

Writing Parallel Programs That Work

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Abstract

Serial algorithms typically run inefficiently on parallel machines. This may sound like an obvious statement, but it is the root cause of why parallel programming is considered to be difficult. The current state of the computer industry is still that almost all programs in existence are serial.

This talk will describe the techniques used in the Intel Parallel Studio to provide a developer with the tools necessary to understand the behaviors and limitations of the existing serial programs. Once the limitations are known the developer can refactor the algorithms and reanalyze the resulting programs with the tools in the Intel Parallel Studio XE to create parallel programs that work.

Remember this slide from earlier?

- Basic approach
 - **Find compute intensive loops**
 - **Make the loop iterations independent ... so they can safely execute in any order without loop-carried dependencies**
 - Place the appropriate OpenMP directive and test

This reminds me of a rather famous cartoon:

(just use Google search on: **then a miracle occurs cartoon**)

Where should we begin?

- Do you start with a blank sheet of paper ... or not?
1. You need to organize your ideas
 - Usually by expressing a serial algorithm
 2. Otherwise you may be asked to improve software with demonstrated value
 - Usually expressed by a serial implementation
 - Or a process in your MPI program, another serial program
- Either way, you likely start serial

Do you really mean that?

1

```
for (int I = 0; I < N; ++I)
    A[I] = B[I] + C[I];
```

- This loop is equivalent to:

```
I = 0;
if (! (I < N)) goto done;

A[0] = B[0] + C[0]; // I = 0

++I;
if (! (I < N)) goto done;

A[1] = B[1] + C[1]; // I = 1
...
done:
```

2

```
for (int I = 0; I < N; ++I)
    Work( &A[I] );
```

- This loop is equivalent to:

```
I = 0;
if (! (I < N)) goto done;

Work( &A[0] ); // I = 0

++I;
if (! (I < N)) goto done;

Work( &A[1] ); // I = 1
...
done:
```

Or did you really mean this...

1

```
for (int I = 0; I < N; ++I)  
    A[I] = B[I] + C[I];
```

$A[0...N-1] = B[0...N-1] + C[0...N-1]$

2

```
for (int I = 0; I < N; ++I)  
    Work( &A[I] );
```

foreach X in A[0...N-1]
 Work(&X);

or even...

Work(&A[0...N-1])

Digression: debugging

- What is still the #1 debugging tool in use today?
 - A “`print`” statement
- Inserting a “`print`” statement into your serial program typically does not change its behavior, but allows observation of what is happening
- Serial languages force you to specify the semantics of your algorithm by enforcing a specific serial execution
- Parallel languages force you to specify what is allowable to execute in concurrently

We can use this debugging technique to bridge the gap and observe potential parallelism

Bridging the gap

- Annotations are statements that *markup* existing algorithms to express the parallel model requested
- Intel® Advisor XE accomplishes this with a core set of modeling annotations:
 - **SITE** (where should I focus)
 - **TASK** (what should I do)
 - **LOCK** (it really is serial)
- Similar to concepts in OpenMP, TBB, or Cilk – but simplified

Annotations can be considered *as-if* they are “print” statements to a special trace file

Annotation: **SITE** (where should I focus)

Intel® Advisor XE uses a **SITE** to:

1. Define a name for a section of the application
2. Declare that all interesting things to analyze occur inside of this section
3. Declare that any parallelism that is declared will be finished before the section exits

Example: SITE

```
#include <advisor-annotate.h>
...
ANNOTATE_SITE_BEGIN(MySite);
Work( &A[0] );
Work( &A[1] );
ANNOTATE_SITE_END();
...
```

- Annotations are just statements with no visible side-effects

Annotation: **TASK** (what should I do)

Intel® Advisor XE uses a **TASK** to:

1. Define a name for a section of the application
2. Declare the statements in this section could be executed immediately or deferred
3. Declare the statements in this section can overlap (concurrent/parallel) execution with other statements in the enclosing **SITE**

Example: TASK

```
#include <advisor-annotate.h>

...
ANNOTATE_TASK_BEGIN(MyTask0);
Work( &A[0] );
ANNOTATE_TASK_END();

ANNOTATE_TASK_BEGIN(MyTask1);
Work( &A[1] );
ANNOTATE_TASK_END();

...
```

