Speculative Runtime Parallelization of Loop Nests: Towards Greater Scope and Efficiency

Aravind Sukumaran-Rajam, Luis Esteban Campostrini,
Juan Manuel Martinez Caamaño, Philippe Clauss

25 May, 2015

HIPS

Apollo

What is this talk about ?

- A dynamic and speculative optimizer
- Optimization of loop nests that cannot be handled statically
- Dynamic application of polyhedral model
- Non linear extensions to polyhedral model

Motivation

- Static approaches are limited due to intractable control and memory instructions
  - Indirect memory accesses (A[B[i]])
  - Pointers (ptr = ptr-> next)
  - While loops (While (ptr!=NULL))
- Dynamic approaches can overcome these limitations by using run-time information

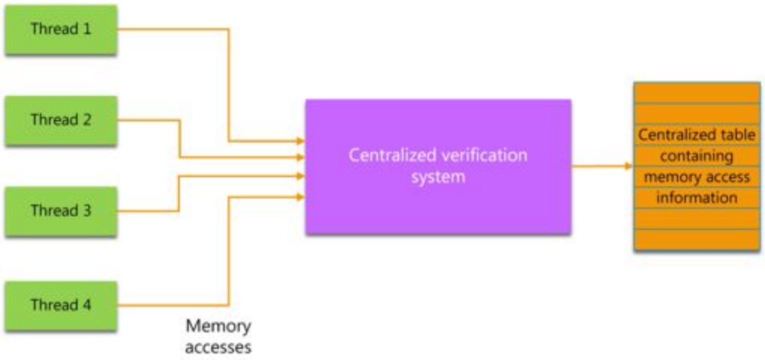
Motivation

- Dynamic approaches require to be speculative to enlarge their scope (Thread level speculation)
- Traditional TLS system relies on centralized verification which is not scalable due to the high memory traffic
- Apollo uses a prediction model based on the polytope model and on linear approximations introduced in this talk

Generic automatic and speculative code optimization

- Predict an optimization
- Verify that the prediction holds
- A fail-safe system to recover from a mis-prediction

Traditional TLS system



Traditional thread level speculation

```
while (cond)
{
    a[i] = ...;
    ..
    ..
    ..
    x = a[j];
}
```

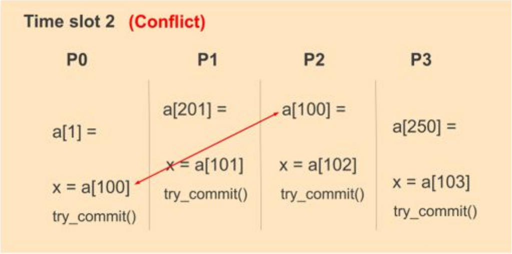
Time slot 1

P0	**P1**	**P2**	**P3**
a[1] =	a[2] =	a[3] =	a[4] =
x = a[100]	x = a[101]	x = a[102]	x = a[103]
try_commit()	try_commit()	try_commit()	try_commit()

Traditional thread level speculation

Sequential execution order

$a[1] = ...$
$x = a[100]$
$a[201] = ...$
$x = a[101]$
$a[100] = ...$
$x = a[102]$
$a[250] = ...$
$x = a[103]$



Traditional thread level speculation

- What is missing ?
  - A dependence prediction model

Traditional thread level speculation

- What is missing ?
  - A dependence prediction model
- How is this affected ?
  - Missed parallelization opportunities
  - Higher mis-prediction rates
  - Huge centralization overhead

Apollo

Figure : Mission control: We have lift off

Apollo

APOLLO : Automatic speculative POLyhedral Loop Optimizer

Features

- Dynamic
- Polytope model
- Speculative with weakly centralized verification
- Handle all loop types
- Extends the applicability of the polytope model to non linear memory accesses

Background: Polytope model

Polytope model

- A mathematical way to model the loop nests in a program
- Each instance of a statement is represented by a point in the lattice of the polyhedron
- Widely used for static program optimization (Pluto)

Background {Dependence representation}

Original user code

```
for(i = 2; i < 10; i++){
  a[i] = a[i - 2] + 1;
}
```

i : source iterator

i' : target iterator

Dependence constraints

$$\left.\begin{array}{r} i >= 2 \\ i <= 9 \\ i' >= 2 \\ i' <= 9 \end{array}\right\} \textit{Domain constraints} \qquad (1)$$

$$\left. i' = i + 2 \right\} \textit{Access constraints} \qquad (2)$$

$$\left. i' >= i + 1 \right\} \textit{Order constraints} \qquad (3)$$

Handling dynamic codes

In this code we can extract the linear functions statically

```
for(i = 2; i < 10; i++){
  a[i] = a[i - 2] + 1;
}
```

