Parallelization of C programs
through dependency analysis

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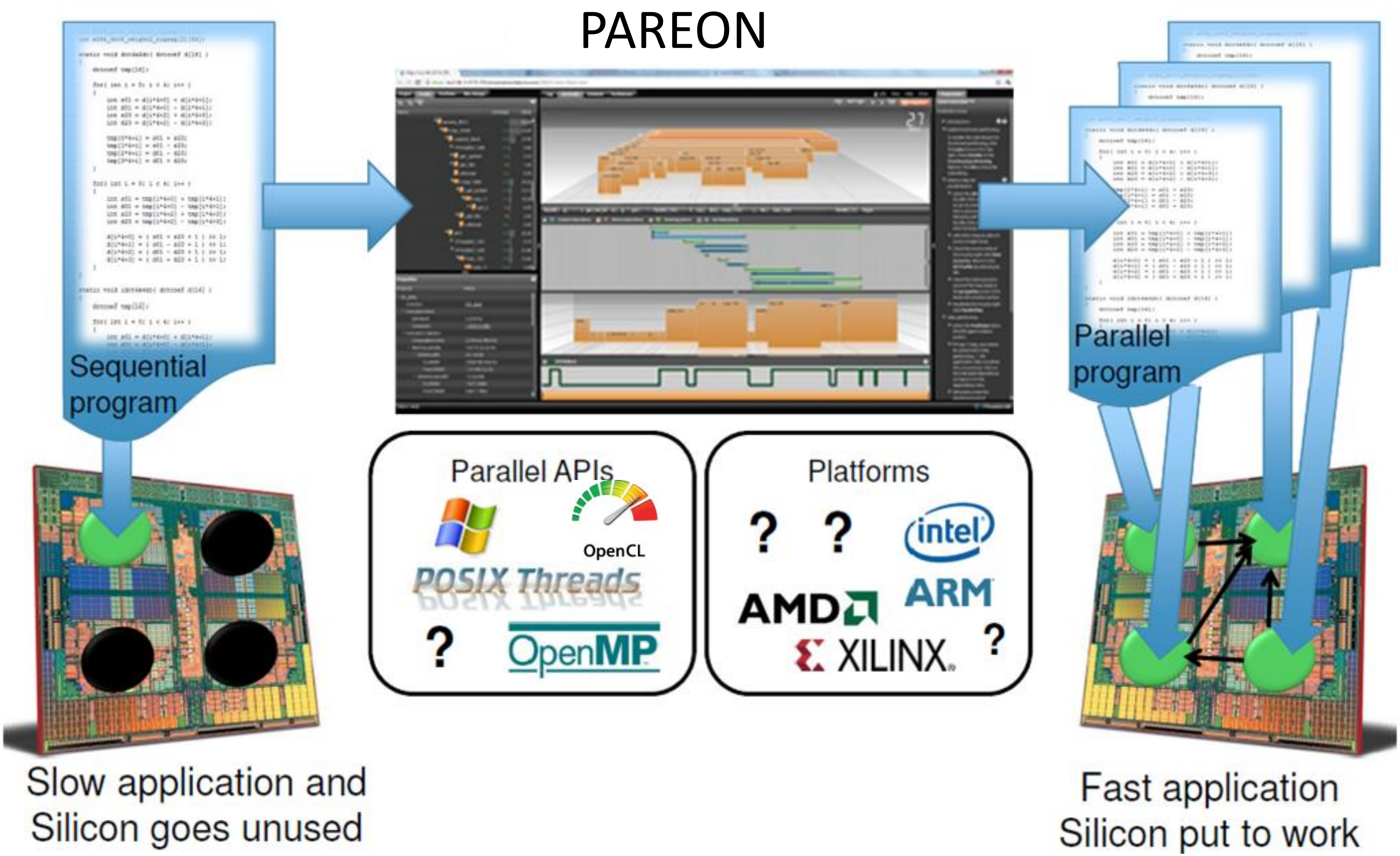
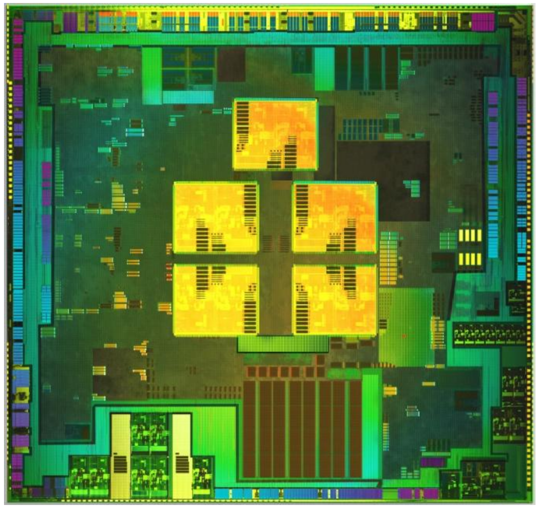
Discovering potential concurrency