- Annotations can partition the serial execution to be a specification for parallel execution

Annotation: **LOCK** (it really is serial)

Intel® Advisor XE uses a **LOCK** to:

1. Define an (non-unique) name for a section of the application
2. Declare that sections with this name are not allowed to execute in parallel, they must be serialized

Example: LOCK

```
#include <advisor-annotate.h>
...
ANNOTATE_LOCK_ACQUIRE(0);
globalCounter = globalCounter + 1;
ANNOTATE_LOCK_RELEASE(0);
...
```

- A **LOCK** is a concept familiar to developers, but it really means a serialized section of code
- This annotation may be implemented with other non-lock based synchronization mechanisms, such as atomic variables

What about loops?

- The combination of a **SITE** + **TASK** using a serial looping construct can be used to model a parallel loop

```
#include <advisor-annotate.h>
...
ANNOTATE_SITE_BEGIN(MyLoopSite);
for (int I = 0; I < N; ++I) {
    ANNOTATE_TASK_BEGIN(MyIteration);
    Work( &A[I] );
    ANNOTATE_TASK_END();
}
ANNOTATE_SITE_END();
...
```

```
#include <omp.h>
...
#pragma omp parallel
#pragma omp single
for (int I = 0; I < N; ++I) {
    #pragma omp task
        Work( &A[I] );
}
...
```

OpenMP equivalent

What about loops (continued)?

- The combination of a **SITE** + **TASK** can be optimized via the **ITERATION_TASK** annotation

```
#include <advisor-annotate.h>
...
ANNOTATE_SITE_BEGIN(MyLoopSite);
for (int I = 0; I < N; ++I) {
    ANNOTATE_ITERATION_TASK(MyIteration);
    Work( &A[I] );
}
ANNOTATE_SITE_END();
...
```

```
#include <omp.h>
...
#pragma omp parallel for
for (int I = 0; I < N; ++I) {
    Work( &A[I] );
}
...
```

OpenMP equivalent

Intel® Advisor XE

- A product in Intel® Parallel Studio 2013, which is a plug-in for Microsoft* Visual Studio, and also available on Linux
- A design tool that assists in making good decisions to transform a serial algorithm to use multi-core hardware
- A serial modeling tool using annotated serial code to calculate what might happen if that code were executed in parallel as specified by the annotations
- A methodology and workflow to help you learn where to use parallel programming

Why estimate performance first?

- If programs were trivial to parallelize we would have already finished converting them
- Amdahl's law states the benefit of parallelism is based on the fraction of execution you parallelize
- Therefore, you must focus effort on the places that are valuable to parallelize, not the places that are easy to parallelize

Until you have a plausible parallelism model that can achieve the benefits you want, it does not pay to check if it can be made correct

(on an ideal machine)

Step: Survey Target

1. Survey Target
Where should I consider adding parallelism? Locate the loops and functions where your program spends its time, and functions that call them.

Collect Survey Data
View Survey Result

2. Annotate Sources
Add Intel Advisor XE annotations to [identify](#) possible parallel tasks and their enclosing parallel sites.

Steps to annotate
View Annotations

3. Check Suitability
Analyze the annotated program to check its predicted parallel [performance](#).

Collect Suitability Data
View Suitability Result

4. Check Correctness
[Predict](#) parallel data sharing problems for the annotated tasks. [Fix](#) the reported sharing problems.

Collect Correctness Data
View Correctness Result

5. Add Parallel Framework
Steps to replace annotations
View Summary

Current Project: pi

Where should I add parallelism? Intel Advisor XE 2013

Summary Survey Report Annotation Report Suitability Report Correctness Report

View Source

Function Call Sites and Loops	Total Time %	Total Time	Self Time	Hot Loops	Source Location
▼ Total	100.0%	1.0200s	0s		
▼ __libc_start_main	100.0%	1.0200s	0s		
▼ [loop in __libc_start_main]	100.0%	1.0200s	0s		
▼ main	100.0%	1.0200s	0s		pi_serial.cpp:30
▼ [loop at pi_serial.cpp:45 in main]	100.0%	1.0200s	0s		pi_serial.cpp:45
▼ compute_pi	100.0%	1.0200s	0s		pi_serial.cpp:17
▶ [loop at pi_serial.cpp:21 in compute_pi]	100.0%	1.0200s	1.0200s		pi_serial.cpp:21

