Optimistic Loop Optimization

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Motivating Example

A POTENTIALLY PARALLEL LOOP

```
for (i = 0; i < N; i++)
  A[i] = A[N + i];
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$\{ A[N + i] \mid 0 \leq i < N \}$

Write Set ($\mathbf{W}$)

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$$\texttt{R} \cap \texttt{W} = \{ \}$$

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$\mathtt{R} \cap \mathtt{W} = \{\ \}$ *Parallel*

A POTENTIALLY PARALLEL LOOP

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unsigned char i, N;

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

Read Set (**R**)

~~$\{\ A[N + i] \mid 0 \leq i < N\ \}$~~

$\{\ A[(N + i) \bmod 256] \mid \dots\ \}$

Write Set (**W**)

$\{\ A[i] \mid 0 \leq i < N\ \}$

A Potentially Parallel Loop

```
unsigned char i, N;

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

Read Set (R)

~~{ A[N + i] | 0 ≤ i < N }~~

{ A[(N + i) mod 256] | … }

Write Set (W)

{ A[i] | 0 ≤ i < N }

R ∩ W = { }, iff N <= 128

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{ A[(N + i) mod 256] | … }

Write Set (**W**)

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R ∩ W = { }, **iff** N <= 128

Potentially Sequential

Problem Statement

PROBLEM STATEMENT

Required:
Program abstractions that capture *all possible semantics*

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Program abstractions that capture *all possible semantics*

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Corner cases are often *missed* or *assumed* not to happen

Consequence:
Poor applicability and *miscompilations* for certain inputs

Solution:
Take *optimistic assumptions statically* that are *verified dynamically*

Solution

OPTIMISTIC LOOP OPTIMIZATION

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```
/* loop nest */
```

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1. Take *Optimistic Assumptions* to model the loop nest

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OPTIMISTIC LOOP OPTIMIZATION

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2. Optimize the loop nest

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/* optimized loop nest */

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2. Optimize the loop nest
3. Version the code

```
if (                          )
  /* optimized loop nest */
else
  /* loop nest */
```

OPTIMISTIC LOOP OPTIMIZATION

1. Take *Optimistic Assumptions* to model the loop nest
2. Optimize the loop nest
3. Version the code
4. Create a *simple* runtime check

```
if (/* simple runtime check */)
  /* optimized loop nest */
else
  /* loop nest */
```

SEMANTIC DIFFERENCES

C	LLVM-IR	Polyhedral Model

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Variant Loads in Control Conditions		
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Integer Wrapping	✓	✓	✗
Out-of-Bound Accesses	✓	✓	✗
Potentially Unbounded Loops	✓	✓	✗

Real World Example

REAL WORLD EXAMPLE

NAS Parallel Benchmark Suite – BT – compute_rhs

- 66 loops, nested up to depth 4
- 38 array writes, 294 array reads
- 45 reads in loop bounds

REAL WORLD EXAMPLE

```
double rhs[JMAX][IMAX][5];



for (j = 0; j < grid[0] + 1; j++)

  for (i = 0; i < grid[1] + 1; i++)
    for (m = 0; m < 5; m++)