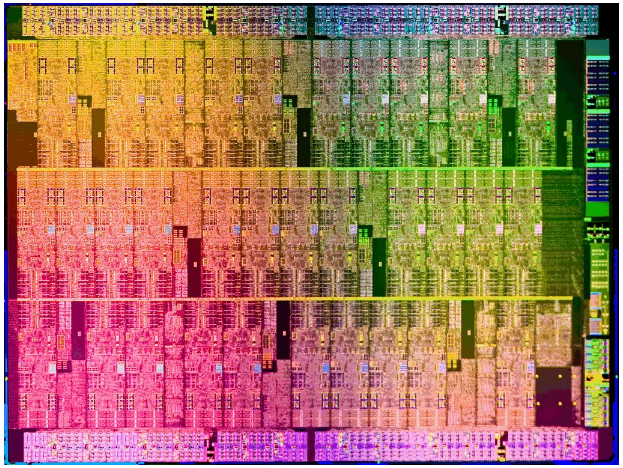
Presentation index

- Multi-processors will further expand
- Partitioning workload across multiple cores:
  - Data partitioning
  - Functional partitioning
- Tooling for dependency analysis
- Example: LAMMPS
- Conclusion

Programming parallel computers



nVidia TEGRA 3



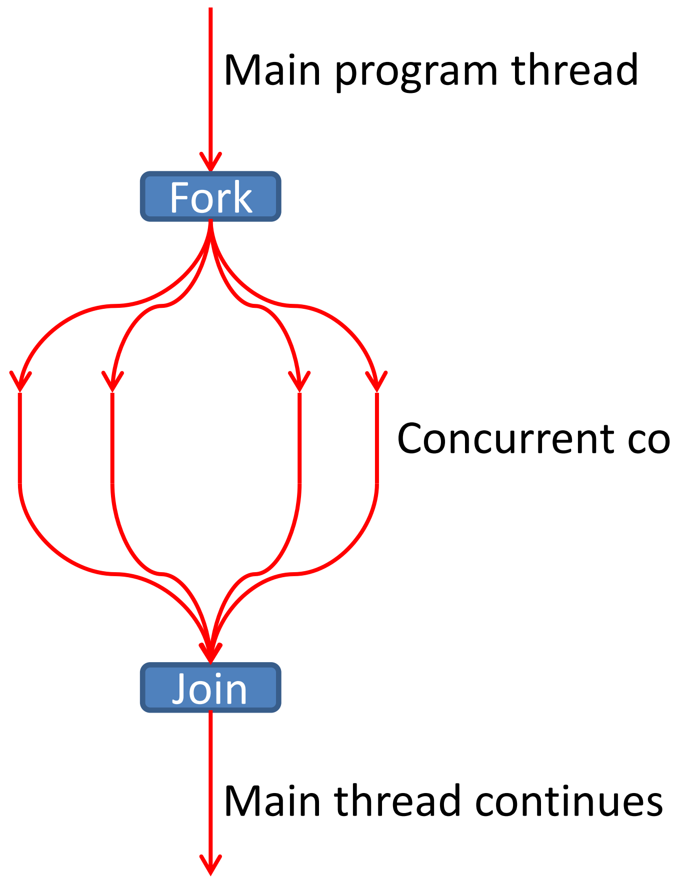
Intel Aubrey Isle (MIC)

- Multi-processor machines are all around us, ranging from mobile to super-computers.
- Multi-processor architectures are driven by technology factors: increased integration densities and power efficiency requirements.
- Parallel (multi-threaded) programs are required to exploit their capability.
- However, parallel programming is difficult and error-prone. Unfortunately, software productivity already is a major bottleneck.
- Distributed-memory architectures and heterogeneous processors (GP-GPUs) add further complications.

Application programmers need more help!

