Vectorization in LLVM

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LLVM-based vectorizers

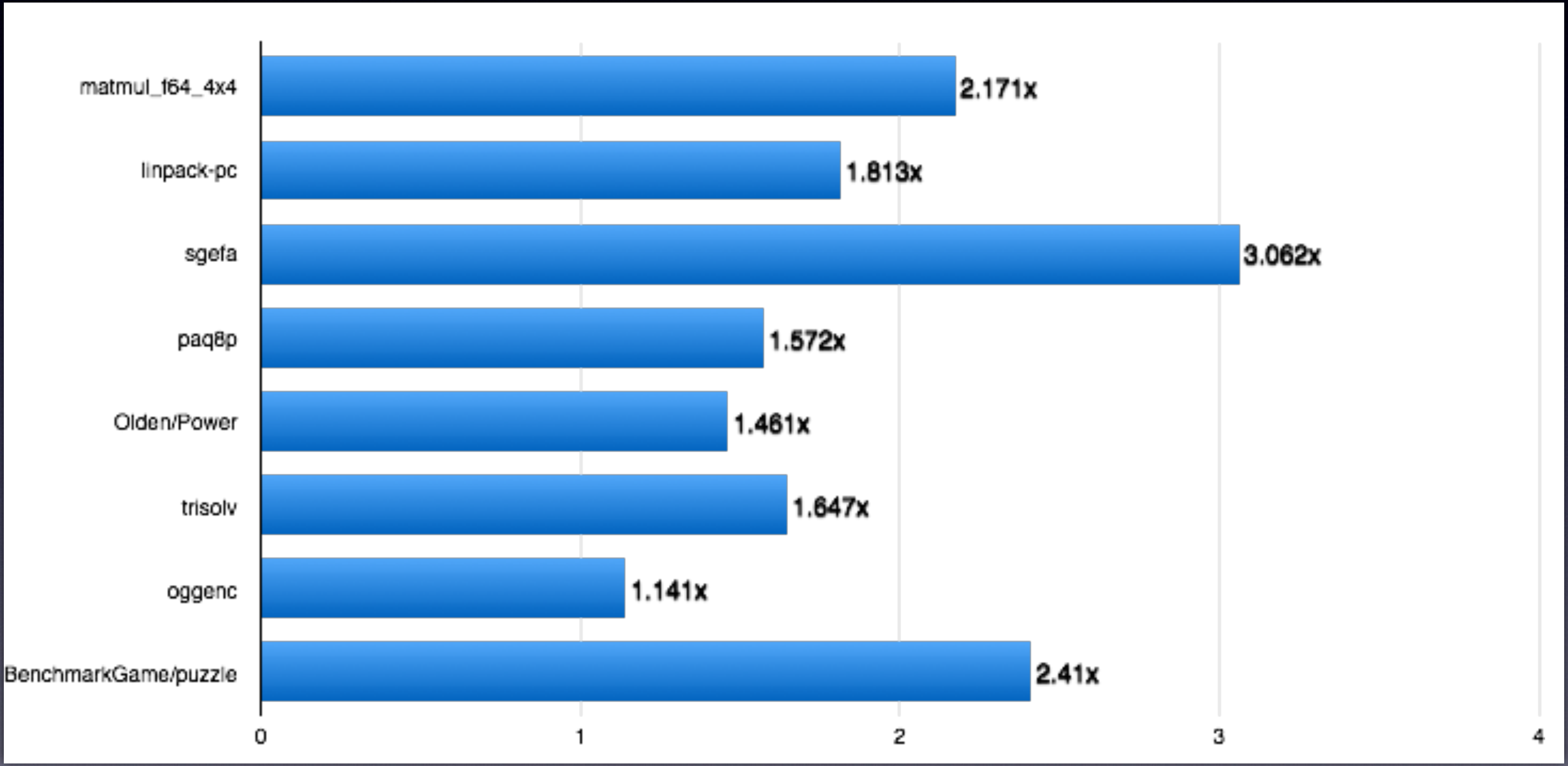
- AnySL
- Intel OpenCL
- Polly
- ISPC

- Hal's BB vectorizer
- Loop vectorizer
- SLP vectorizer

Thanks!

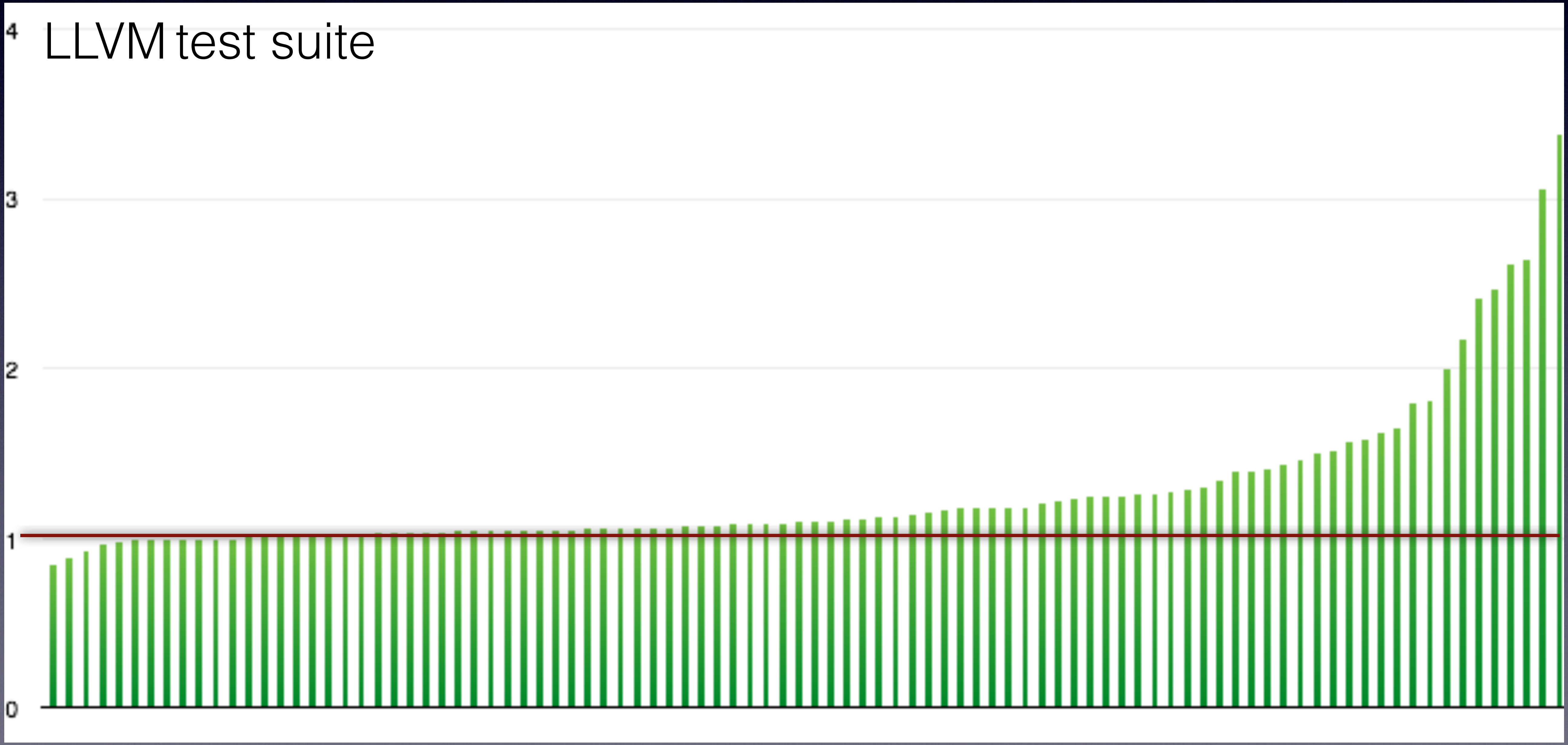
Thanks to all of the people who contributed to the vectorizer in the last year