Example: Iteration Loop, Single

Copy to Clipboard

```
// To copy compiler options, select Build Settings from the drop-down list.

#include "advisor-annotate.h" // Add to each module that contains Intel Advisor XE annotations

// Begin a parallel code region (parallel site)
ANNOTATE_SITE_BEGIN( MySite1 ); // Place before the loop control statement
// loop control statement
// If the entire loop body is not a single task, select Loop, One or More Tasks from the list
ANNOTATE_ITERATION_TASK( MyTask1 ); // Place at the start of loop body. This iterative-task annotation
// loop body
```

Step: Survey Target – View Sources

1. Survey Target
Where should I consider adding parallelism? Locate the loops and functions where your program spends its time, and functions that call them.
Collect Survey Data
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Add Intel Advisor XE annotations to identify possible parallel tasks and their enclosing parallel sites.
Steps to annotate
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Predict parallel data sharing problems for the annotated tasks. Fix the reported sharing problems.
Collect Correctness Data
View Correctness Result

5. Add Parallel Framework
Steps to replace annotations
View Summary

Current Project: pi

Project Navigator: Advisor XE Work

Welcome pi - e000

Where should I add parallelism? (Source)

Annotation Report Suitability Report Correctness Report Survey Source

File: pi_serial.cpp:21 compute_pi

Line	Source	Total Time	%	Loop Time	%
7	double compute_pi(int n, long num_steps)				
8	{				
9	long i;				
10	double step;				
11	double sum;				
12	double x;				
13					
14	// TODO: The argument 'n' specifies the				
15					
16	sum = 0.0;				
17	step = 1.0/(double) num_steps;				
18					
19	x = 0.5 * step;				
20					
21	for (i=0; i < num_steps; i++) {	0.080s		1.020s	
22	x += step;	1.020s			
23	sum += 4.0/(1.0+x*x);	0.880s			
24	}				
25					
26	return (step * sum);				
27	}				
Selected (Total Time):		0.080s			

Call Stack with Loops

- compute_pi - pi_serial.cpp:21
- compute_pi - pi_serial.cpp:17
- main - pi_serial.cpp:45
- main - pi_serial.cpp:30
- _libc_start_main
- _libc_start_main

Example: Iteration Loop, Single

Copy to Clipboard

```
// To copy compiler options, select Build Settings from the drop-down list.

#include "advisor-annotate.h" // Add to each module that contains Intel Advisor XE annotations

// Begin a parallel code region (parallel site)
ANNOTATE_SITE_BEGIN( MySite1 ); // Place before the loop control statement
// loop control statement
// If the entire loop body is not a single task, select Loop, One or More Tasks from the list
ANNOTATE_ITERATION_TASK( MyTask1 ); // Place at the start of loop body. This iterative-task annotation
// loop body
```

Survey – How Does it Work?

- Statistical Call Stack Sampling
- Focus on top-down inclusive execution time
- Define a periodic timer to sample IP addresses
- Unwind the call-stack at sample points
- Statically analyze the binary to detect loops
- Display the aggregate time a sample:
 - hits a basic block (IP or call stack-frame)
 - a call-stack frame intersects a loop

Step: Annotate Sources

The screenshot shows the Intel Advisor XE 2013 interface. The main window displays the source code for 'compute_pi' in 'pi_annotated.cpp'. The code is annotated with 'ANNOTATE_SITE_BEGIN' and 'ANNOTATE_SITE_END' to mark a parallel region, and 'ANNOTATE_ITERATION_TASK' to mark a task within the loop. A call stack on the right shows the execution path: 'compute_pi - pi_annotated.cpp:18', 'main - pi_annotated.cpp:287', 'main - pi_annotated.cpp:41', and '_libc_start_main'. A callout box highlights the annotated code snippet.

