VICO: Demand-Driven Verification for Improving Compiler Optimizations

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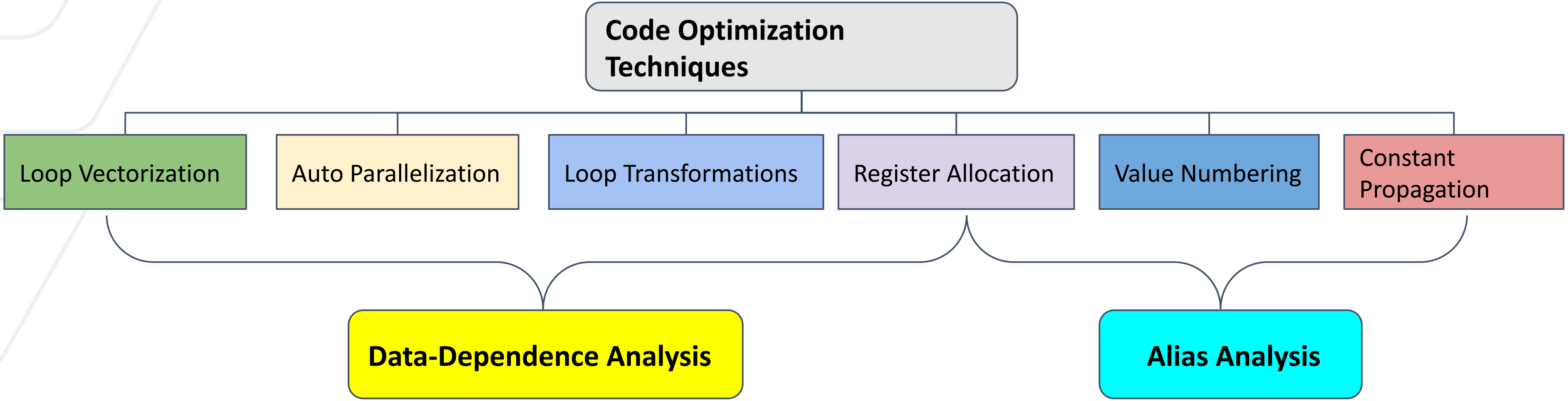
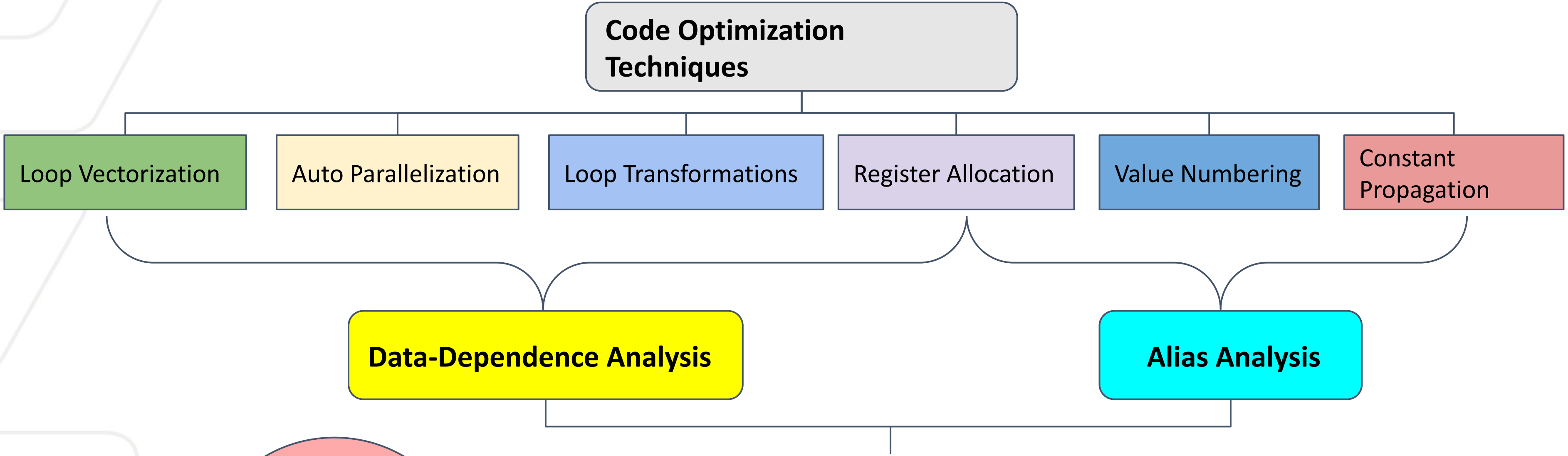
<u>Motivation</u>: Traditional Compiler Analysis suffer from Imprecision



- ⏩ **Dependence Analysis** & **Alias Analysis** form the backbone of many important code optimization techniques
- ⏩ Goal of these analyses is to yield optimized end code, while keeping compilation time low

Motivation: Traditional Compiler Analysis suffer from Imprecision



Conservative (Safe) Approximations

Hinders optimization opportunities

- ❌ Inability to check infeasible program paths
- ❌ Inability to symbolically propagate and evaluate expressions
- ❌ inability to verify statically unknown properties *inter-procedurally*

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Example: Liebmann's Method with generalized boundary conditions

```
int getK (int par) {

if (par % 2)
  return 2*(par + 1);
else
 return 2*par;
}
```

Possible implementation of boundary offset values

k1 and k2 initialized by external function calls

```
void liebmann2D (/*arguments*/) {

int k1 = getK(N), k2 = getK(N);
for (t = 0; t <= M; t++)
 for (i = 1; i <= N; i++)
  for (j = 1; j <= N; j++)
        A[i][j] = (A [i - k1] [j - k1] + A[i - k1][j] + A[i][j]
              + A[i - k1][j + k2] + A[i][j - k1] + A[i][j + k2]
              + A[i + k2][j - k1] + A[i + k2][j]
              + A[i + k2][j + k2])/c;
}
```

Interprocedural whole program flow analysis unable to prove the (k1,k2 > N) invariant

⇧

Proving (k1,k2 > N) breaks most dependencies

⇧

$0 \leq k1 , k2 \leq N$ (Dependence Equation)
Compiler assumes all possible dependencies

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Example: 505.mcf_r (SPEC 2017)

```
void marc_arcs(/*arguments*/) {
/* function body definitions */
while(global_new < *new_arcs && global_new < max_new_arcs) {
   if (values[0] < new_arcs_array[0])
      arc = *positions[0];
   else
      ..
   for (i = 1; i < num_threads; i++) {
      if ((values[i] < new_arcs_array[i]) &&
         ((arc_compare(positions[i], &arc) < 0) ||
          !arc)) {
            arc = *positions[i];
         }}
      global_new++;
   }
}
```

arc and *positions[0:num_threads] point to the same locations

LLVM considers these two as May-Aliases

arc and *positions[0:num_threads] should be considered as Must-Aliases

LLVM considers pointers which begin at same location and points to the same overlapping area as Must-Alias

Adverse effect on value numbering and register allocation

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Solution: Need for a demand-driven verification based solution