Creating multi-threaded concurrency

Basic fork-join pattern, created through different higher-level programming constructs



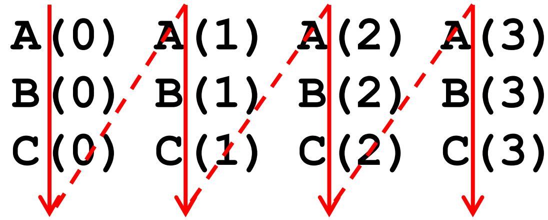
Creation of threads is application responsibility.
Operating System handles run-time scheduling across available processors.

Parallelization – two partitioning options

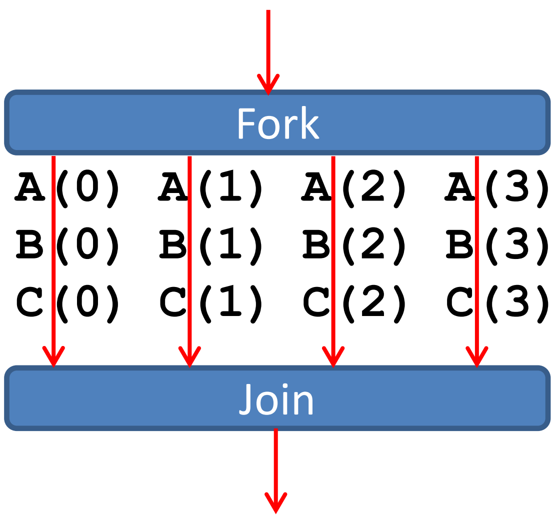
Source code:

```
for (i=0; i<4; i++) {
    A(i);
    B(i);
    C(i);
}
```

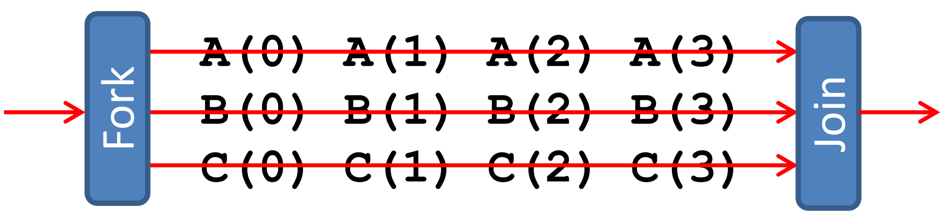
Sequential execution order:



Data partitioning:



Functional partitioning:



Functional versus data partitioning

Data partitioning:

- Allows a high degree of parallelization for loops with high iteration count.
- Allows good distribution of workload across (homogeneous) processors.
- Loop-carried data dependencies can severely impact performance.

Functional partitioning:

- Best for separation of workload across heterogeneous processors.
- Inter-function data dependencies typically converted into buffered streams.

Choice is directed by data dependency patterns.

Example functional partitioning

```
int A[N][M];

while (..)
{ produce_img();
  consume_img();
}

produce_img()
{ for (i ...)
    for (j ...)
     A[i][j] = ...
}

consume_img()
{ for (i ...)
    for (j ...)
      ... = A[i][j];
}
```

```
Thread1: while (..)
    produce_img();

Thread2: while (..)
    consume_img();
```

Synchronize thread progress:

- True dependency: consumer must wait for valid data
- Anti dependency: producer must wait with over-writing until after consumption