Line	Source	Total Time	Loop Time
19	step = 1.0/(double) num_steps;		
20			
21	x = 0.5 * step;		
22			
23	[&]() { // Trick to isolate the site into a separate stack frame for better		
24	[&]() {		
25			
26	ANNOTATE_SITE_BEGIN(pi_loop);		
27	for (int i=0; i < num_steps; i++) {		
28	ANNOTATE_ITERATION_TASK(pi_task);		
29	x += step;		
30	sum += 4.0/(1.0+x*x);		
31	}		
32	ANNOTATE_SITE_END(pi_loop);		
33			
34	}();		
35	}();		
36			
37	return (step * sum);		
38	}		

Call Stack with Loops

- compute_pi - pi_annotated.cpp:18
- main - pi_annotated.cpp:287
- main - pi_annotated.cpp:41
- _libc_start_main
- _libc_start_main

```
[&]() { // Trick to isolate the site into a separate
[&]() {

ANNOTATE_SITE_BEGIN(pi_loop);
for (int i=0; i < num_steps; i++) {
ANNOTATE_ITERATION_TASK(pi_task);
x += step;
sum += 4.0/(1.0+x*x);
}
ANNOTATE_SITE_END(pi_loop);

}();

}();
```

Example: Iteration Loop, Single

```
// To copy compiler options, select Build Setting

#include "advisor-annotate.h" // Add to each modul

// Begin a parallel code region (parallel site)
ANNOTATE_SITE_BEGIN( MySite1 ); // Place before the
// loop control statement
// If the entire loop body is not a single task
ANNOTATE_ITERATION_TASK( MyTask1 ); // Place at the
// loop body
ANNOTATE_SITE_END(); // End the parallel code region
```


Step: Check Suitability

Intel Advisor XE 2013

What are the performance implications of the annotated sites?

Summary Survey Report Annotation Report **Suitability Report** Correctness Report

Instances of task pi_task are too small. Suitability data may be unreliable.

A significant fraction of the total time spent in parallel site pi_loop is in instances of iteration task pi_task taking less than 50 nanoseconds. This can result in measurement errors which can make the Suitability data for this site unreliable. It also means that this is unlikely to be a suitable task, because task overhead is likely to be greater than the time saved by parallelizing the tasks.

[View Source](#)

All Sites

Maximum Program Gain For All Sites:

7.69x

Target CPU Count: 8 Threading Model: Intel TBB

Annotation Label	Source Location	Maximum Site Gain	Maximum Total Gain	Average Instance Ti...	Total Time
pi_loop	pi_annotated.cp...	7.69x	7.66x	0.4497s	3.5974s