Proving Optimization Constraints

Whole Program Interprocedural Analysis

❌ Exponential number of program paths

❌ Edge based, context-insensitive, flow Insensitive approximations

❌ Whole program = unnecessary propagation, slow

❌ Not supported by most production compilers

Whole Program Verification

✅ Leverages pruning techniques to counter exponential path growth

❌ Proves all possible properties unrelated to optimization

❌ Doesn't have a starting point for choosing properties

Demand-Driven Verification

✅ Proves only those properties that are related to optimization instance at hand

✅ Has the ability to pick properties that can break maximum constraints

Key Insight: "Verification can boost Compiler Optimizations"

Use of Software Verification in Compilers

To the best of our knowledge, this line of work has not been tackled previously

Verified Compiler Optimizations

⏩ Goal is to check the legality of various compiler optimizations

⏩ Focus is on checking the correctness of generated code i.e if the optimization preserves program semantics

Formally Verified Compilers

⏩ Goal is to avoid miscompilation using mathematical reasoning

⏩ Focus is on proving the correctness of generated IR code

Verification for Compiler Optimizations

⏩ Use of software verification in a demand-driven manner to boost compiler optimizations

⏩ Focus is on finding out the bottlenecks for compiler analysis, formulate the necessary invariants and then verify them - demand driven

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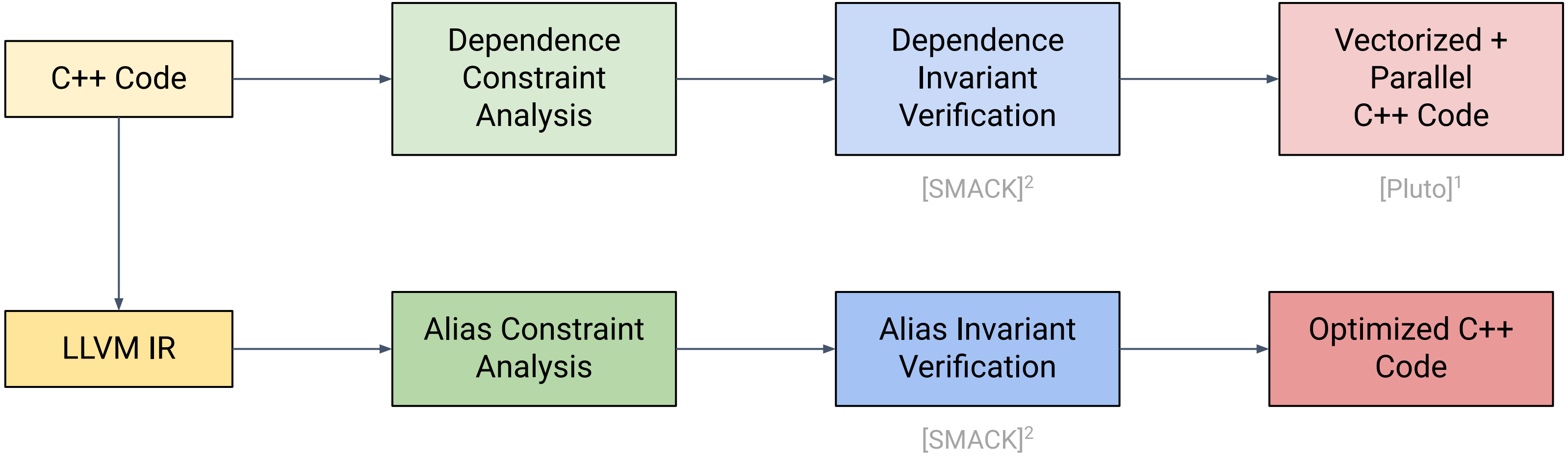
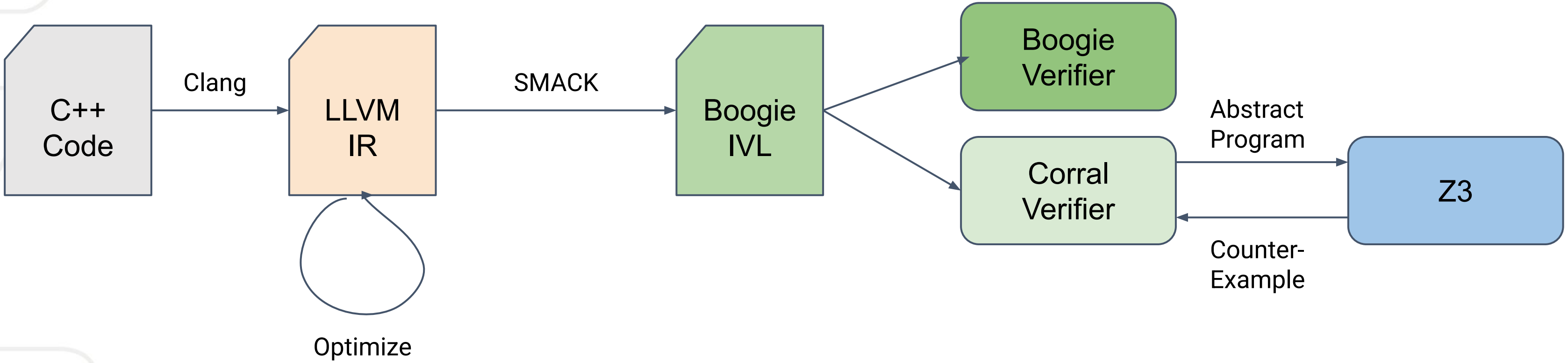


1. https://github.com/bondhugula/pluto 2. https://github.com/smackers/smack

Smack Verifier Toolchain[2]



A Verification Framework that uses LLVM optimizations and converts the IR into Boogie IVL to prove properties about the code

2. https://github.com/smackers/smack

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Smack Example

```
int main () {
  int x = 0, i = 0;
  for (i  = 0; i < M; ++i) {
    x = i;
  }
  assert (x == M - 1);
  return 0;
}
```

Source Code

```
define dso_local i32 @main() #0 !dbg !34 {
      store i32 0, i32* @x, align 4, !dbg !40, !verifier.code !39
      br label %1, !dbg !41, !verifier.code !39
1:    preds = %4, %0
      %0 = phi i32 [ 0, %0 ], [ %5, %4 ], !dbg !43, !verifier.code !39
      %2 = icmp slt i32 %.0, 10, !dbg !44, !verifier.code !39
      br i1 %2, label %3, label %7, !dbg !46, !verifier.code !39
3:    preds = %1
      store i32 %.0, i32* @x, align 4, !dbg !47, !verifier.code !39
      br label %4, !dbg !49, !verifier.code !39
4:    preds = %3
      %5 = add nsw i32 %.0, 1, !dbg !50, !verifier.code !39
      br label %1, !dbg !51, !llvm.loop !52, !verifier.code !39
7:    preds = %1
      %8 = load i32, i32* @x, align 4, !dbg !56, !verifier.code !39
      %9 = icmp eq i32 %8, 9, !dbg !56, !verifier.code !39
      br i1 %9, label %12, label %10, !dbg !59, !verifier.code !39
10:   preds = %7
      call void @__VERIFIER_assert(i32 0), !dbg !56, !verifier.code
!60
      br label %12, !dbg !56, !verifier.code !39
12:   preds = %7, %10
      ret i32 0, !dbg !61, !verifier.code !39
}
```