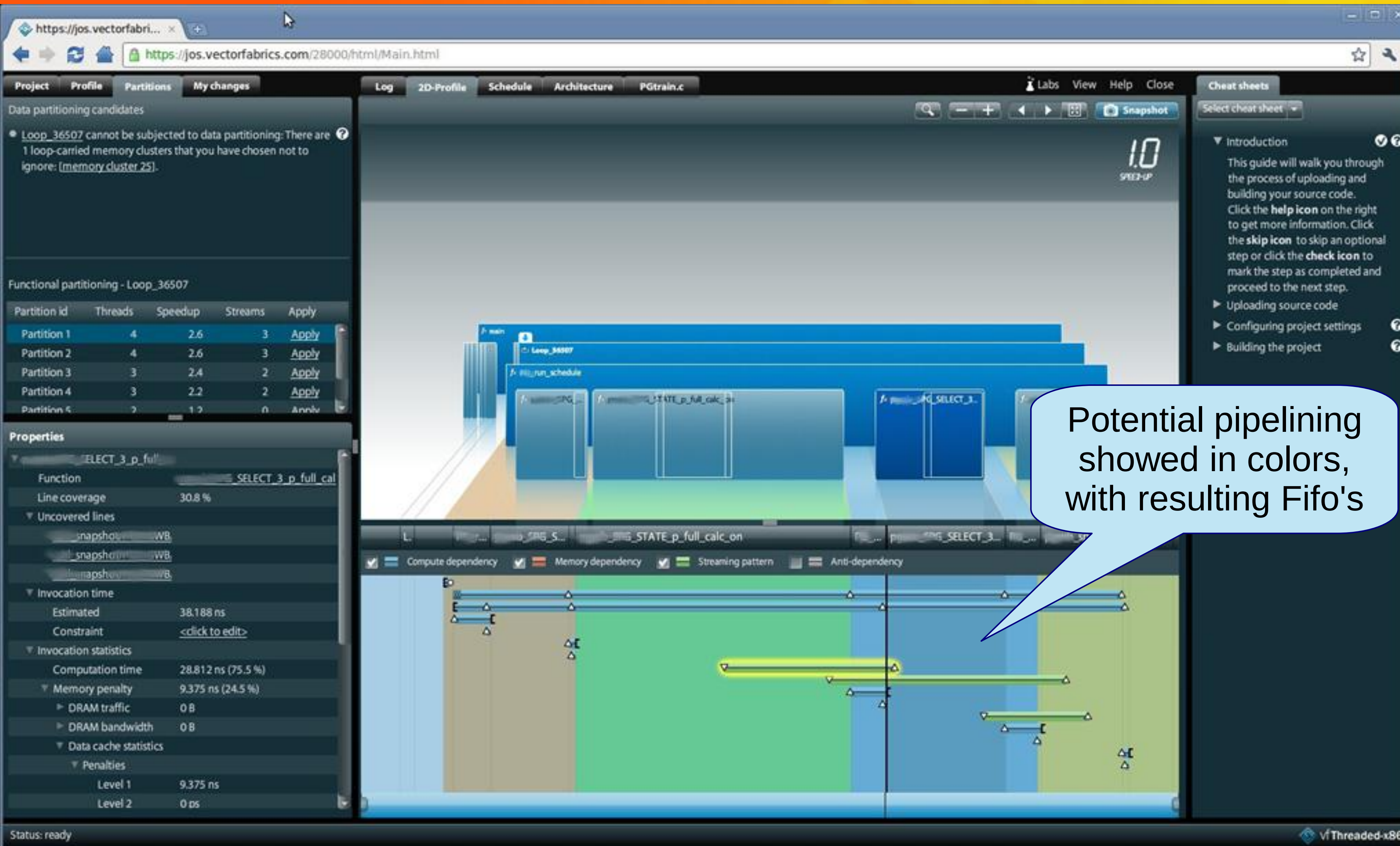
Function pipelining: synchronization

```
int A[N][M];

while (..)
{ produce_img();
  consume_img();
}

produce_img()
{ for (i ...)
    for (j ...)
     A[i][j] = ...
}

consume_img()
{ for (i ...)
    for (j ...)
       ... = A[i][j];
}
```

```
Channel ch;


Thread1: while (..)
   produce_img();

Thread2: while (..)
   consume_img();

produce_img()
{ for (i ...)
    for (j ...)
     write_int( ch, ...)
}

consume_img()
{ for (i ...)
    for (j ...)
      ... = read_int(ch);
```

Channel access functions implement thread stall.

Pipeline dependency analysis



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Function pipelining: Channel APIs

Too many choices for channel-based communication:

- Standard Java util.concurrent queue classes
- Intel's TBB (C++) queues
- Linux 'pipes' and 'sockets'
- OpenCL channels
- OpenMAX IL for streaming media processing
- MPI message-passing channels
- . . .

Very different queue implementations:

- Inter-thread, inside process memory context
- Inter-process, inside shared-memory system
- Inter-system, through device interfaces

NOTE: C++ STL queues are NOT thread-safe!