This code requires dynamic analysis to extract linear functions

```
while(ptr1 && ptr2){
  ptr1->val = ptr2->val + 1;
  ptr1 = ptr1->next;
  ptr2 = ptr2->next;
}
```

Handling dynamic codes

Speculate the linear functions for

- Dynamic memory accesses
- Dynamic loop bounds
- Scalar variables which carry cross iteration dependencies

Apollo

- Profile the code by sampling
- Interpolate memory addresses and scalar values
- Compute the data dependencies and build the prediction model
- Compute optimizing valid transformation
- Speculatively execute the optimized code
- Verify the speculation while the optimized code is running

Apollo

Challenges

- How to instrument?
- How to build the prediction model?
- How to compute the optimizing transformation?
- How to generate the optimized code?
- How to verify the speculation?

Apollo

Apollo consists of two core components

- Static module
- Runtime module

Static Module

- A set of dedicated LLVM compiler passes
- Statically analyze memory instructions which can be disambiguated at compile time
- Transforms any kind of target loops into *for* loops
- Generates an instrumented version to track memory accesses
- Creates optimized code skeletons

Code skeleton

- General frameworks representing a class of transformations.
- Skeletons are parametrized. Instantiating different parameters results in different transformations.
- Instrumentation skeleton is used to track memory accesses
- Optimized skeletons are used for parallelization and other code optimizations (data locality . . .)

Apollo {Code skeleton}

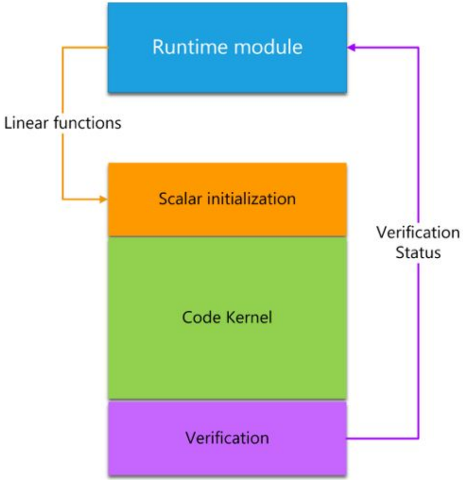


Figure : Optimized skeleton

Runtime Module

- Runs the instrumentation skeleton for a small outermost loop slice
- Builds a linear prediction model for the loop bounds and memory accesses
- Computes the dependencies between the memory accesses
- Computes the transformation
- Selects and instantiates the appropriate code skeleton
- Monitor the execution to verify the correctness of the linear functions and thereby the transformation

Chunking

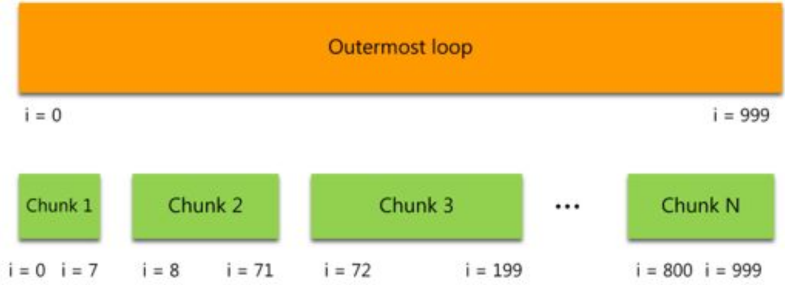
consider the following simple code

```
for(i = 0; i < 1000; i++){
  a[i] = b[i + 2] + 1;
}
```