LLVM IR

```
procedure main () {
var $i, $x, $MAXSIZE, $check, $r, $temp, $sub: int;
$bb0:
    $i := 0;
    $x := 0;
    goto $bb1;
$bb1:
   $temp := $slt.i32($i, $MAXSIZE);
   assume {:branchcond $temp} true;
   goto $bb2, $bb4;
$bb2:
    $x := $i;
    goto $bb3;
$bb3:
    $i := $add.i32($i, 1);
    goto $bb1;
$bb4:
   $sub := $sub.i32($MAXSIZE, 1);
   $check := $eq.i32($x, $sub);
   assume {:branchcond $check} true;
   goto $bb7, $bb6;
$bb6:
   call __VERIFIER_assert(0);
    goto $bb7
$bb7:
    $r := 1;
    return;
}
```

Boogie IVL

Same Assertion Check

Counter-example that bb4 will never go to bb6
so the assertion is true

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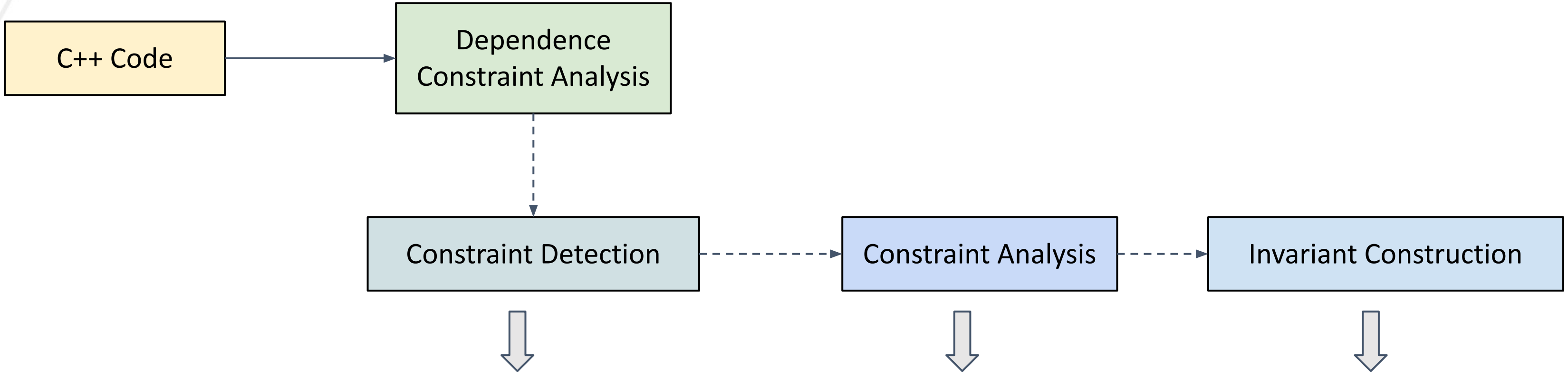

- PLuTo[1] dependence logs
- Detecting *absolute* & *derived* constraints

- Constraint transformation
- Constraint selection

- Operator flipping

1. https://github.com/bondhugula/pluto

Dependence Constraint Analysis

Constraint Detection → Constraint Analysis → Invariant Construction

```
void liebmann2D (/*arguments*/) {

int k1 = getK(N), k2 = getK(N);
for (t = 0; t <= M; t++)
 for (i = 1; i <= N; i++)
  for (j = 1; j <= N; j++)
        A[i][j] = (A [i - k1] [j - k1] + A[i - k1][j] + A[i][j]
            + A[i - k1][j + k2] + A[i][j - k1] + A[i][j + k2]
            + A[i + k2][j - k1] + A[i + k2][j]
            + A[i + k2][j + k2])/c;
}
```

Original C/C++ Code

Derived

Absolute

```
-j+j'-k1 = 0
-i+i'+k2 = 0
-k2-1 >= 0
k1-1 >= 0
j+k1-1 >= 0
-j+j'+k2 = 0
-i+i'-k1 = 0
-t+t'-1 >= 0
-t'+999 >= 0
i+k1-1 >= 0
j-k2-1 >= 0
...
```

39 Data-Dependencies with
30 Optimization Constraints (24 derived and 6 absolute)

```
k2 > 1
k1 < 1
k1 <= 1
k2 > N
..
```

All derived constraints are converted to absolute constraints

Constraints are converted to potential invariants

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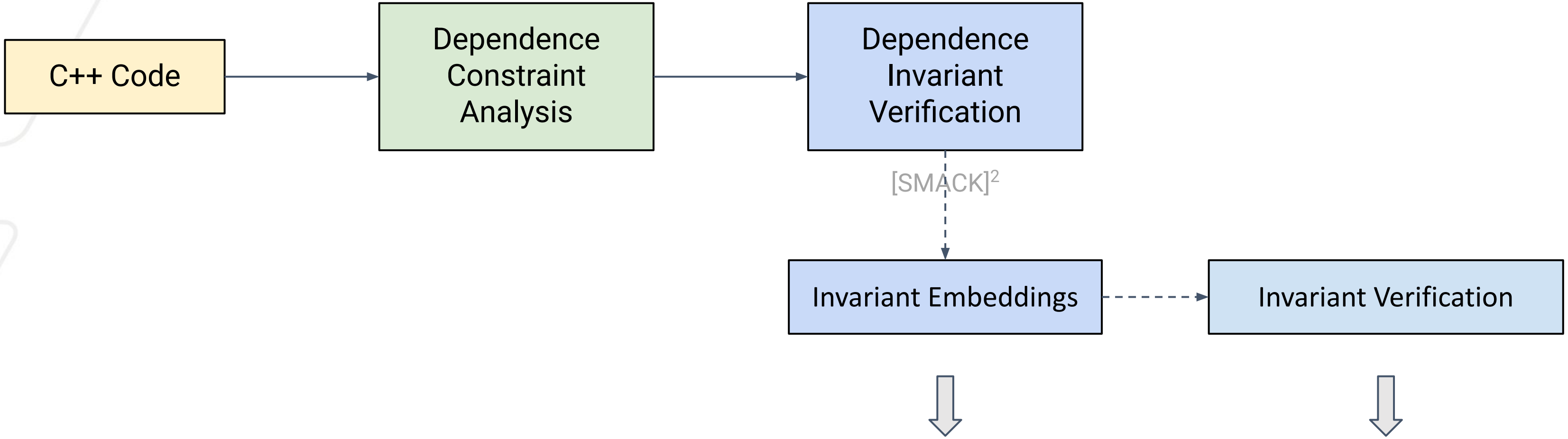