Selected Site

Scalability of Maximum Site Gain

Changes I will make to this site to improve performance

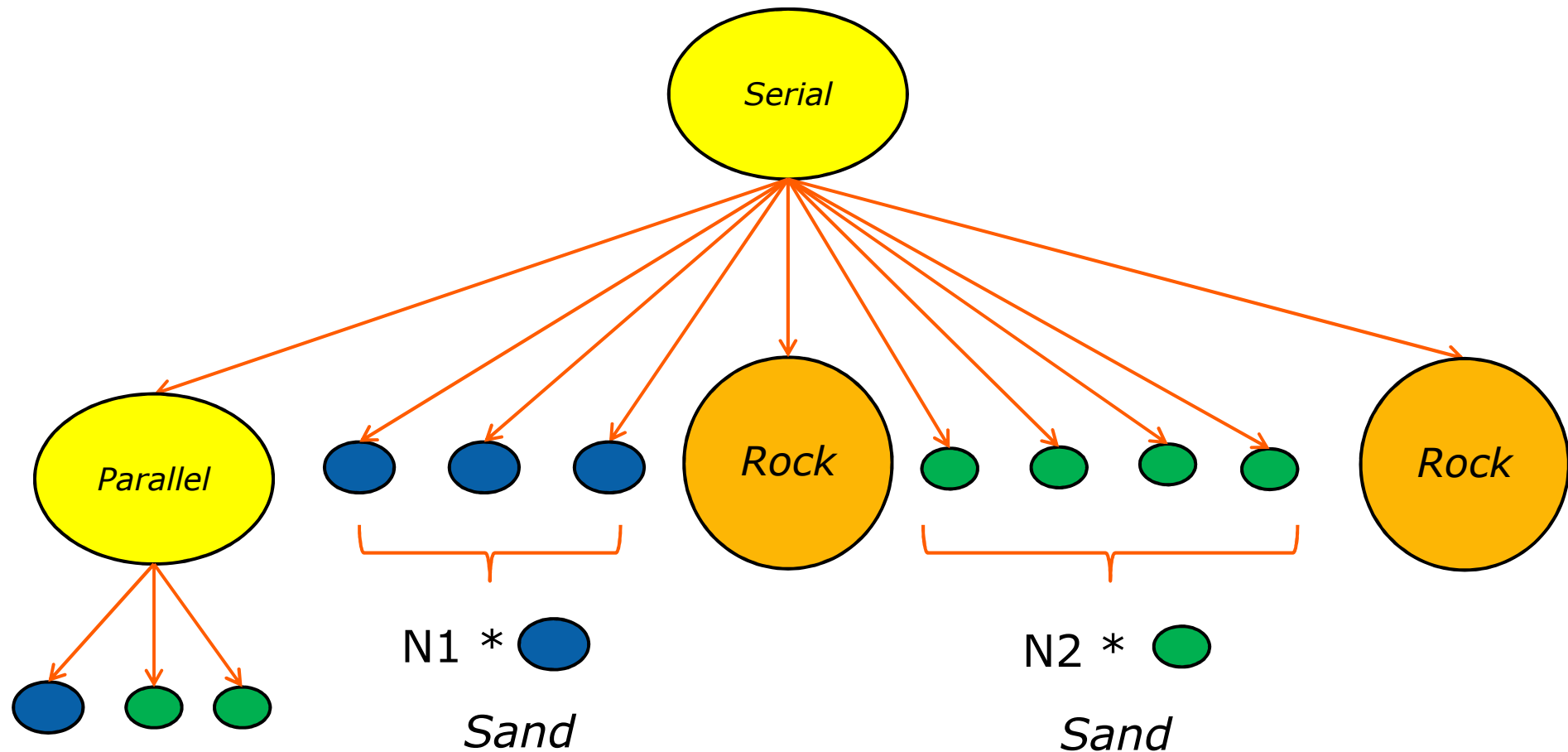
Type of Change	Benefit if Checked	Loss if Unchecked	Recommended
<input type="checkbox"/> Reduce Site Overhead	0.04x		No
<input type="checkbox"/> Reduce Task Overhead	0.20x		No
<input type="checkbox"/> Reduce Lock Overhead			No
<input type="checkbox"/> Reduce Lock Contention			No
<input checked="" type="checkbox"/> Enable Task Chunking		7.69x	Yes

Annotation	Annotation Label	Source Location	Number of Instances	Maximum Instance Time	Average Instance Time	Minimum Instance Time	Total Time
Selected Site	pi_loop	pi_annotated.cpp:26	8	3.2255s	0.4497s	< 0.0001s	3.5974s
Task	pi_task	pi_annotated.cpp:28	111,111,110	< 0.0001s	< 0.0001s	< 0.0001s	3.5950s

Suitability – How Does It Work?

- Performance Modeling
 - Gather an event trace of modeling annotations at runtime
 - Build a compressed execution tree
 - Simulate the execution tree
 - On an ideal parallel machine
 - Under varying number of threads
 - With varying assumptions about overhead and scheduling
 - Display the results and show how to improve the model
-
- The purpose is to check if the performance model is “suitable” as a starting point for parallelization
 - It is not designed as an accurate performance prediction
 - Tree compression, Greedy Scheduling,
 - Ideal machine, No memory model, ...

Suitability – *Rocks and Sand* Trace Compression



Count the *rocks*, but weigh the *sand*

Step: Check Correctness

Intel Advisor XE 2013

Did the annotated tasks expose data sharing problems?