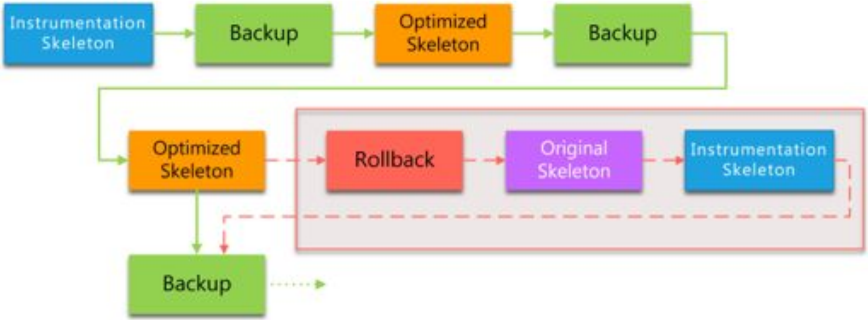
Chunking

consider the following simple code

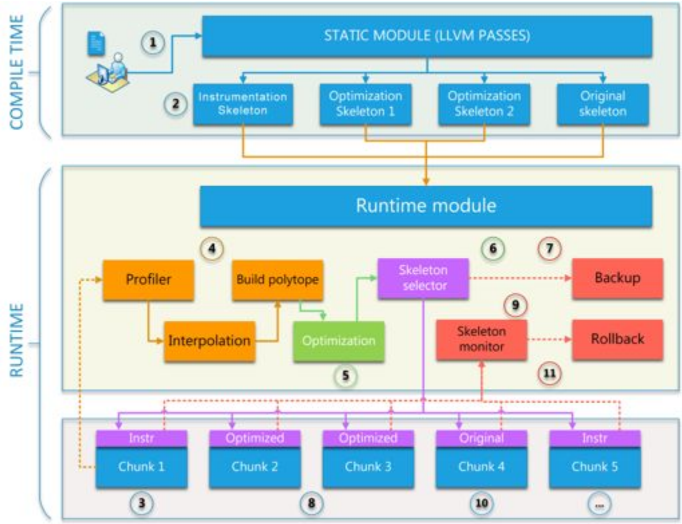
```
for(i = 0; i < 1000; i++){
  a[i] = b[i + 2] + 1;
}
```



Execution flow



Apollo global view



Memory backup

- The execution is speculative
- A mis-speculation can trigger rollback
- In order to prevent memory corruption, all the predicted memory write regions are backed up
- Thanks to the linear prediction model; the exact write regions can be identified

Verification Module

- The validity of the polytope model is proven by construction
- The transformation is valid as long as the predicted linear functions are valid
- Uses the linear access functions generated during the instrumentation phase

Verification Module

- Runtime verification system ensures that the memory accesses follows the predicted linear functions
- Polyhedral transformations will also affect the execution order of iterations inside each thread. Hence each iteration must be verified
- If verification fails a rollback is triggered

Apollo {Runtime Verification}

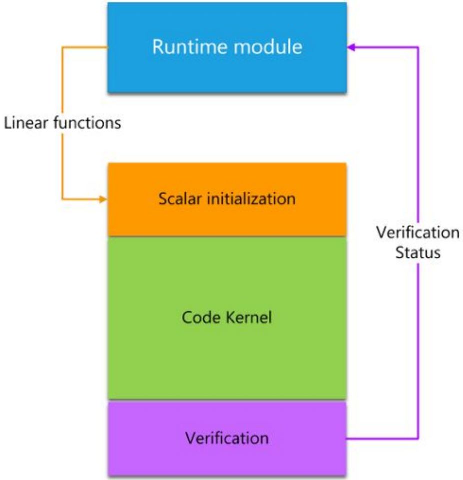


Figure : Optimized skeleton

Non affine memory accesses

- The polyhedral model cannot handle non affine accesses (even with dynamic analysis)
- In the presence of non affine accesses, the computed dependencies may be inaccurate
- The validity of the transformation cannot be guaranteed

Why should we be concerned about non affine accesses

- Most of the dynamic programs exhibit non affine behavior
- Most of the indirect accesses and pointers to dynamic memory are typically non linear
- A dependence prediction model is vital for the efficiency of TLS systems

Apollo {Non Affine}

Challenges

- Polytope model as such is not compatible
- Non linear accesses will require a centralization system
- Live backup is required
- There is no linear function available for validation
- The overhead cost should be acceptable

Solution

- Relax the polytope model by adding some non affine accesses
- Account for the relaxation by adding additional verification

Apollo {Non Affine}

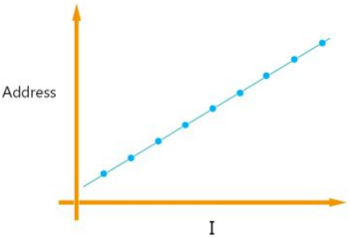
During Instrumentation

- Identify potential non linear accesses
- Compute regression lines modeling each non linear access
- Refine the regression line by removing outliers

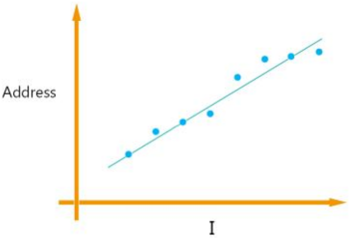
During Instrumentation

- Compute the regression correlation coefficient
- Correlation coefficient measures the quality of regression line
- Characterize each memory access as
  - Affine
  - Non affine
  - Nearly affine