🔺 Potential invariants are added to the code

🔺 Code is executed through SMACK

Dependence Invariant Verification

Invariant Embeddings → Invariant Verification

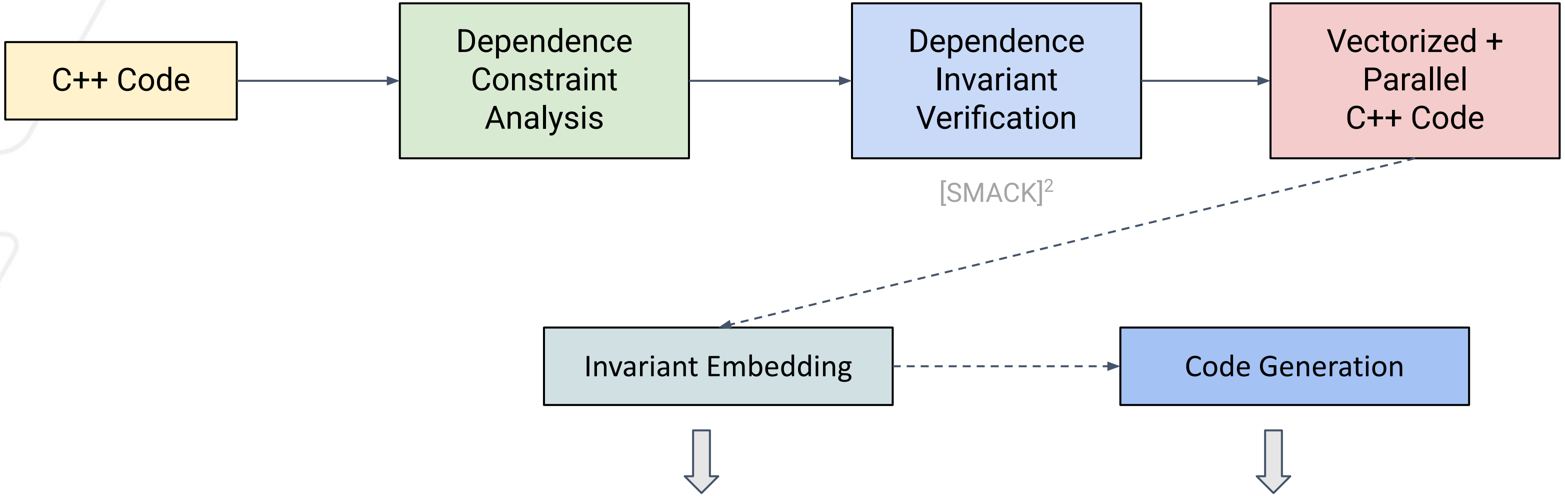
```
void liebmann2D (/*arguments*/) {

int k1 = getK(N), k2 = getK(N);
for (t = 0; t <= M; t++)
 assert(k2 > N);
 for (i = 1; i <= N; i++)
  for (j = 1; j <= N; j++)
          A[i][j] = (A [i - k1] [j - k1] + A[i - k1][j] + A[i][j]
                 + A[i - k1][j + k2] + A[i][j - k1] + A[i][j + k2]
                 + A[i + k2][j - k1] + A[i + k2][j]
                 + A[i + k2][j + k2])/c;
}
```

Original C/C++ Code with a potential Invariant

```
SMACK found no errors
k2 > N is an invariant
```

Invariant Verification with Smack

VICO: Demand-Driven Verification for Improving Compiler Optimization



- Choose invariants that break maximum number of dependencies
- Add invariants in the original code

- PLuTo[1] generates optimized code from the embedded code

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Vectorized + Parallelized C++ Code

Invariant Embedding ‐ ‐ ‐ → Code Generation

```
void liebmann2D (/*arguments*/) {

int k1 = getK(N), k2 = getK(N);
#pragma scop
if (k2 > N) {
for (t = 0; t <= M; t++)
 for (i = 1; i <= N - 2; i++)
  for (j = 1; j <= N - 2; j++)
        A[i][j] = (A [i - k1] [j - k1] + A[i - k1][j] + A[i][j]
              + A[i - k1][j + k2] + A[i][j - k1] + A[i][j + k2]
              + A[i + k2][j - k1] + A[i + k2][j]
              + A[i + k2][j + k2])/c;
 }
}
#pragma endscop
```

Embedded C/C++ Code

```
void liebmann2D (/*arguments*/) {
int k1 = getK(N), k2 = getK(N);
for (t = 0; t <= 2*M+N; t++) {
    lbp = max(ceild(t+1, 2),t-M+1);
    ubp = min(floord(t+N, 0),t);
    #pragma omp parallel for private(lbv,ubv,j)
    for (i = lbp; i <= ubp; i++)
      for (j = t + 1; j <= t + N; j++)
        A[(-t+2*i)][(-t+j)] = (A[(-t+2*i)-1][(-t+j)-1] + A[(-t+2*i)-1][(-t+j)]
                        + A[(-t+2*i)-1][(-t+j)+1]
                        + A[(-t+2*i)][(-t+j)-1]
                        + A[(-t+2*i)][(-t+j)] + A[(-t+2*i)][(-t+j)+1]
                        + A[(-t+2*t2)+1][(-t+j)-1]
                        + A[(-t+2*i)+1][(-t+j)]
                        + A[(-t+2*i)+1][(-t+j)+1])/c;
}
```

Parallelized C/C++ Code

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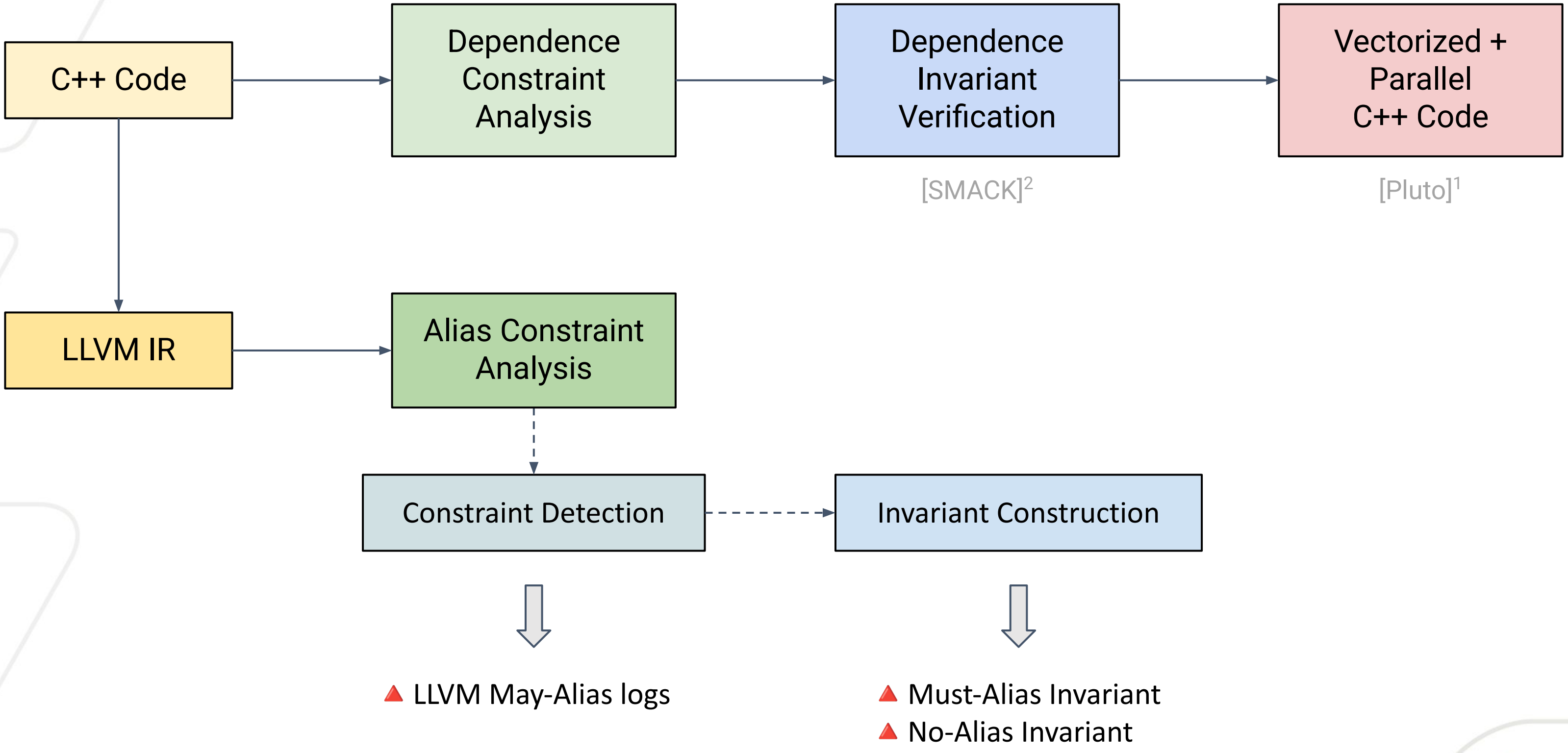