Example data partitioning

```
int sum = 0;
for (i=0; i<N; i++) {
    int value = some_work(i);
    sum += value;
}
```

- Distribute the workload over multiple cores.
- Each core handles part of the loop index space.

```
int sum = 0;
#pragma omp parallel for reduction (+:sum)
for (i=0; i<N; i++) {
    int value = some_work(i);
    sum += value;
}
```

- Workload scales nicely across multiple cores
- Easy to write down ☺, but hard to grasp all consequences!
- Highly dangerous, might cause extremely hard-to-track bugs! ☹

Application Analysis

Finding data dependencies

Vector Fabrics' approach:

- Compile program source code, compiler is adapted for instrumentation.
- Execute the instrumented program:
  - Traps all memory load/store operations:
    match ld/st operations that address the same memory location
  - Relates ld/st operations with nested loop structure:
    separate loop-carried dependencies from loop in-bound and loop out-bound dependencies
  - Builds an execution profile (call tree), across file boundaries
- Analyze loops with their data dependencies for parallelization patterns

Recognize parallelization patterns

Analyze loops with data dependencies for parallelization patterns:

- Reduction expressions
- Induction expressions
- Streaming dependencies, allowing data duplication and localization

Avoid considering ‘false’ memory dependencies:

- Local variables on stack, duplicated through thread local storage
- Re-use of memory locations through `malloc()` and `free()`.

Relate data dependencies and patterns to locations in C(++) source code for required code transformations.

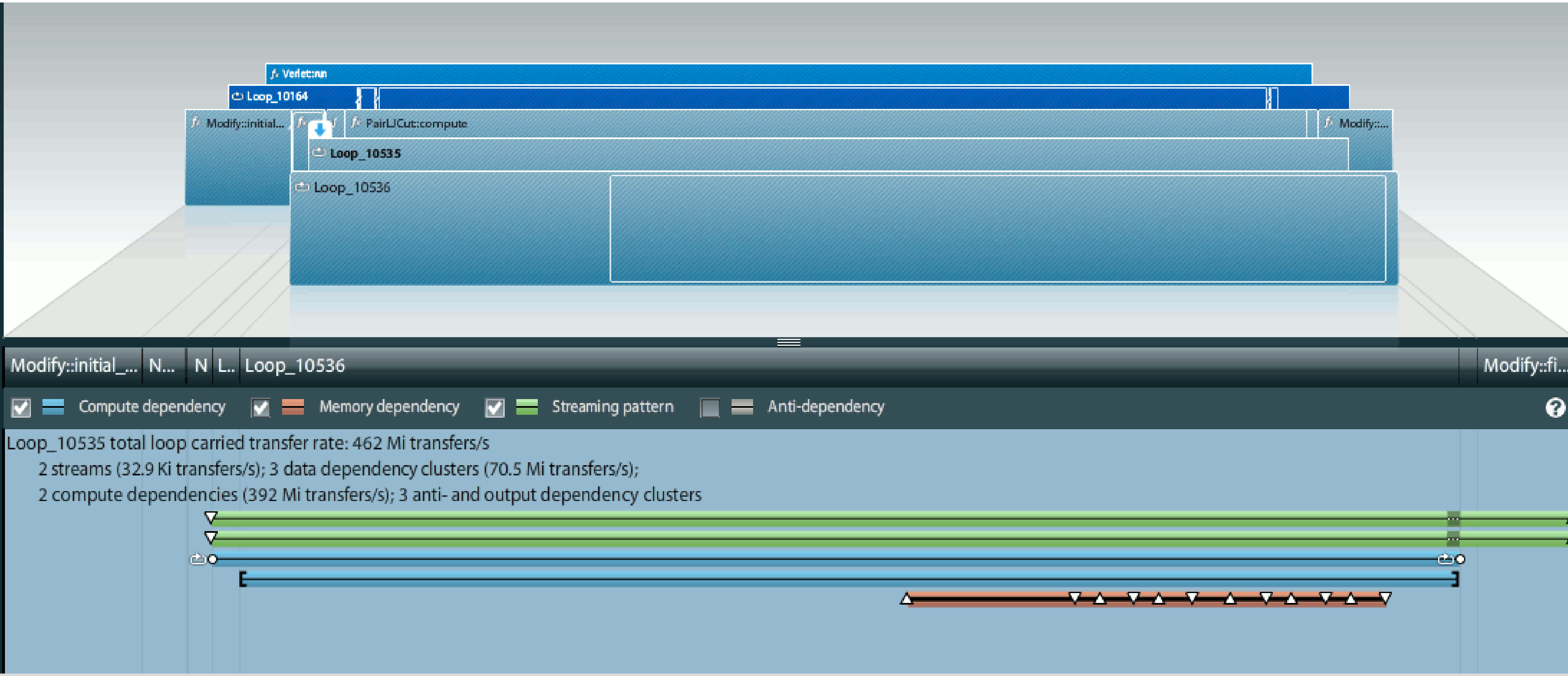
Example: LAMMPS molecular simulator

- Source code configured for sequential version.
- About 187Klines of C++ source code in 636 files.