Performance



*x86, +AVX, Sandybridge

Performance



**x86_64, +avx, sandybridge, higher better

Usage

- Loop Vectorizer.
  - -fvectorize / -fno-vectorize
- SLP Vectorizer.
  - -fslp-vectorize / -fno-slp-vectorize
- Both on by default on -Os, -O2 and -O3

Loop Vectorizer

- Vectorizes innermost loops
- Unrolls loops for ILP

Features

- Loops with unknown trip count

```
void foo(float *A, float* B, int start, int end) {

  for (int i = start; i < end; ++i)
    A[i] *= B[i];

}
```

Features

- Loops that count backwards

```
void foo(int *A, int n) {

  for (int i = n; i > 0; --i)
    A[i] += i;

}
```

Features

- Runtime array bounds check

```
void foo(float *A, float *B, float K) {

  for (int i = 0; i < N; ++i)
    A[i] += B[i] + K;

}
```

Features

- Reductions

```
int foo(int *A, int *B, int K) {
  int sum = 0;

  for (int i = 0; i < N; ++i)
    sum += A[i] + K;

  return sum;
}
```

Features

- Inductions

```
int foo(int *A) {

  for (int i = 0; i < N; ++i)
    A[i] = i;

}
```

Features

- If-conversion (loops with ifs)

```
int foo(int *A, int *B) {
  int sum = 0;

  for (int i = 0; i < N; ++i)
    if(A[i] > B[i])
      sum += A[i] +5

  return sum;
}
```

Features

- Pointer and C++ iterators vectorization

```
int foo(int *A, int n) {
  return std::accumulate(A, A + n, 0);
}
```

Features

- Partial vectorization (parts of the code are scalar)

```
int foo(int *A, int *B, int n, int k) {

  for (int i = 0; i < n; ++i)
    A[i] += B[i*k];

}
```

Features

- Vectorization of mixed types

```
int foo(int *A, char *B, int n) {

  for (int i = 0; i < n; ++i)
    A[i] += 4 * B[i];

}
```

Features

- Vectorization of some function calls

```
int foo(float *A) {

  for (int i = 0; i < 1024; ++i)
    A[i] += floorf(f[i]);

}
```

Features

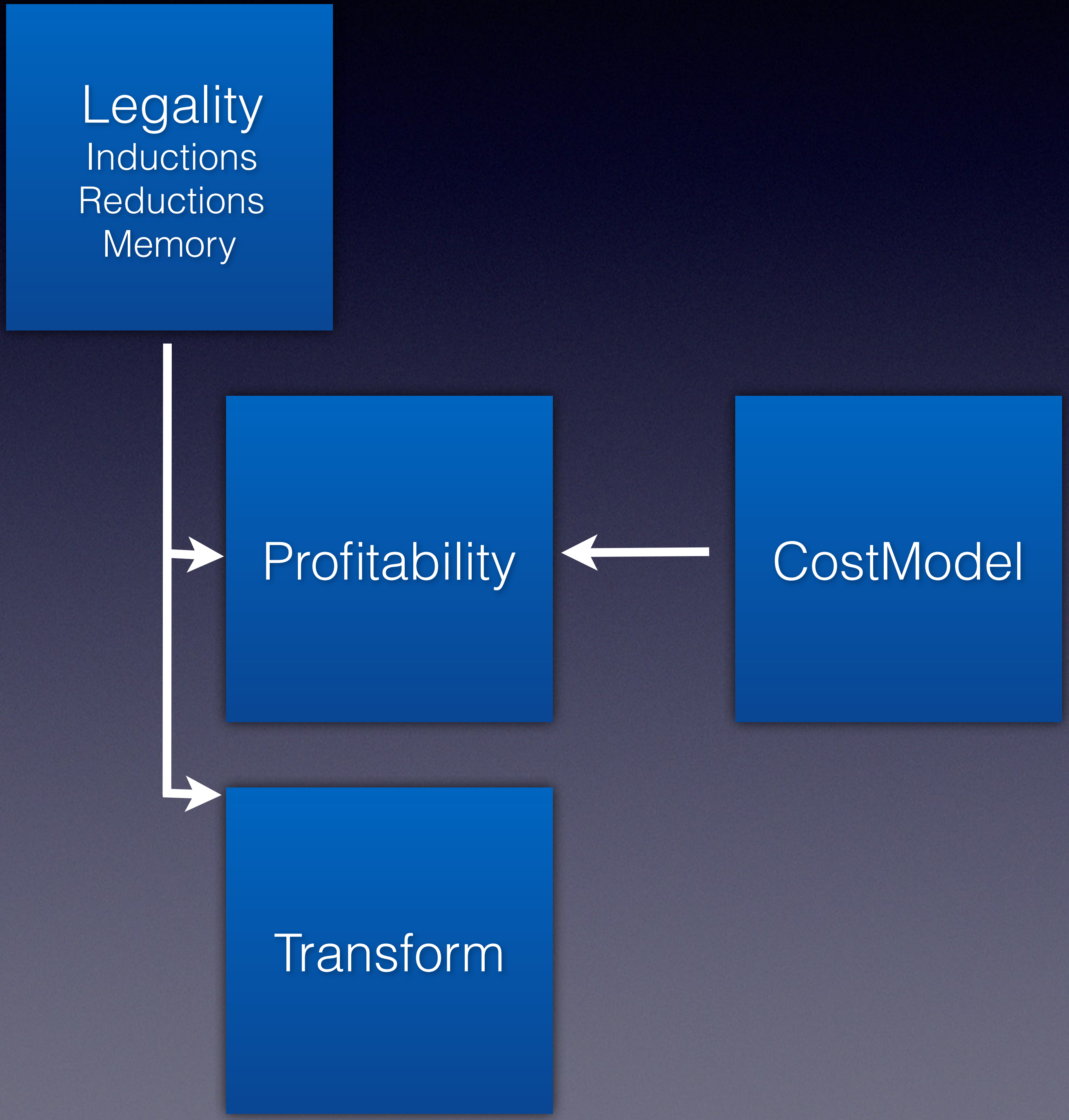
- Unrolling for ILP during vectorization

```
for (i = 0; i < N; ++i) {
  r += A[i];
}
```

```
for (i = 0; i < (N/8)*8; i+=8) {
  r1 += A[i:i+3];
  r2 += A[i+4:i+7];
}
r = r1 <+> r2
...
```

Design

- 3 phases:
  - Legality
  - Profitability
  - Transform



Legality
Inductions
Reductions
Memory

Profitability

CostModel

Transform

Legality

- Inductions/Reductions

```
for (int i = 0; i < N; i++)
  r += A[i] + i;
```

- Memory access safety

```
for (int i = 1; i < N; i++)
  A[i] ~~=~~ A[i-1];
```

- Memory checks

```
// A !overlap B
for (int i = 0; i < N; i++)
  A[i+1] = B[i];
```

- Vectorizable intrinsics

```
for (int i = 0; i < N; i++)
  A[i] = pow(B[i], 2.0);
```

Profitability

```
Cost of load i64
Cost of add i64
...
```

vs.

```
Cost of load <2 x i64>
Cost of add <2 x i64>
...
```

- Query cost model
- Choose vector width with lowest cost

```
unsigned getArithmeticInstrCost(unsigned Opcode, Type *Ty);
```