1. https://github.com/bondhugula/pluto 2. https://github.com/smackers/smack

Alias Constraint Analysis

Constraint Detection → Constraint Analysis → Invariant Construction

```c
int main (/*arguments*/) {
/* function body definitions */
int temp = getk(30);
if(temp >= 30)
   p = &l;
else if(temp >= 10 && temp < 20)
   p = &i;
else if(temp >= 0 && temp < 10)
   p = &j;
else
   p = &k;

for(i = 0; i < n; i +=1){
   for(j = 0; j < n; j +=1) {
      for(k = 0; k < n; k +=1) {
         *p = *p + 1;
         A[i][j][k] = B[i][j][k] + 11;
      }}}
/* More Code */}
```

Original C/C++ Code

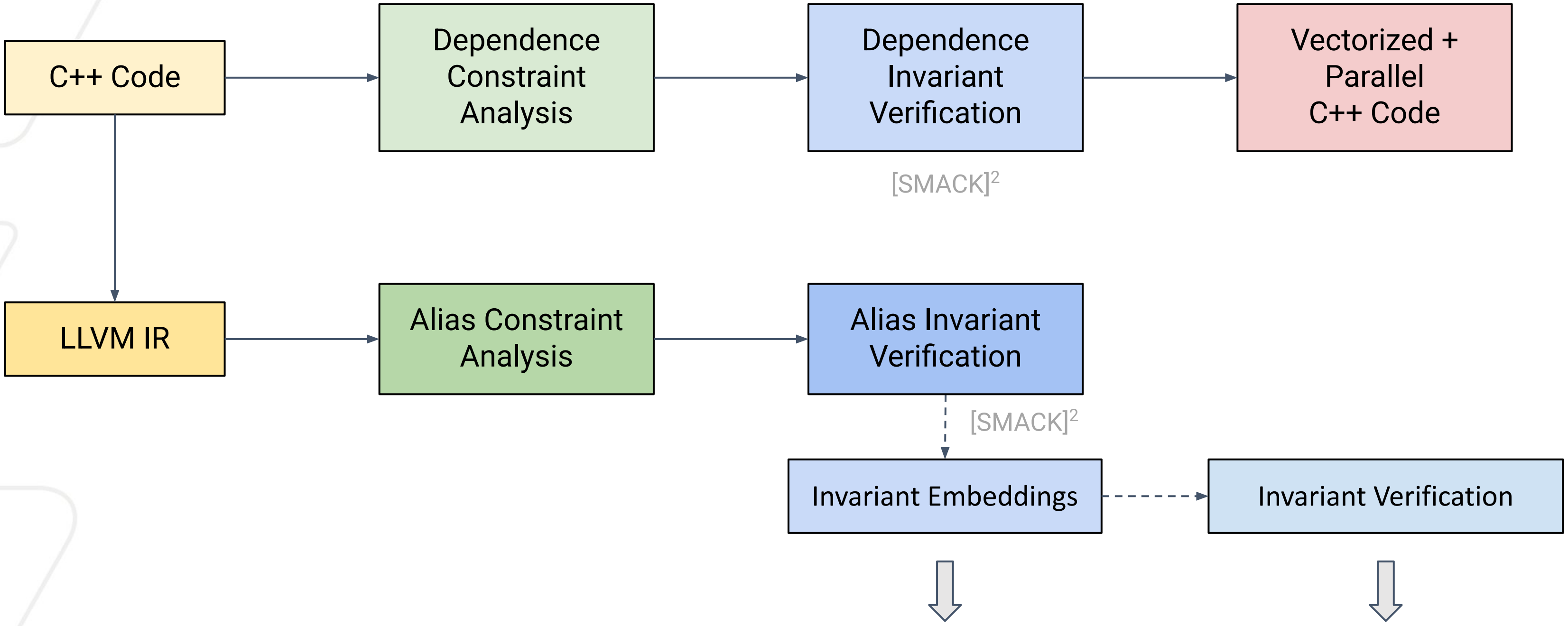
```
p ≟ &i
p ≟ &j
p ≟ &k
p ≟ &l
```

4 optimization constraints

```
p = &i
p = &j
p = &k
p = &l
p ≠ &i
p ≠ &j
p ≠ &k
p ≠ &l
```

Constraints are converted to potential invariants

VICO: Demand-Driven Verification for Improving Compiler Optimization



- 🔺 Must Alias Invariants Embedded
- 🔺 No Alias Invariants Embedded

- 🔺 Code is executed through SMACK

2. https://github.com/smackers/smack

Alias Invariant Analysis

Invariant Embeddings

Invariant Verification

```
int main (/*arguments*/) {
/* function body definitions */
int temp = getk(30);
if(temp >= 30)
  p = &l;
else if(temp >= 10 && temp < 20)
  p = &i;
else if(temp >= 0 && temp < 10)
  p = &j;
else
  p = &k;
for(i = 0; i < n; i +=1){
  assert(p = &l);
  for(j = 0; j < n; j +=1) {
    for(k = 0; k < n; k +=1) {
      *p = *p + 1;
      A[i][j][k] = B[i][j][k] + 11;
    }}}
/* More Code */}
```