Summary Survey Report Annotation Report Suitability Report **Correctness Report**

Problems and Messages

ID	Type	Site Name	Sources	Modules	State
P1	Parallel site informat...	pi_loop	pi_annotated.cpp	2_pi_annotated_debug	✓ Not...
P2	Data communication	pi_loop	pi_annotated.cpp	2_pi_annotated_debug	New
P3	Data communication	pi_loop	pi_annotated.cpp	2_pi_annotated_debug	New

Data communication: Code Locations

ID	Description	Source	Function	Module	State
X2	Parallel site	pi_annotated.cpp:...	_ZZZ10compute_piil...	2_pi_annotated_deb...	New
X3	Read	pi_annotated.cpp:...	_ZZZ10compute_piil...	2_pi_annotated_deb...	New
X4	Write	pi_annotated.cpp:...	_ZZZ10compute_piil...	2_pi_annotated_deb...	New

Filter

Severity

- Error 2 items
- Remark 1 item

Type

- Parallel site infor... 1 item
- Data communica... 2 items

Site Name

- pi_loop 3 items

Source

- pi_annotated.cpp 3 items

Module

- 2_pi_annotated_... 3 items

State

- New 2 items
- Not a problem 1 item

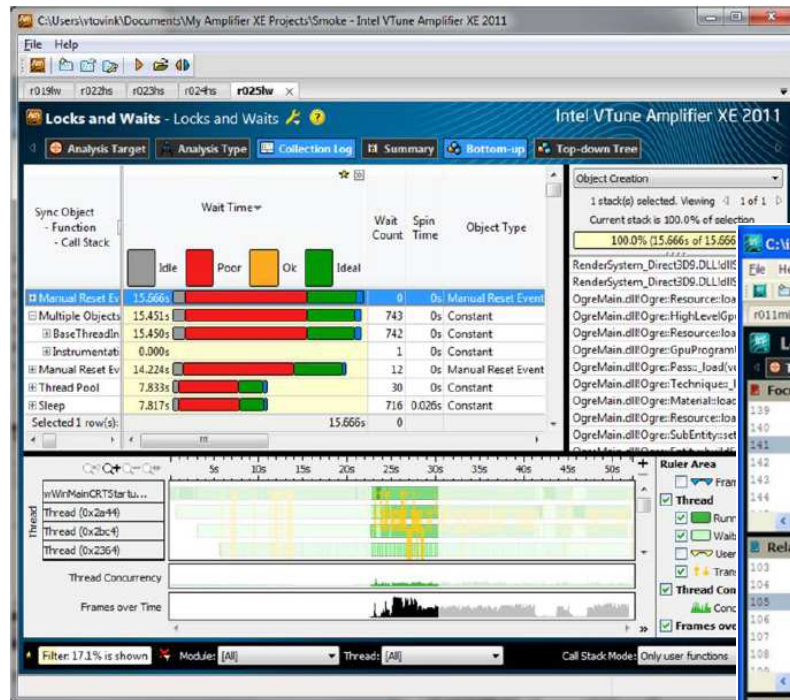
Current Project: pi_annotated

Correctness – How Does It Work?

- Memory Trace Analysis
- Only instrument the program when inside a SITE
- Record a history of prior memory accesses
- Record the SITE/TASK structure
- When the next memory location is accessed, check:
 - If the prior access was in a concurrent TASK
 - If the prior access was in an equivalent LOCK context
 - Either this access or the prior access was a write
- Tell the user about
 - Data Communication - RAW dependence
 - Memory Reuse – WAR or WAW dependence
 - Inconsistent LOCK usage

