }
}
```

SPEC CPU 2006 456.hmmer

```
for (k = 1; k <= M; k++) {
  mc[k] = mpp[k-1]   + tpmm[k-1];
  if ((sc = ip[k-1]  + tpim[k-1]) > mc[k])  mc[k] = sc;
  if ((sc = dpp[k-1] + tpdm[k-1]) > mc[k])  mc[k] = sc;
  if ((sc = xmb  + bp[k])         > mc[k])  mc[k] = sc;
  mc[k] += ms[k];
  if (mc[k] < -INFTY) mc[k] = -INFTY;
  dc[k] = dc[k-1] + tpdd[k-1];
  if ((sc = mc[k-1] + tpmd[k-1]) > dc[k]) dc[k] = sc;
  if (dc[k] < -INFTY) dc[k] = -INFTY;
  if (k < M) {
    ic[k] = mpp[k] + tpmi[k];
    if ((sc = ip[k] + tpii[k]) > ic[k]) ic[k] = sc;
    ic[k] += is[k];
    if (ic[k] < -INFTY) ic[k] = -INFTY;
  }
}
```

Compute `mc[k]` (*vectorizable*)

Compute `dc[k]` (**not** vectorizable)

Compute `ic[k]` (*vectorizable*)

LoopDistribution/LoopVectorizer -enable-loop-distribute

- Gerolf Hoflehner, *LLVM Performance Improvements and Headroom*, LLVM DevMtg 2015

```
for (k = 1; k <= M; k++) {
  mc[k] = mpp[k-1]   + tpmm[k-1];
  if ((sc = ip[k-1]  + tpim[k-1]) > mc[k])  mc[k] = sc;
  if ((sc = dpp[k-1] + tpdm[k-1]) > mc[k])  mc[k] = sc;
  if ((sc = xmb  + bp[k])         > mc[k])  mc[k] = sc;
  mc[k] += ms[k];
  if (mc[k] < -INFTY) mc[k] = -INFTY;
}
```

loop-vectorized

```
for (k = 1; k <= M; k++) {
  dc[k] = dc[k-1] + tpdd[k-1];
  if ((sc = mc[k-1] + tpmd[k-1]) > dc[k]) dc[k] = sc;
  if (dc[k] < -INFTY) dc[k] = -INFTY;
  if (k < M) {
    ic[k] = mpp[k] + tpmi[k];
    if ((sc = ip[k] + tpii[k]) > ic[k]) ic[k] = sc;
    ic[k] += is[k];
    if (ic[k] < -INFTY) ic[k] = -INFTY;
  }
}
```

not vectorized

LoopDistribution/LoopVectorizer

-loop-distribute-non-if-convertible

```
for (k = 1; k <= M; k++) {
  mc[k] = mpp[k-1]   + tpmm[k-1];
  if ((sc = ip[k-1]  + tpim[k-1]) > mc[k])  mc[k] = sc;
  if ((sc = dpp[k-1] + tpdm[k-1]) > mc[k])  mc[k] = sc;
  if ((sc = xmb  + bp[k])         > mc[k])  mc[k] = sc;
  mc[k] += ms[k];
  if (mc[k] < -INFTY) mc[k] = -INFTY;
}
```

loop-vectorized

```
for (k = 1; k <= M; k++) {
  dc[k] = dc[k-1] + tpdd[k-1];
  if ((sc = mc[k-1] + tpmd[k-1]) > dc[k]) dc[k] = sc;
  if (dc[k] < -INFTY) dc[k] = -INFTY;
}
```

not vectorized

```
for (k = 1; k <= M; k++) {
  if (k < M) {
    ic[k] = mpp[k] + tpmi[k];
    if ((sc = ip[k] + tpii[k]) > ic[k]) ic[k] = sc;
    ic[k] += is[k];
    if (ic[k] < -INFTY) ic[k] = -INFTY;
  }
}
```

vectorized with if-conversion

Polly -polly-stmt-granularity=bb

```
      for (k = 1; k <= M; k++) {
Stmt1:  mc[k] = mpp[k-1]   + tpmm[k-1];
        if ((sc = ip[k-1]  + tpim[k-1]) > mc[k])  mc[k] = sc;
        if ((sc = dpp[k-1] + tpdm[k-1]) > mc[k])  mc[k] = sc;
        if ((sc = xmb  + bp[k])         > mc[k])  mc[k] = sc;
        mc[k] += ms[k];
        if (mc[k] < -INFTY) mc[k] = -INFTY;
        dc[k] = dc[k-1] + tpdd[k-1];
        if ((sc = mc[k-1] + tpmd[k-1]) > dc[k]) dc[k] = sc;
        if (dc[k] < -INFTY) dc[k] = -INFTY;

        if (k < M) {
Stmt2:    ic[k] = mpp[k] + tpmi[k];
          if ((sc = ip[k] + tpii[k]) > ic[k]) ic[k] = sc;
          ic[k] += is[k];
          if (ic[k] < -INFTY) ic[k] = -INFTY;
        }
      }
```

Polly -polly-stmt-granularity=scalar-indep