How it works

- As much as possible from TargetLowering

```
TLI->isOperationLegalOrPromote(Opcode)
TLI->getTypeLegalizationCost(Ty)
```

- Generic rules

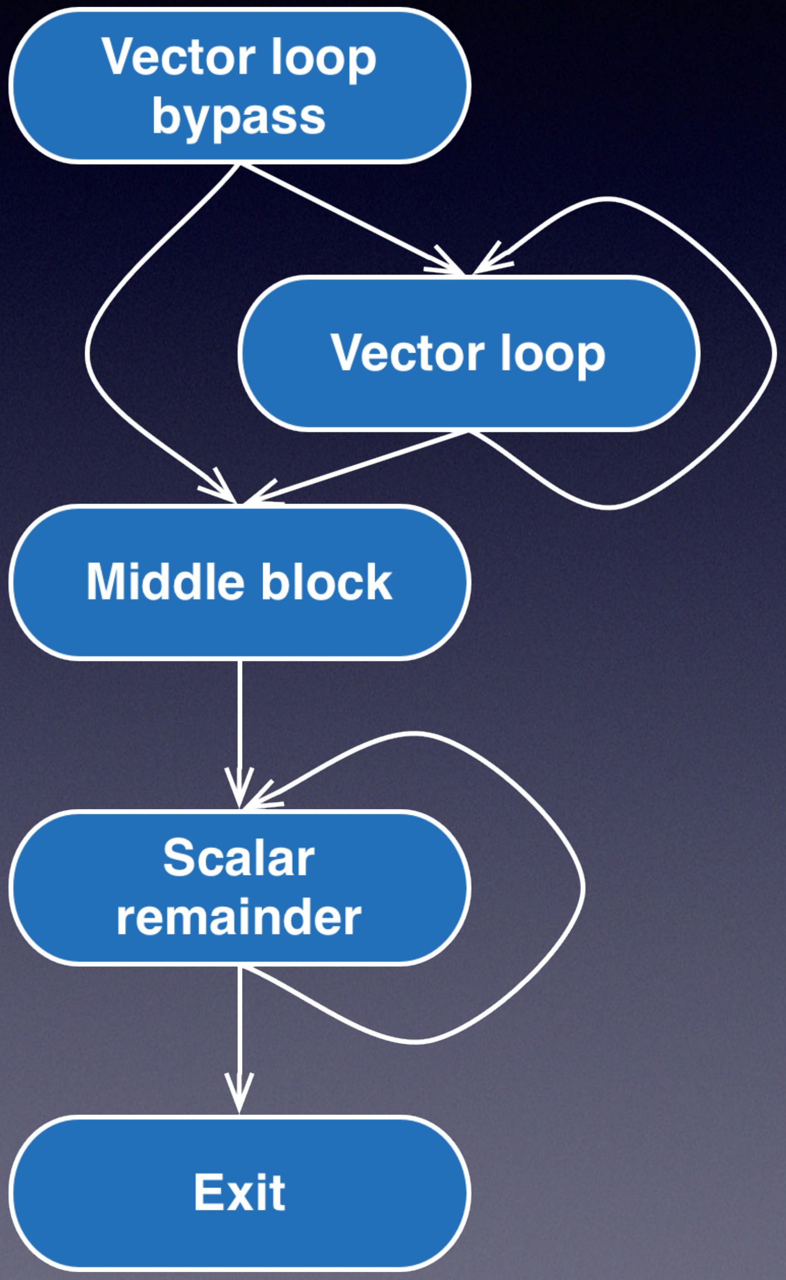
```
 Cost = 1;
 if (isExpand) Cost = 2;
```

```
Cost *= LegalizationCost;
Cost *= Width; // Scalarize.
```

- Exceptions from target specific tables

```
    { ISD::ZEXT,  MVT::v4i8, 1 },
    { ISD::SEXT,  MVT::v4i8, 3 },
```

Transformation



```
if (A overlap B)
  goto scalar loop
```

```
for (i = 0; i < (N/8)*8; i+=8) {
  r1 += A[i:i+3];
  r2 += A[i+4:i+7];
}
r = r1 <+> r2; // Horizontal
```

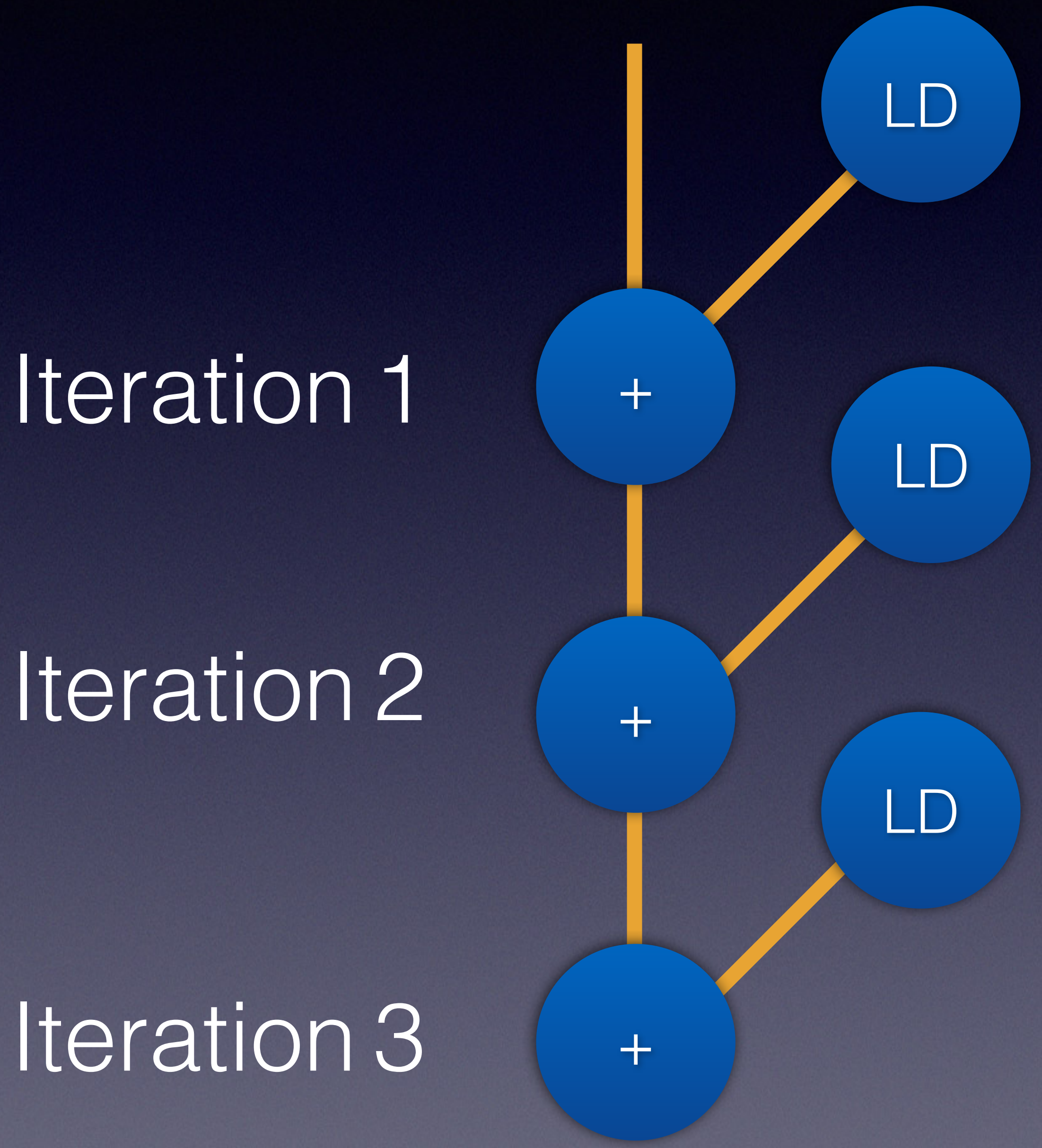
```
for (; i < N; i++) {
  r += A[i];  // Remainder
}
```