      rhs[j][i][m] = /* ... */;
```

ASSUMPTION GENERATION

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(a) Loads in control and access functions are invariant

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(c) Expressions do not wrap

Assumption Generation

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double rhs[JMAX][IMAX][5];

assume grid[0] != MAX_VALUE;
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Given an expression e with m bits:

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No Wrapping Assumptions

Given an expression e with m bits:

$$[\![\mathrm{e}]\!]_{\mathbb{Z}} \qquad [\![\mathrm{e}]\!]_{\mathbb{Z}_{2^m}/\mathbb{Z}}$$

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NO WRAPPING ASSUMPTIONS

Given an expression e with m bits:

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Given an expression e with m bits:

$$\mathcal{I}_W(\mathsf{e}) = \{(\underline{i}) \mid [\![\mathsf{e}]\!]_{\mathbb{Z}} \neq [\![\mathsf{e}]\!]_{\mathbb{Z}_{2^m}/\mathbb{Z}}\}$$

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Let e be *textually* part of statement S with domain $\mathcal{I}_{\mathsf{S}}$.

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$\mathcal{I}_{W_{\mathsf{S}}}(\mathsf{e})$ describes executed *loop instances* for which e *will wrap*.

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$\mathcal{I}_{W_{\mathsf{S}}}(\mathsf{e})$ describes executed *loop instances* for which **e** *will wrap*.

$\neg\, \mathcal{I}_{W_{\mathsf{S}}}(\mathsf{e})$ describes sufficient *constrains* under which **e** *will not wrap*.

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Hoist, Combine & Simplify Assumptions

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```

Constraints: $0 \leq$ `j` $\leq$ `grid[0]`

Assumption: `j < JMAX`

ASSUMPTION HOISTING

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Constraints: $0 \leq j \leq \texttt{grid[0]}$

Assumption: $\texttt{grid[0] < JMAX} \implies \texttt{j < JMAX}$

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Quantifier elimination is used to *eliminate loop variables*.

The result is a *pre-condition* of the original assumption.

ASSUMPTION HOISTING

```
double rhs[JMAX][IMAX][5];

assume grid[0] != MAX_VALUE &&
       grid[1] != MAX_VALUE &&
       grid[0] + 1 <= JMAX &&
       grid[1] + 1 <= IMAX &&
       (&rhs[0][0][0] >= &grid[2] ||
        &rhs[grid[0]][grid[1]][5] <= &grid[0]);

for (j = 0; j < grid[0] + 1; j++)
  for (i = 0; i < grid[1] + 1; i++)
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      rhs[j][i][m] = /* ... */;
```

ASSUMPTION SIMPLIFICATION

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Eliminate Redundant Constraints:

```
assume N < 128 && N < 127;
=>
assume N < 127;
```

Assumption Simplification

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```
assume N < 128 && N < 127;
=>
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```

Approximate Complicated Constraints:

```
assume &B[N + 2 - ((N - 1) % 3)] <= &A[0] ||
       &A[N + 2 - ((N - 1) % 3)] <= &B[0];
```

Assumption Simplification

Eliminate Redundant Constraints:

```
assume N < 128 && N < 127;
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assume N < 127;
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Approximate Complicated Constraints:

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assume &B[N + 2 - ((N - 1) % 3)] <= &A[0] ||
       &A[N + 2 - ((N - 1) % 3)] <= &B[0];
=>
assume &B[N + 2] <= &A[0] ||
       &A[N + 2] <= &B[0];
```

Evaluation

ASSUMPTION STATISTICS

	SPEC 2006	*SPEC* 2000
No Variant Loads ∧:	553	6
No Aliasing ∧:	132	52
No Wrapping ∧:	611	82
No Out-Of-Bounds ∧:	5	6
No Unbounded Loop ∧:	42	6
Total:	1343	152

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	SPEC 2006	*SPEC* 2000
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Total:	1343	152
After Simplification:	$<$ 671 (or $<$ 50%)	$<$ 99 (or $<$ 66%)

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Two's complement modeling increased compile time by $3 - 3000\%$.

Applicability & Validity

SPEC 2006

	w/o Λssumptions	w/ Λssumptions	
modeled:	35	191	×5.45
feasible:	35	102	×2.91
executed:	61k	5.2M	×85.24
valid:	61k	99.68% ∗ 5.2M	×85.21

SPEC 2000

	w/o Λssumptions	w/ Λssumptions	
modeled:	24	83	×3.45
feasible:	24	78	×3.25
executed:	11k	729k	×66.27
valid:	11k	89.3% ∗ 729k	×59.18

APPLICABILITY & VALIDITY

SPEC 2006

	w/o Assumptions	w/ Assumptions	
modeled:		191	×5.45
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Assumptions fail

$\approx 2\%$

of the time and cause

$< 4\%$

runtime overhead.

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Conclusion

ARCHITECTURE OVERVIEW

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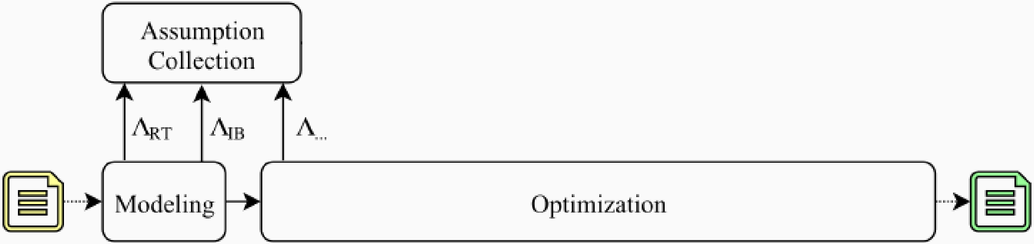
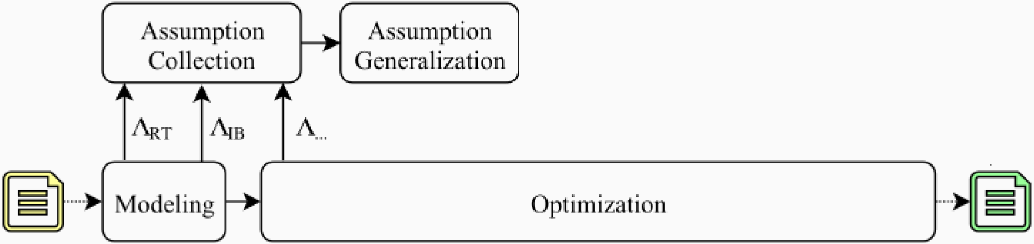
Modeling

Optimization

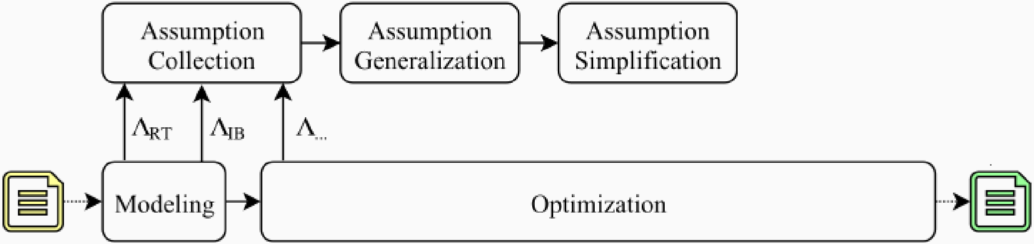
ARCHITECTURE OVERVIEW



ARCHITECTURE OVERVIEW



Architecture Overview



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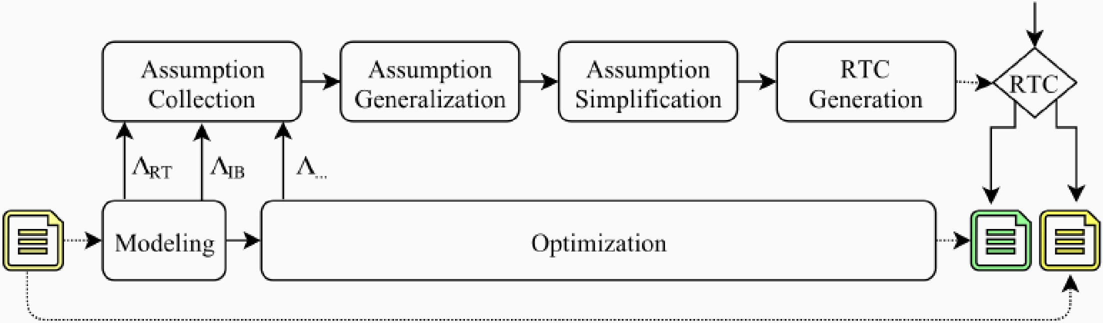

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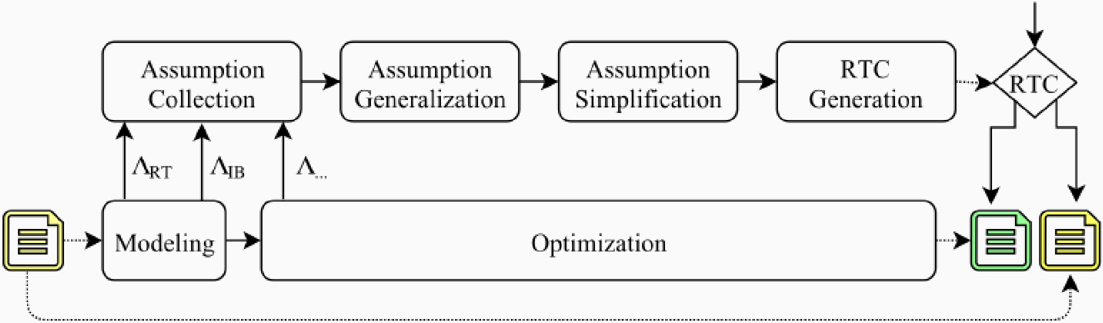

Thank You.

Backup

FINITE LOOP ASSUMPTION

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```
for (unsigned i = 0; i != N; i+=2)
  A[i+4] = A[i];
```