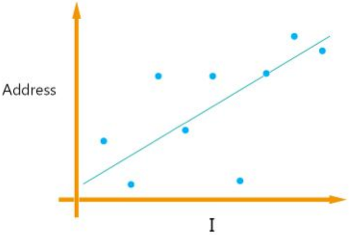
Apollo {Access types}



(a) Affine



(b) Nearly affine



(c) Non affine

Building the dependence polytope

- Nearly affine : The correlation coefficient is greater than 0.9
- Non affine : The correlation coefficient is lower than 0.9

Building the dependence polytope : Nearly affine

- The memory accesses are well characterized
- Approximate the regression hyperplane from $\mathbb{R}$ domain to $\mathbb{Z}$ domain
- Compute two bounding hyperplanes *close* to the regression hyperplane (tubes), one *lower* and the other *higher*
- Encode these bounding hyperplanes to the polytope model

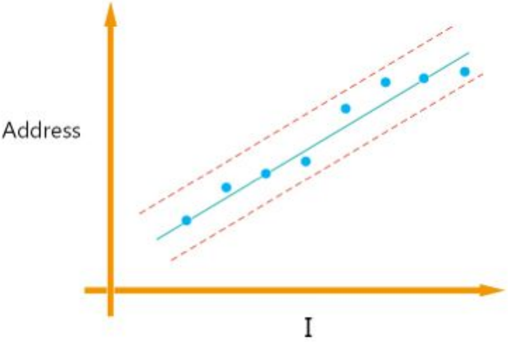


Figure : Bounding hyperplanes

Building the dependence polytope : Non affine

- The memory accesses are not well characterized
- Adding them to the dependence polytope will have adverse effects
- Hence do not encode them to the dependence polytope

Apollo {Non Affine}

Pre-execution validation

- Detect any possible violation as early as possible
- For the instrumented memory accesses, verify that non linear memory accesses do not invalidate transformation
- This can be done by checking for intersection of memory access between affine and non affine accesses

Building safe point

- Backing up while running can hurt performance a lot
- For non affine and nearly affine accesses there is no way to exactly predict the memory addresses that will be written
- For non affine accesses, compute a range information, and backup
- For nearly affine accesses, compute the area inside the bounding hyperplanes and backup this region

Execution

- Based on the transformation suggested by the scheduler, select and initiate a skeleton
- Pluto is used dynamically for scheduling

Apollo {Non Affine}

Verification

- Affine access: Verify that accesses follow the affine function
- Nearly affine access: If the instance falls inside the tube, the access is valid. If not treat that particular instance as a non affine access
- Non affine access: For the non predicted ranges, perform live backup.

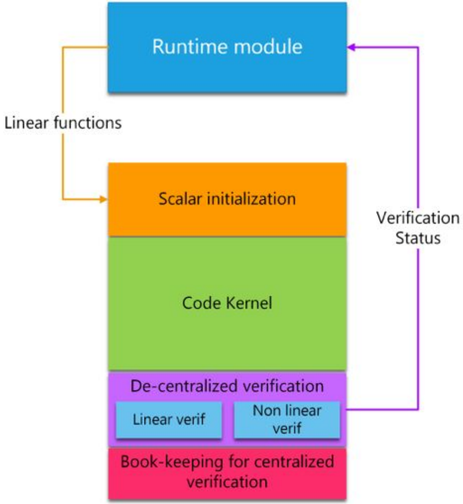


Figure : Optimized skeleton with non linear support

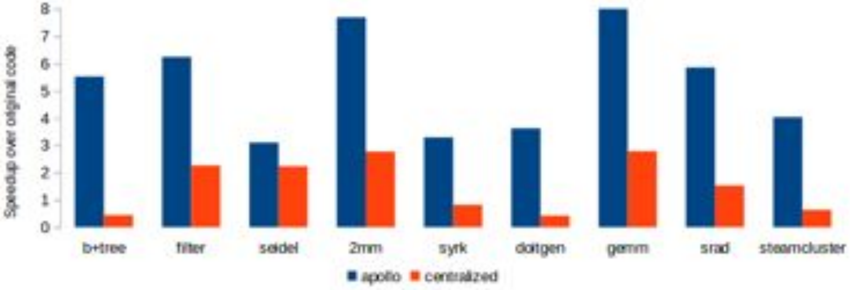


Figure : Speedup : The higher the better

Conclusion

- A dependence model is a must for the TLS system
- Thanks to dynamic and speculative environment, a well designed extension to the polytope model can amend the model to consider non linear accesses
- Can be used in any general dynamic speculative system

Questions?