Unrolling for ILP

- Modern processors can execute many instructions at once
- Reductions introduce data-hazards (compute depends on previous iteration)

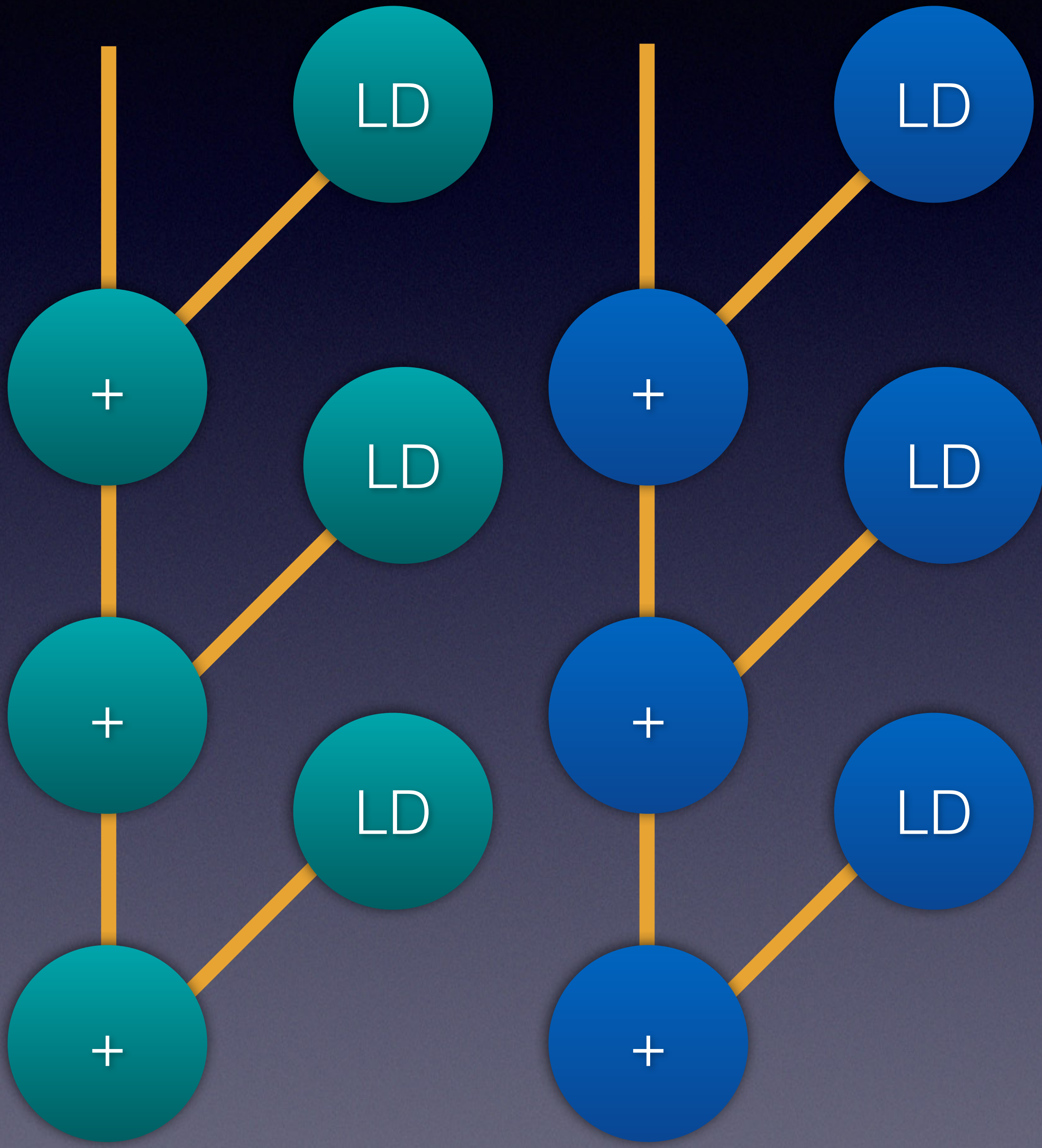
```
for (i = 0; i < N; ++i)
  sum += A[i];
```

Unrolling in the vectorizer



```
for (i = 0; i < n; ++i)
  sum += A[i];
```

Unrolling in the vectorizer



```
for (i = 0; i < n; i+=2) {
   sum0 += A[i];
   sum1 += A[i+1];
}
```

Why unroll in the vectorizer?

- Same kind of analysis that the vectorizer does (e.g. reductions + tail loop)
- Loop Vectorizer often unrolls and keeps the code scalar

Loop Vectorizer TODO

- Support for vectorizer #pragma
- Vectorization with library functions
- Inlining + restrict
- Vectorization of interleaved data
- Support for AVX512 (predication, ...)

#pragma

- Control vectorization width and unrolling
- Mark as legal (no runtime checks needed)

```
void foo(int *A, int *B) {

  #pragma vectorize factor(2) unroll(2)
  for (i = 0; i < N; i++)
    B[i+1] = A[i];

}
```

Vectorization with library functions

- Vectorized library function calls available
- Use vectorized library function

```
void foo(float *A, float *B, float P) {
  for (int i = 0; i < 256; ++i)
    A[i] = pow(B[i], P);
}
```

```
void foo(float *A, float *B, float P) {
  for (int i = 0; i < 256; i += 4)
    A[i:i+3] = vector_pow(B[i:i+4], <P, P, P, P>);
}
```

Inlining and restrict

- After inlining we lose 'restrict' keyword

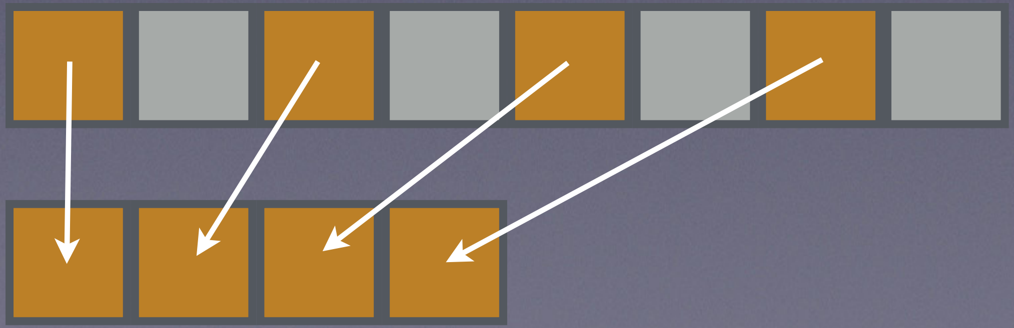
```
int foo(int *restrict A, int *restrict B) {
  for (int i = 0; i < N; i++)
    A[i+1] = B[i];
}

void bar() {
  foo(Ptr1, Ptr2)
}
```

```
void bar() {
  int *restrict Ptr1 = Ptr1; int *restrict Ptr2 = Ptr2;
  for (int i = 0; i < N; i++)
    Ptr1[i+1] = Ptr2[i];
}
```