FINITE LOOP ASSUMPTION

Infinite loops create unbounded optimization problems

```
if (N % 2 == 0) {

  for (unsigned i = 0; i != N; i+=2)
    A[i+4] = A[i];

} else {
  /* original code */
}
```

INVARIANT LOAD ASSUMPTIONS

```
for (i = 0; i < *Size1; i++)
  for (j = 0; j < *Size0; j++)
    ...
```

INVARIANT LOAD ASSUMPTIONS

```
auto Size0V, Size1V = *Size1;

if (Size1V > 0)
  Size0V = *Size0;

for (i = 0; i < Size1V; i++)
  for (j = 0; j < Size0V; j++)
    ...
```

Hoist invariant loads but *keep control conditions* intact.

INVARIANT LOAD ASSUMPTIONS

```
auto Size0V, Size1V = *Size1;

if (Size1V > 0)
  Size0V = *Size0;

for (i = 0; i < Size1V; i++)
  for (j = 0; j < Size0V; j++)
    ...
```

Hoist invariant loads but *keep control conditions* intact.

Powerful *in combination* with *runtime alias checks*.

ASSUMPTION SIMPLIFICATION

Simplify Complicated Constraints:

```
assume &B[N + 2 - ((N - 1) % 3)] <= &A[0] ||
       &A[N + 2 - ((N - 1) % 3)] <= &B[0];

assume &B[N + 2] <= &A[0] ||
       &A[N + 2] <= &B[0];

for (i = 0; i < N; i += 3) {
  A[i + 0] += 1.3 * B[i + 0];
  A[i + 1] += 1.7 * B[i + 1];
  A[i + 2] += 2.1 * B[i + 2];
}
```

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SPEC 2006 – 456.hmmer – P7_Viterbi
−28% execution time

NAS Parallel Benchmark Suite – BT – compute_rhs
6× fold speedup with 8 threads [Metha and Yew, PLDI'15]

Semantic Differences

	Rust	Java	C	LLVM-IR	Polyhedral Model
Variant Loads in Control Conditions	✓	✓	✓	✓	✗
Aliasing Arrays	✗	✗	✓	✓	✗
Integer Wrapping	✓	✓	✓	✓	✗
Out-of-Bound Accesses	✓	✓	✓	✓	✗
Potentially Unbounded Loops	✓	✓	✓	✓	✗