```
    for (k = 1; k <= M; k++) {
Stmt1: mc[k] = mpp[k-1]   + tpmm[k-1];
       if ((sc = ip[k-1]  + tpim[k-1]) > mc[k])  mc[k] = sc;
       if ((sc = dpp[k-1] + tpdm[k-1]) > mc[k])  mc[k] = sc;
       if ((sc = xmb  + bp[k])         > mc[k])  mc[k] = sc;
       mc[k] += ms[k];
       if (mc[k] < -INFTY) mc[k] = -INFTY;

Stmt2: dc[k] = dc[k-1] + tpdd[k-1];
       if ((sc = mc[k-1] + tpmd[k-1]) > dc[k]) dc[k] = sc;
       if (dc[k] < -INFTY) dc[k] = -INFTY;

       if (k < M) {
Stmt3:   ic[k] = mpp[k] + tpmi[k];
         if ((sc = ip[k] + tpii[k]) > ic[k]) ic[k] = sc;
         ic[k] += is[k];
         if (ic[k] < -INFTY) ic[k] = -INFTY;
       }
    }
```

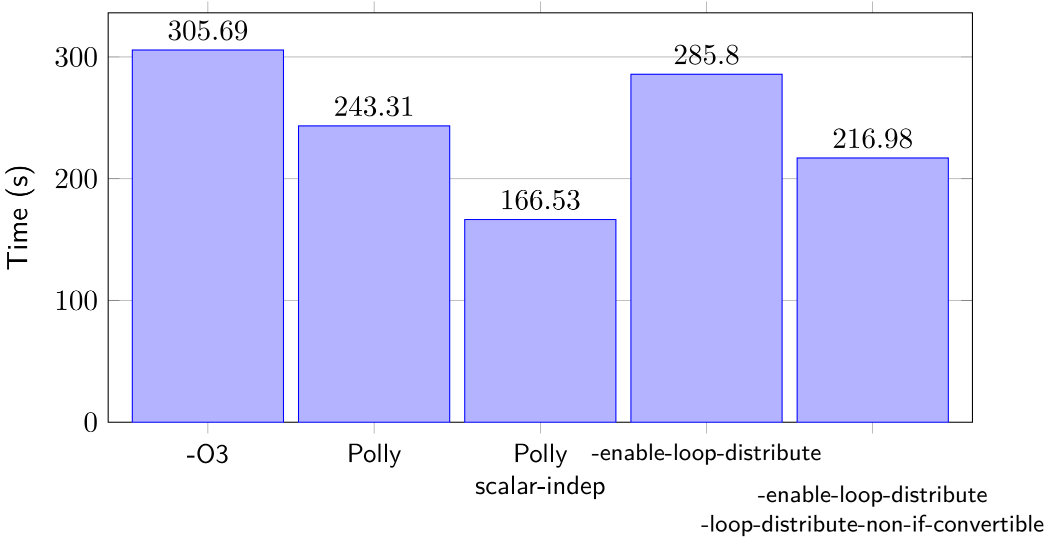
Loop Distribution by Polyhedral Scheduler

```
$ opt -polly-stmt-granularity=scalar-indep -polly-invariant-load-hoisting -polly-use-llvm-names \
  fast_algorithms.ll -polly-opt-isl -polly-ast -analyze

[...]

    {
      for (int c0 = 0; c0 < _lcssa; c0 += 1)
        Stmt_for_body72(c0);
      for (int c0 = 0; c0 < _lcssa; c0 += 1)
        Stmt_for_body721(c0);
      for (int c0 = 0; c0 < _lcssa - 1; c0 += 1)
        Stmt_if_then167(c0);
      if (_lcssa >= 1)
        Stmt_for_end204_loopexit();
    }
```

Experiments



Chapter Summary

- Finer-grained statements
- One basic block => multiple statement if no computation is shared
- Enables loop distribution by Polly
- Speed-up of 80% in 456.hmmer

- With support from Nandini Singhal

That's all Folks!

Summary

1. COSMO weather forecasting on GPGPUs
2. Life Range Reordering (Verdoolaege IMPACT'16)
3. DGEMM detection also with C++ expression templates (Roman Gareev)
4. Correct types for loop transformations (Maximilian Falkenstein)
5. Some LLVM passes make polyhedral optimization harder
6. `-polly-position=early` vs. `-polly-position=before-vectorizer`
7. DeLICM: Avoiding scalar dependencies
8. `-polly-stmt-granularity` and loop-distribution in 456.hmmer (with Nandini Singhal)