Original C/C++ Code with a Must Alias Invariant

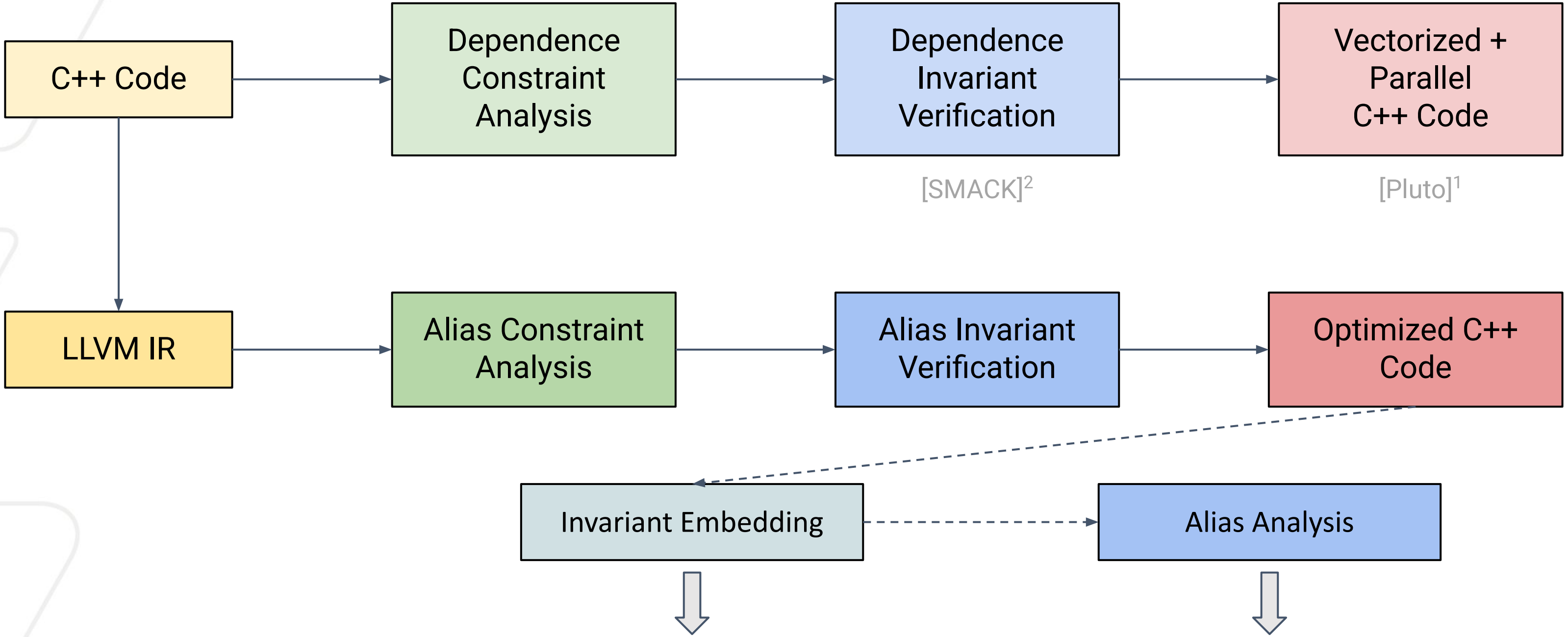
```
int main (/*arguments*/) {
/* function body definitions */
int temp = getk(30);
if(temp >= 30)
  p = &l;
else if(temp >= 10 && temp < 20)
  p = &i;
else if(temp >= 0 && temp < 10)
  p = &j;
else
  p = &k;
for(i = 0; i < n; i +=1){
  assert(p != &l);
  for(j = 0; j < n; j +=1) {
    for(k = 0; k < n; k +=1) {
      *p = *p + 1;
      A[i][j][k] = B[i][j][k] + 11;
    }}}
/* More Code */}
```

Original C/C++ Code with No Alias Invariant

```
p = &l is verified
p != &l is not verified
```

Invariant Verification with Smack

VICO: Demand-Driven Verification for Improving Compiler Optimization



- Add invariants in the original code

- Verified invariants inserted as SMACK asserts
- Alias pass finds saves the invariants in a map
- Allows chaining for other cases

1. https://github.com/bondhugula/pluto 2. https://github.com/smackers/smack

Optimized C++ Code

Invariant Embedding → Alias Analysis

```
int main (/*arguments*/) {
/* function body definitions */
int temp = getk(30);
if(temp >= 30)
   p = &l;
else if(temp >= 10 && temp < 20)
   p = &i;
else if(temp >= 0 && temp < 10)
   p = &j;
else
   p = &k;

for(i = 0; i < n; i +=1){
   assert(p = &l); assert(p != &k);
  assert(p != &j); assert(p !=&i);
   for(j = 0; j < n; j +=1) {
      for(k = 0; k < n; k +=1) {
         *p = *p + 1;
         A[i][j][k] = B[i][j][k] + 11;
      }}}
/* More Code */}
```

Original C/C++ Code with a verified Invariant

```
define dso_local i32 @main(i32 %0, i8** %1) #2 !dbg !356 {
50:                                              ; preds = %49
  %51 = icmp ne i32* %3, %6, !dbg !430, !verifier.code !344
  br i1 %51, label %53, label %52, !dbg !433, !verifier.code !344
52:                                              ; preds = %50
  call void @__VERIFIER_assert(i32 0), !dbg !430, !verifier.code !428
  br label %53, !dbg !430, !verifier.code !344
56:                                              ; preds = %55
  %57 = icmp ne i32* %3, %5, !dbg !435, !verifier.code !344
  br i1 %57, label %59, label %58, !dbg !438, !verifier.code !344
58:                                              ; preds = %56
  call void @__VERIFIER_assert(i32 0), !dbg !435, !verifier.code !428
  br label %59, !dbg !435, !verifier.code !344
62:                                              ; preds = %61
  %63 = icmp ne i32* %3, %4, !dbg !440, !verifier.code !344
  br i1 %63, label %65, label %64, !dbg !443, !verifier.code !344
64:                                              ; preds = %62
  call void @__VERIFIER_assert(i32 0), !dbg !440, !verifier.code !428
  br label %65, !dbg !440, !verifier.code !344
}
```

LLVM IR representation

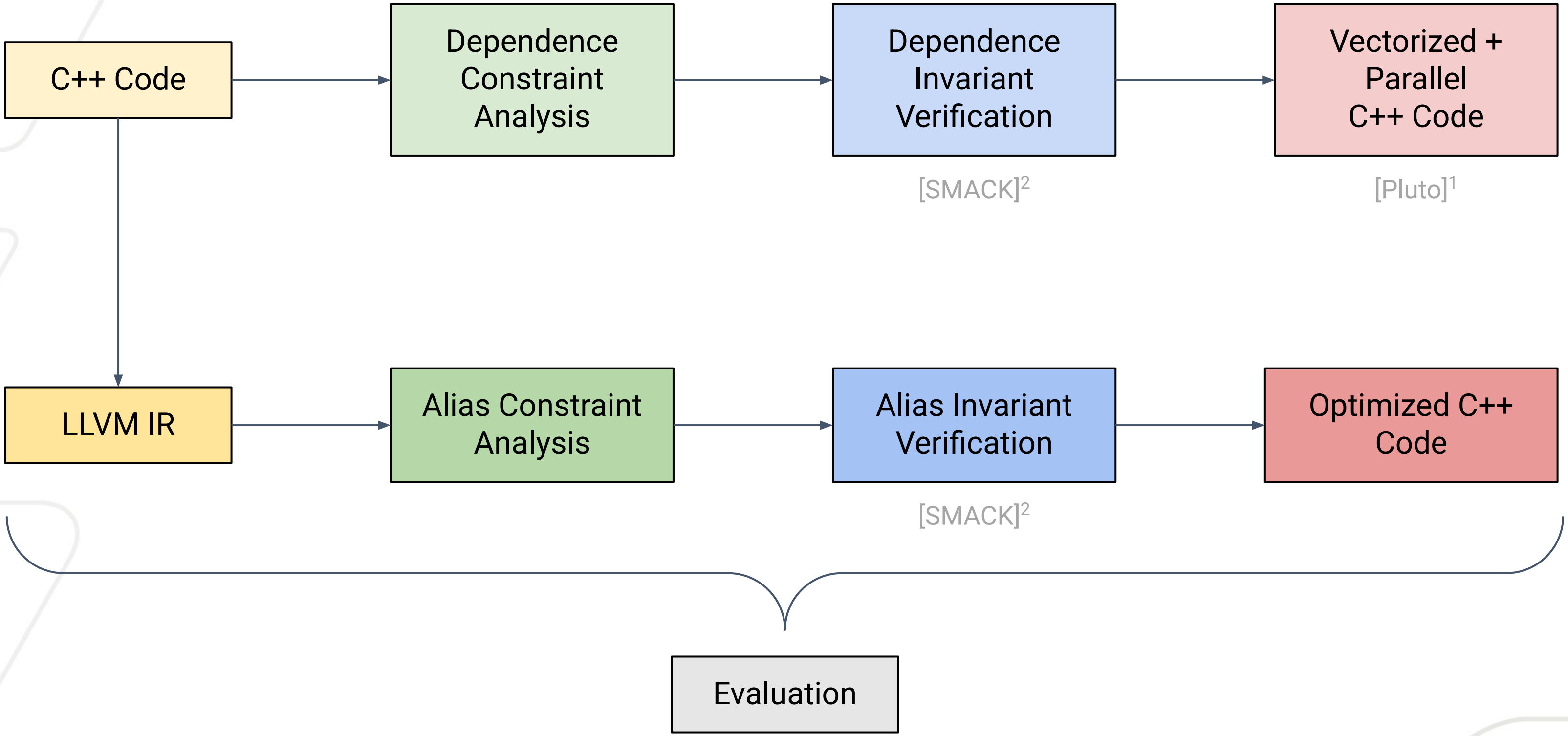
```
%3 ≠ null  (p = &l)
%3 ≠ %6  (p != &k)
%3 ≠ %5  (p != &j)
%3 ≠ %4  (p != &i)
```