Vectorization of interleaved data

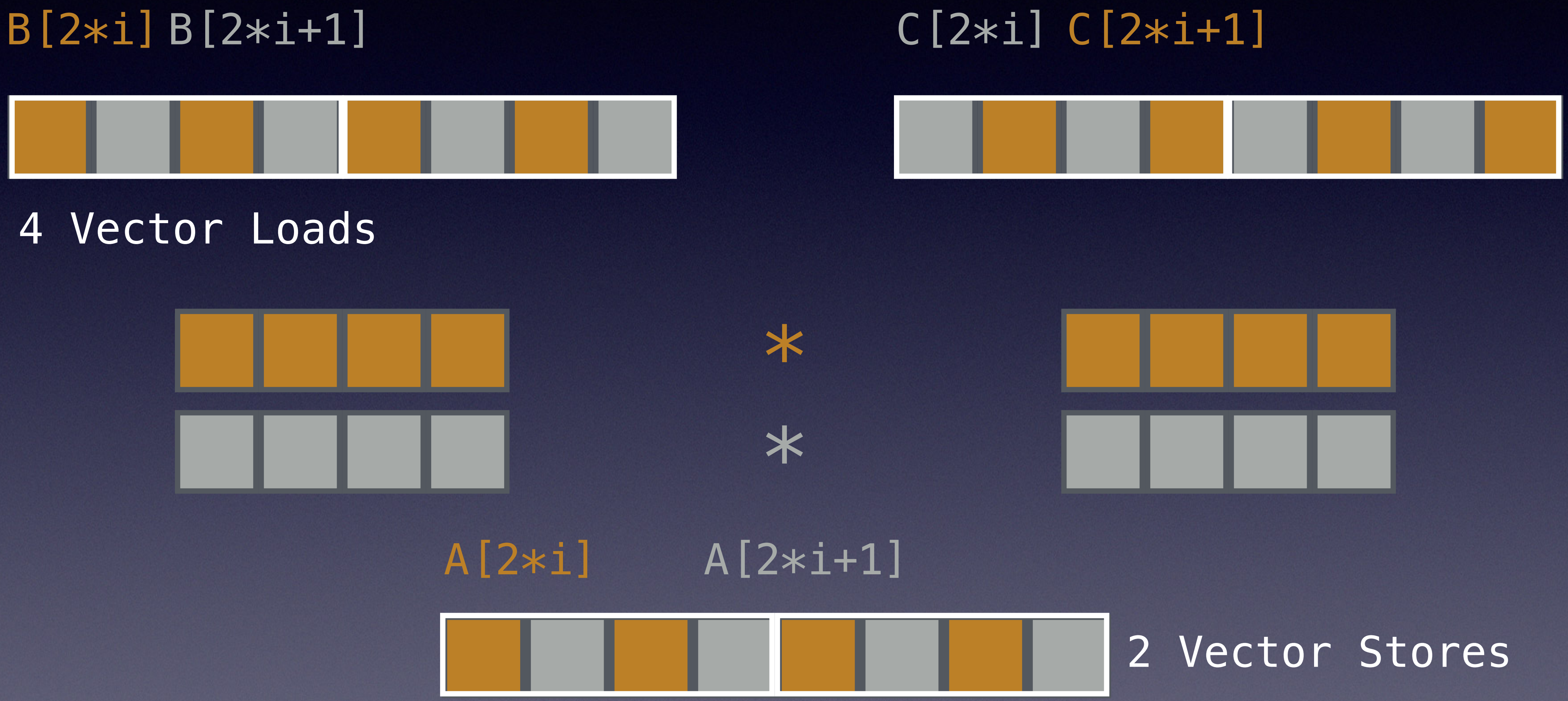
- Vectorizer looks at each instruction individually
- Deemed too expensive due to gather/scather

```
void foo(float *A, float *B, float *C) {
  for (int i = 0; i < 256; ++i) {
    A[2*i]   = B[2*i]     * C[2*i+1]
    A[2*i+1] = B[2*i+1]   * C[2*i];
  }
}
```



`4 Loads + Inserts into vector just for B[2*i]`

Look at all accesses



B[2*i] B[2*i+1]

C[2*i] C[2*i+1]

4 Vector Loads

*

*

A[2*i] A[2*i+1]

2 Vector Stores

```
A[2*i]   = B[2*i]   * C[2*i+1]
A[2*i+1] = B[2*i+1] * C[2*i];
```

SLP Vectorization

SLP vectorizer

- Superword-Level Parallelism
- Combines multiple scalars into one vector operation
- Reduce code size and register pressure
- Excellent for graphics code that uses RGBA
- Example:

```
void foo(double *A, double *B) {
  A[0] = B[0] + 56.0;
  A[1] = B[1] + 11.2;
}
```

Example

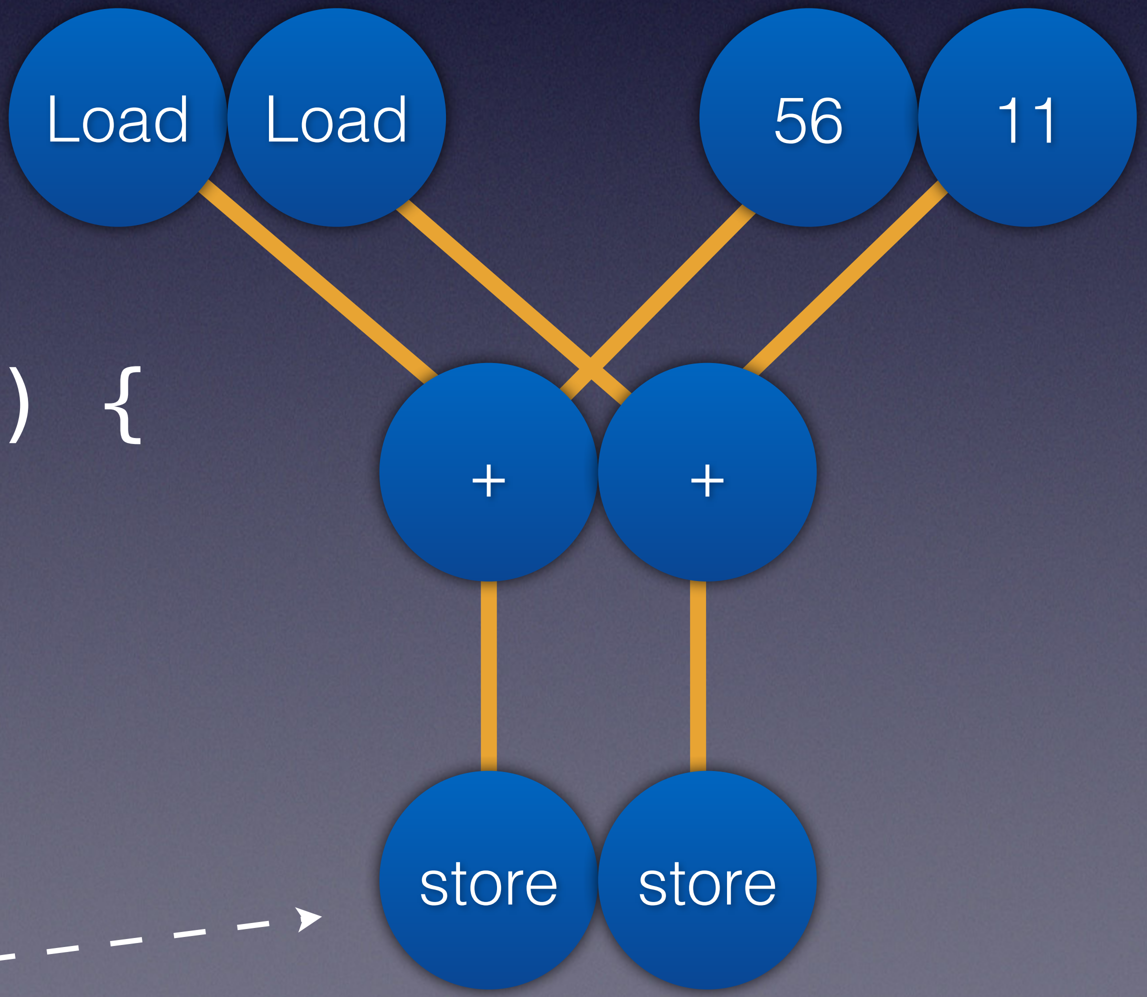
- 2X boost in performance on matmul_f64_4x4:

```
static void mul4(double *Out,  double A[4][4],  double B[4][4]) {
    unsigned n;   double Res[16];

    Res[ 0] = A[0][0]*B[0][0] + A[0][1]*B[1][0] + A[0][2]*B[2][0] + A[0][3]*B[3][0];
    Res[ 1] = A[0][0]*B[0][1] + A[0][1]*B[1][1] + A[0][2]*B[2][1] + A[0][3]*B[3][1];
    Res[ 2] = A[0][0]*B[0][2] + A[0][1]*B[1][2] + A[0][2]*B[2][2] + A[0][3]*B[3][2];
    Res[ 3] = A[0][0]*B[0][3] + A[0][1]*B[1][3] + A[0][2]*B[2][3] + A[0][3]*B[3][3];

    ...
}
```