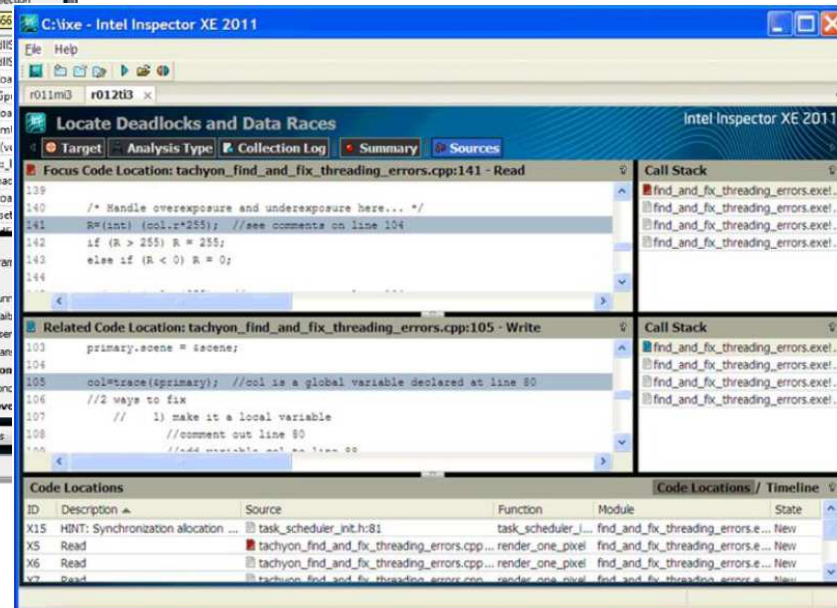
What Is The Next Step?

- Great parallel performance requires real hardware on which to tune your implementations
- Parallelism is not just relaxation of serial algorithms



← VTune Amplifier XE

Inspector XE →



Writing Parallel Programs That Work

1. You need the ability to express your computation
... usually serially
2. You need to understand the serial code
... as a specification of what computations must happen
3. You should create a parallel model of the code
... Intel® Advisor XE can be very helpful
4. You then express the parallel computation
... with your favorite parallel framework
5. You should finish by tuning on parallel hardware
... Intel® Parallel Studio XE can be very helpful

Intel® Parallel Studio 2013 XE

- More information about Parallel Studio XE and Advisor XE is available online, including a 30-day free trial

www.intel.com/go/parallel

- Supports Microsoft Visual Studio* 2005, 2008 and 2010.
- Support Linux



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Optimization Notice

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Step: Add Parallel Framework

- Final step: Convert annotations into uses of a parallel framework
- Examples in three parallel frameworks are used
 - Intel® Cilk™ Plus
 - Intel® Threading Building Blocks (Intel® TBB)
 - OpenMP*
- Converting a parallel model into explicitly parallel implementation is straightforward
- Each parallel framework you might use has concepts similar to a **SITE**, **TASK**, or **LOCK**
- Learning how common parallel framework features match annotations allows easy conversion to an explicitly parallel implementation

Parallel Framework: OpenMP

Specialized syntax can represent our parallel models efficiently

```
#include <advisor-annotate.h>
...
ANNOTATE_SITE_BEGIN(MyLoopSite);
for (int I = 0; I < N; ++I) {
    ANNOTATE_TASK_BEGIN(MyLoopIteration);
    Work( &A[I] );
    ANNOTATE_TASK_END();
}
ANNOTATE_SITE_END();
...
```

```
#pragma parallel for
    for (int I = 0; I < N; ++I) {
        Work( &A[I] );
    }
```

Parallel Framework: Intel® Cilk™ Plus

Specialized syntax can represent our parallel models efficiently

```
#include <advisor-annotate.h>
...
ANNOTATE_SITE_BEGIN(MyLoopSite);
for (int I = 0; I < N; ++I) {
    ANNOTATE_TASK_BEGIN(MyLoopIteration);
    Work( &A[I] );
    ANNOTATE_TASK_END();
}
ANNOTATE_SITE_END();
...
```

```
cilk_for (int I = 0; I < N; ++I)
    Work( &A[I] );
```

Parallel Framework: Intel® Threading Building Blocks (Intel® TBB)

Libraries can also represent our parallel models efficiently

```
#include <advisor-annotate.h>
...
ANNOTATE_SITE_BEGIN(MyLoopSite);
for (int I = 0; I < N; ++I) {
    ANNOTATE_TASK_BEGIN(MyLoopIteration);
    Work( &A[I] );
    ANNOTATE_TASK_END();
}
ANNOTATE_SITE_END();
...
```

```
#include "tbb/parallel_for.h"
...
tbb::parallel_for (0, N, 1,
    [=](int I) { Work ( &A[I] ); } );
....
```

Parallel Framework: OpenMP

Exploit unique parallel framework features

```
#include <advisor-annotate.h>
...
ANNOTATE_ACQUIRE_BEGIN(0);
std::cout << A[I] << std::endl;
ANNOTATE_RELEASE_END(0);
...
```

```
#include <omp.h>
...
#pragma omp critical
    std::cout << A[I] << std::endl;
...
```

Parallel Framework: Intel® Cilk™ Plus (cont.)