Our Alias Analysis saving the invariants

↓

LLVM's Alias Analysis

Evaluation



1. https://github.com/bondhugula/pluto 2. https://github.com/smackers/smack

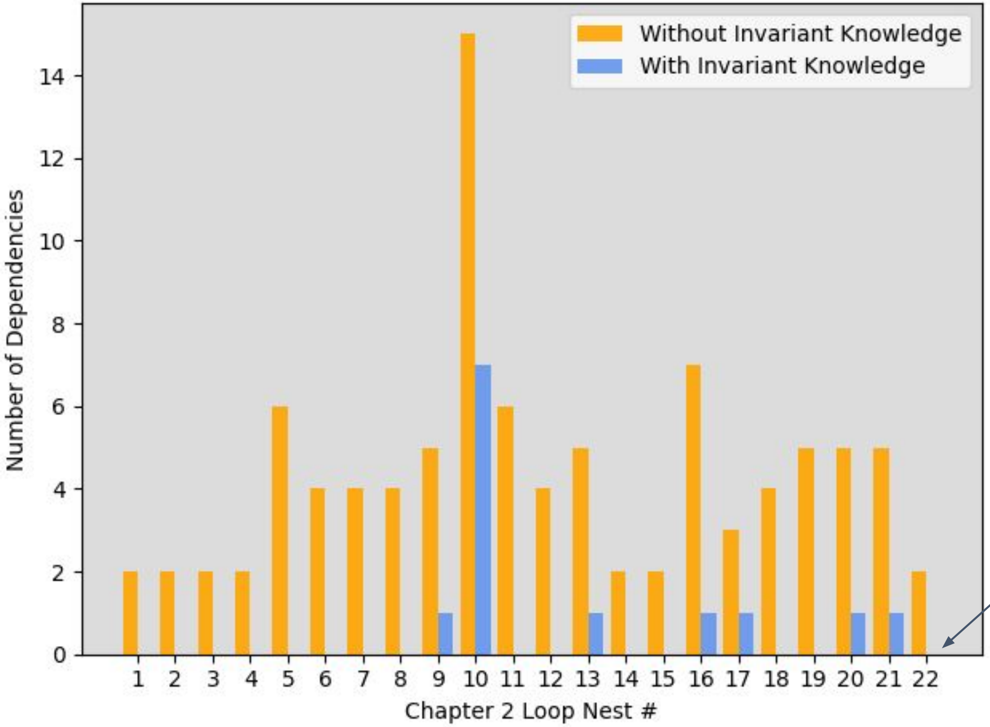
Summary of Results

- Improving precision of dependence analysis by 45% in real-world cases
  - Better optimizations in over 75 loops
  - Average speed-up of 14.7x on Apple M1 Pro
  - Average speed-up of 6.07x on Intel Xeon E5-2660
  - Took a total time of more than 5 hours
- Improving precision of alias analysis
  - Average code size reduction by 1.621% with up to 4.1% in real-world applications
  - Average speed-up of 2.2% on Intel Xeon E5-2660
  - Average improvement in load/store instructions of 4.227% with up to 7.08% in real-world applications
  - Took a total time of more than 6 hours to verify the 93 alias cases

Benchmarks

- Source-to-Source Parallelization Improvement
  - Kernel Programs (From Kennedy et al. book) combined with Invariant implementations from Si et al.
  - Mathematical Applications from Polybench adapted with generalized boundaries
- Backend Compiler Optimizations Improvement
  - Micro-benchmarks useful to force may-alias cases
  - Real-world applications from SPEC 2017 and CoreUtils