How SLP Vectorization works

- Bottom-up search
- Vectorize profitable trees

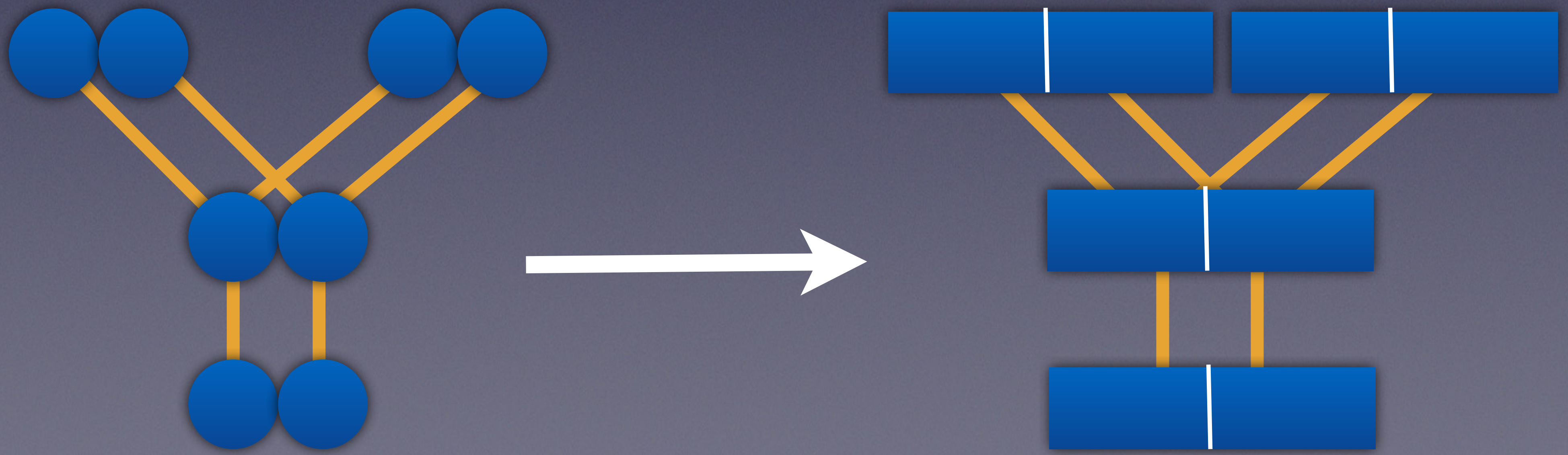
```
int foo(int *A, int *B) {
  A[0] = B[0] + 56;
  A[1] = B[1] + 11;
}
```



'roots'

SLP Vectorization Phases

1. Build a vectorizable tree
2. Estimate the cost of the tree
3. Vectorize the tree



Finding roots

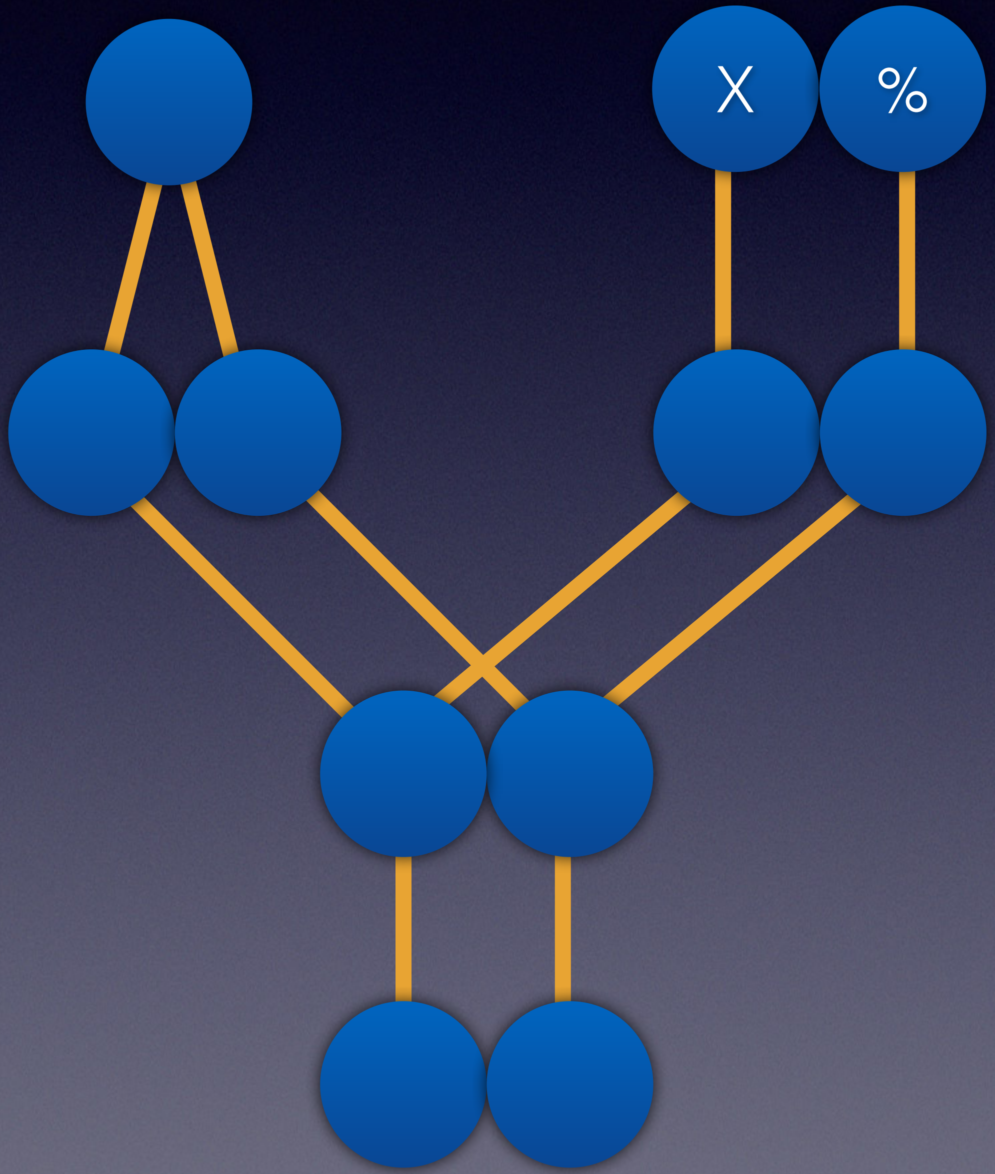
- Consecutive stores
- Arithmetic reductions
- PHI node sequences
- Other popular patterns

```
A[i] = ...
A[i+1] = ...
```

```
sum += ...
sum += ...
```