Exploit unique parallel framework features

```
#include <advisor-annotate.h>
...
ANNOTATE_ACQUIRE_BEGIN(0);
std::cout << A[I] << std::endl;
ANNOTATE_RELEASE_END(0);
...
```

```
#include <cilk/reducer_ostream.h>
...
cilk::reducer_ostream cout_reducer(std::cout);
...
cout_reducer << A[I] << std::endl;
...
```

Parallel Framework: OpenMP

Generic models can translate to specialized implementations

```
#include <advisor-annotate.h>
...
ANNOTATE_LOCK_ACQUIRE(0);
globalCounter = globalCounter + 1;
ANNOTATE_LOCK_RELEASE(0);
...
```

```
#include <omp.h>
...
#pragma atomic
    ++globalCounter;
...
```


Parallel Framework: Intel® TBB (cont.)

Generic models can translate to specialized implementations

```
#include <advisor-annotate.h>
...
ANNOTATE_LOCK_ACQUIRE(0);
globalCounter = globalCounter + 1;
ANNOTATE_LOCK_RELEASE(0);
...
```

```
#include "tbb/atomic.h"
...
tbb::atomic<int> globalCounter;
...
++globalCounter;
...
```

About the speaker

Paul Petersen is a Sr. Principal Engineer in the Software and Solutions Group (SSG) at Intel. He received a Ph.D. degree in Computer Science from the University of Illinois in 1993.

After UIUC, he was employed at Kuck and Associates, Inc. (KAI) working on auto-parallelizing compiler (KAP), and was involved in the early definition and implementations of OpenMP. While at KAI, he developed the Assure line of parallelization/correctness products, for Fortran, C++ and Java.

In 2000, Intel Corporation acquired KAI, and he joined the software tools group. At Intel, he worked with the tools group to create the Thread Checker products, which evolved into the Inspector and Advisor components of the Intel® Parallel Studio. Inspector uses dynamic binary instrumentation to detect memory and concurrency bugs, and Advisor uses similar techniques along with performance measurement and modeling to assist developers in transforming existing serial applications to be ready for parallel execution.

- **Abstract:** Serial algorithms typically run very inefficiently on parallel machines. This may sound like an obvious statement, but it is the root cause of why parallel programming is considered to be difficult. The current state of the computer industry is still that almost all programs in existence are serial. To address this situation, Intel has created Parallel Studio XE, and in particular Advisor XE.
- This talk will describe the techniques used in Advisor XE to provide a developer with the tools necessary to understand the limitations of the existing serial algorithms. Once the limitations are known the developer can refactor the algorithms and reanalyze the resulting code to see if it could run effectively on parallel hardware. Almost all implementations of serial algorithms are serial for a reason, and the tools available in Advisor XE help the user expose these reasons so that appropriate rewrites can be done.
- **Bio:** Paul Petersen is a Sr. Principal Engineer in the Software and Solutions Group (SSG) at Intel. He received a Ph.D. degree in Computer Science from the University of Illinois in 1993. After UIUC, he was employed at Kuck and Associates, Inc. (KAI) working on auto-parallelizing compiler (KAP), and was involved in the early definition and implementations of OpenMP. While at KAI, he developed the Assure line of parallelization/correctness products, for Fortran, C++ and Java. In 2000, Intel Corporation acquired KAI, and he joined the software tools group. At Intel, he worked with the tools group to create the Thread Checker products, which evolved into the Inspector and Advisor components of the Intel® Parallel Studio. Inspector uses dynamic binary instrumentation to detect memory and concurrency bugs, and Advisor uses similar techniques along with performance measurement and modeling to assist developers in transforming existing serial applications to be ready for parallel execution.