Kernel Programs



0 Dependencies in 15 loop nests

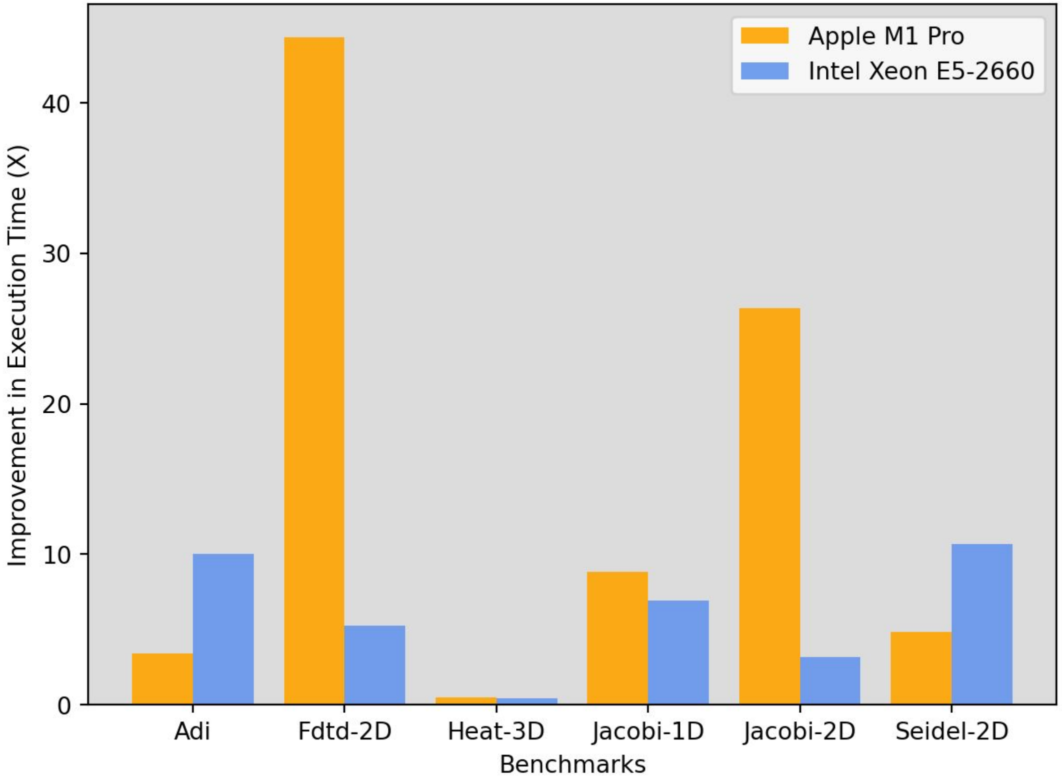
Mathematical Applications

Applications	Potential Invariants		Data-Dependencies	
	Absolute Invariants	**Derived Invariants**	**Without Invariant Knowledge**	**With Invariant Knowledge**
Alternating Direction Implicit method with generalized shift parameters	15	56	214	118
Multi-dimensional Finite Difference Time Domain	7	48	38	28
Heat Equation in three dimensions with artificial boundary conditions in unbounded domain	0	54	106	42
Jacobi Iterative Method in one dimension with generalized boundary conditions	0	18	14	14
Jacobi Iterative Method in two dimensions with generalized boundary conditions	0	36	22	22
Liebmann's Method in two dimensions with generalized boundary conditions	6	24	39	19

Mathematical Applications

Applications	Loop Optimizations	
	Without Invariant Knowledge	**With Invariant Knowledge**
Alternating Direction Implicit method with generalized shift parameters	Serial Loop, Serial Loop, Serial Loop	Serial Loop, Parallel Loop, Serial Loop + Loop Splitting
Multi-dimensional Finite Difference Time Domain	Serial Loop, Serial Loop, Parallel Loop, Parallel Loop + Loop Splitting	Serial Loop, Parallel Loop Parallel Loop, Parallel Loop + Loop Splitting
Heat Equation in three dimensions with artificial boundary conditions in unbounded domain	Serial Loop, Serial Loop, Serial Loop	Parallel Loop, Vectorized Loop, Vectorized Loop + Loop Splitting
Jacobi Iterative Method in one dimension with generalized boundary conditions	Serial Loop, Serial Loop, Serial Loop	Parallel Loop, Parallel Loop, Parallel Loop + Loop Splitting
Jacobi Iterative Method in two dimensions with generalized boundary conditions	Serial Loop, Serial Loop, Parallel Loop + Loop Splitting	Serial Loop, Parallel Loop, Parallel Loop + Loop Splitting
Liebmann's Method in two dimensions with generalized boundary conditions	Serial Loop, Serial Loop	Serial Loop, Parallel Loop

Performance Improvement



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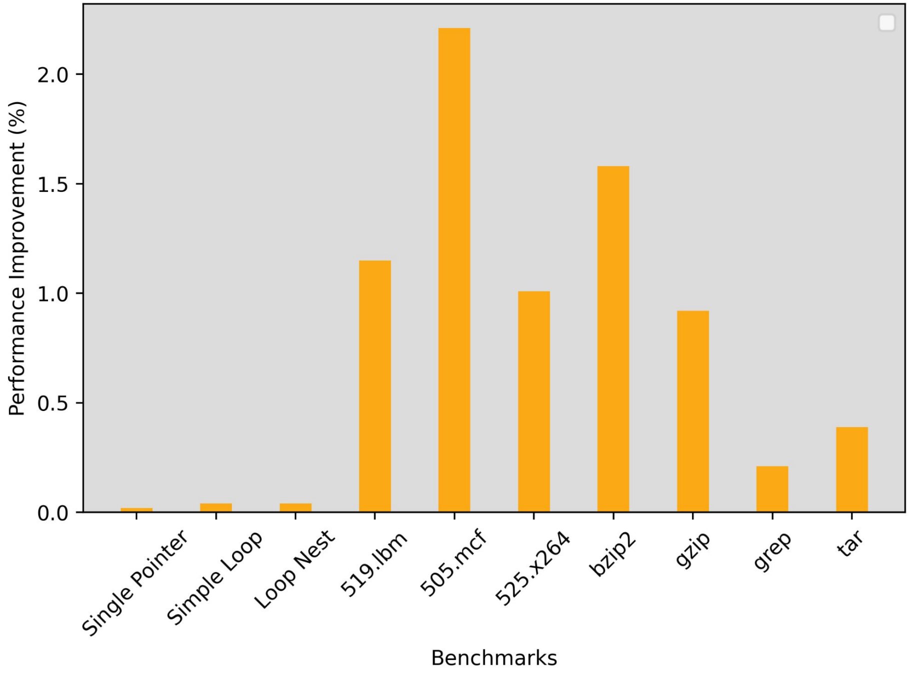
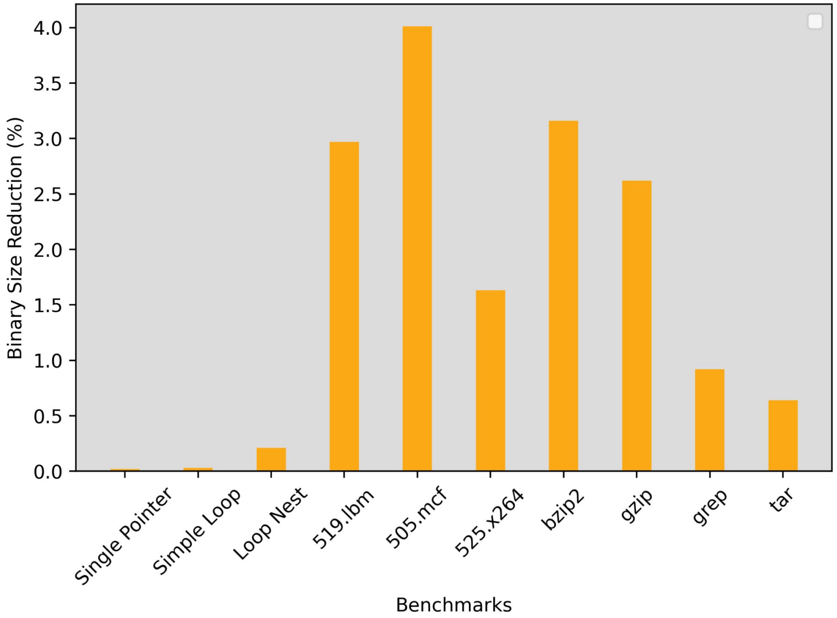
Backend Results

	Number of Constraints	Number of Verified Must-Alias	Number of Verified No-Alias	Changes in Value Numbering	New PRE Removed Redundancies
Single Pointer	1	1	0	1	0
Simple Loop	4	1	3	2	2
Loop Nest	5	4	1	3	1
LBM	9	2	2	2	1
MCF	22	6	2	6	4
X264	13	4	0	4	0
Bzip2	14	4	1	4	2
Gzip	9	3	3	3	3
Grep	7	0	3	0	0
Tar	9	1	1	1	0

Backend Applications





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Conclusion

- VICO: A Demand-Driven Verification Framework for improving Compiler Optimizations
  - Improves both dependence analysis and alias analysis
  - To the best of our knowledge, this is the first paper that leveraged verification to **enhance** compiler optimizations (*Note that this is very different problem than verifying compiler optimizations*).

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