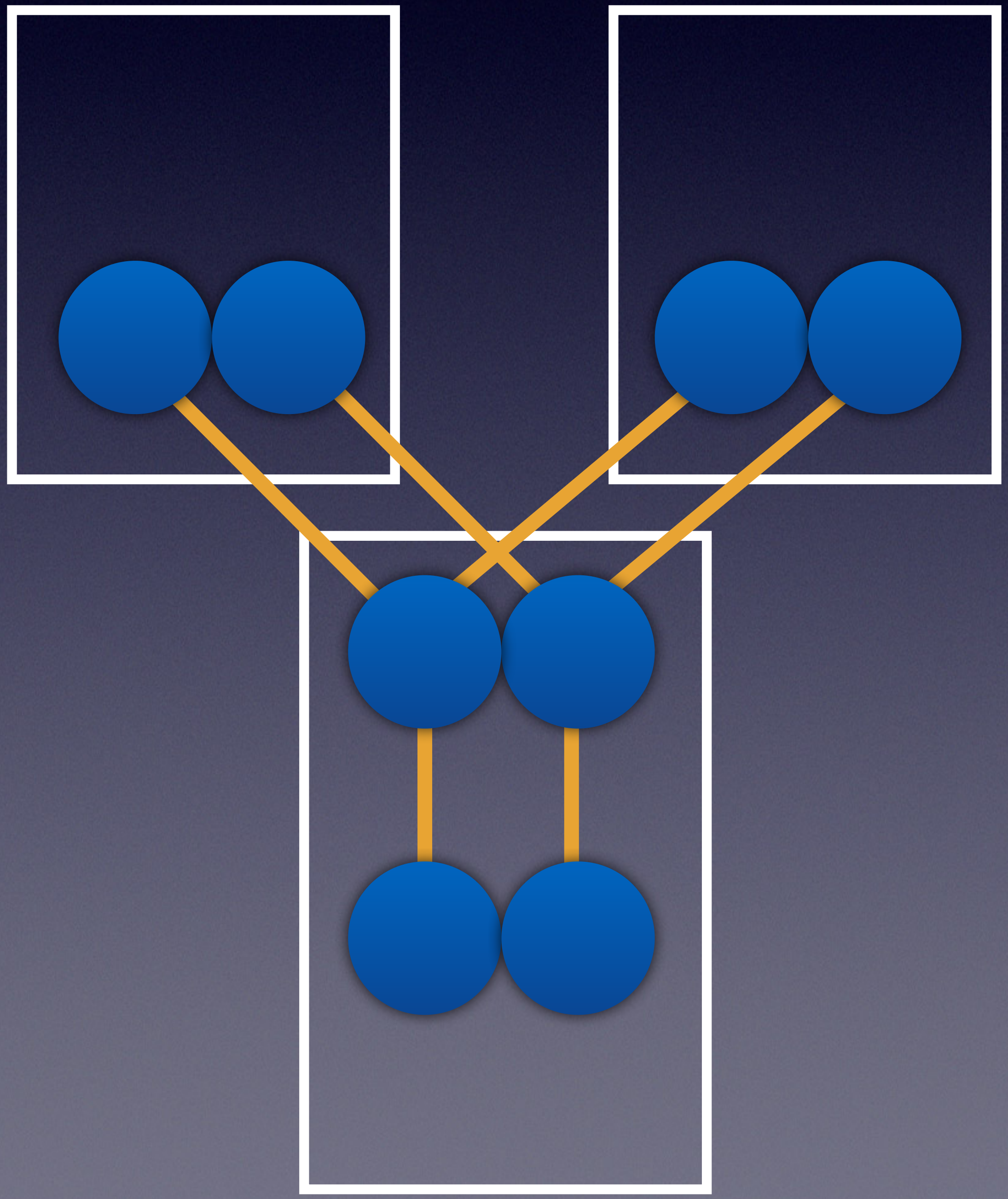
Features

- Gather and broadcast sequences



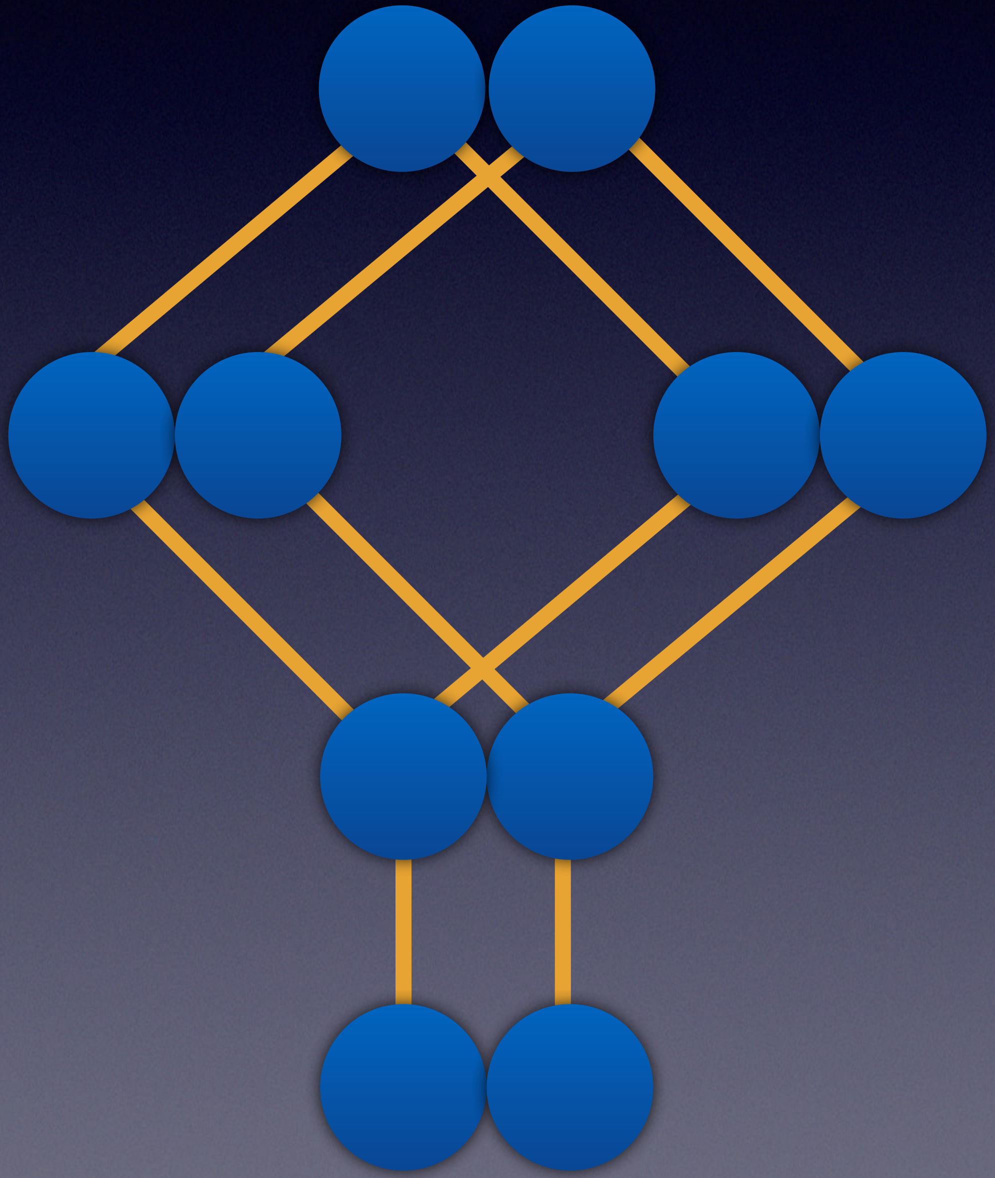
Features

- Multiple basic blocks
- Vectorize PHIs to reduce register pressure



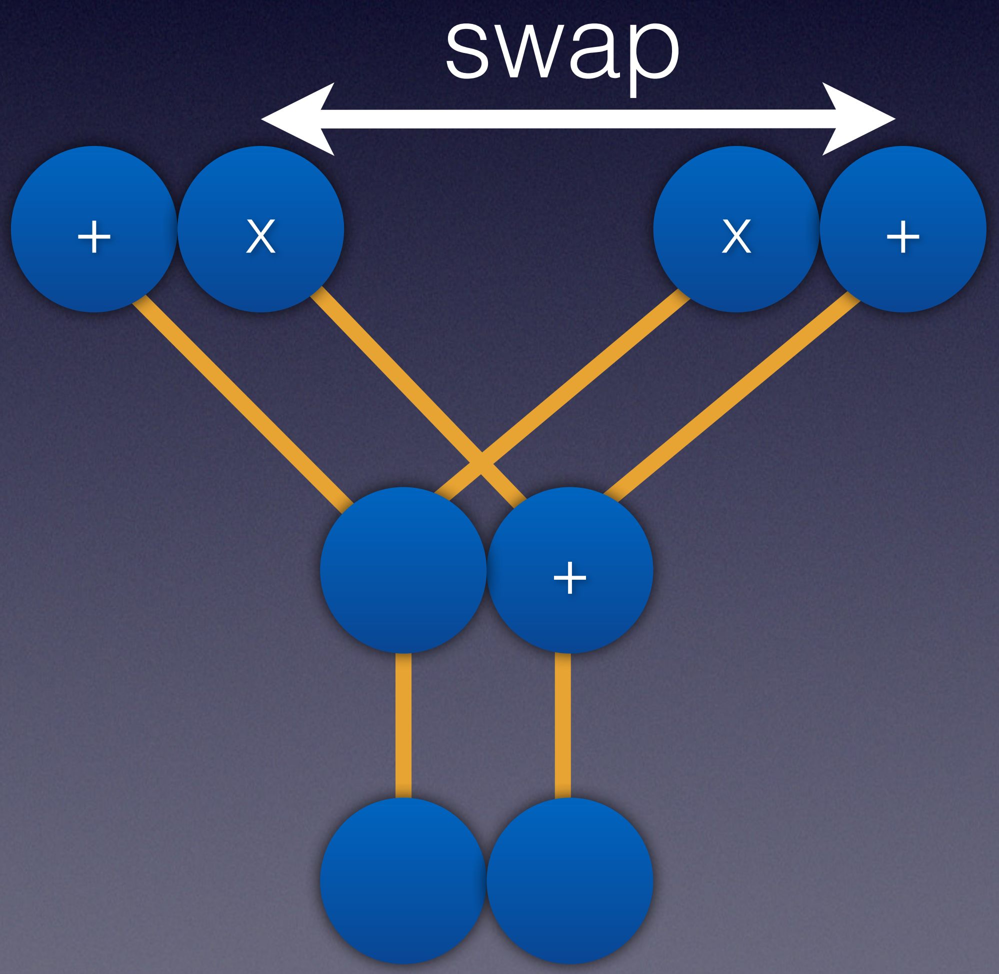
Features

- Diamond-shaped ~~tree~~ graph



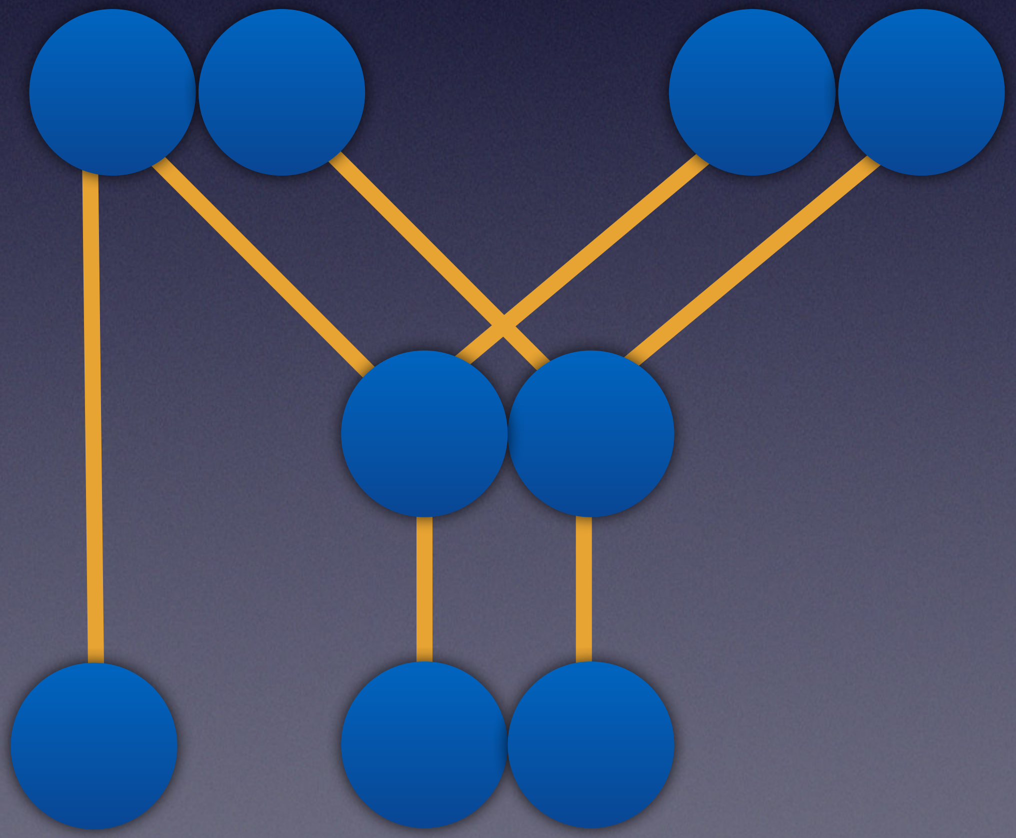
Features

- Swizzle binary operations



Features

- External users



TODO

- Function call vectorization
- Cost model for vector width = 3
- Loop aware multi-block cost model tuning
- Additional root patterns

How can you help?

- Analyze workloads
- Benchmark LLVM
  - Compare to other compilers
  - Try different cpu features, vector width, etc
- Improve vector code generation and cost model
- Implement a new feature

Questions?