Name	Coverage	Delay
_entry	0	100.00
main	100	100.00
Input::file	80	100.00
Loop_3344	78	100.00
Input::execute_command	99	100.00
Run::command	32	99.78
Verlet::setup	79	0.50
Verlet::run	86	99.26
Loop_10164	84	99.26
Modify::initial_integrate	100	8.72
Neighbor::decide	67	2.78
Neighbor::build	40	1.56
PairLJCut::compute	100	78.95
Loop_10535	100	78.91
Loop_10536	100	77.07
Modify::post_force	100	0.99
Modify::final_integrate	100	6.15

Example: LAMMPS data dependencies

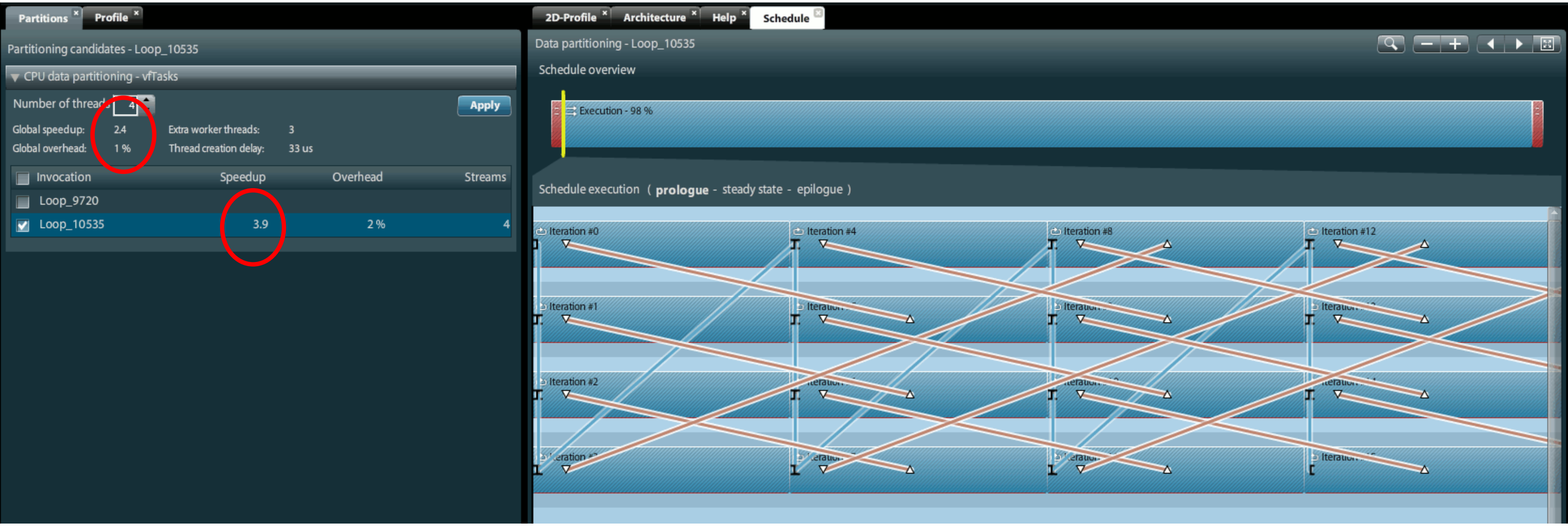
- Parallelization opportunity detected in loop over particles, inside loop over time steps
- Different dependency patterns shown in different colors



Parallel performance prediction

- Estimate overhead from thread fork/join and synchronization
- Estimate execution schedule with loop-carried dependencies

Speedup of this loop: 3.9x, overall speedup: 2.4x



Conclusion

- Today's gap: multi-processor machines are everywhere, yet multi-threaded programming is difficult and error-prone.
- Proper tooling is required to avoid (data race-) errors and obtain insight in performance issues. Obtain such insight before spending time on re-coding for parallelization.
- Various tools are available today. They do support real-world application analysis.

Questions?

- Todays gap: multi-core CPUs and multi-processor machines are everywhere, yet multi-threaded programming is difficult and error-prone.
- Proper tooling is requir[illegible] (data race-) errors and obtain insight in performance [illegible]sues. Ob[illegible]in such insight before spending time on re-coding for parallelizati[illegible]
- Various tools are available tod[illegible]hey do support real-world application analysis.

Thank you

Check www.vectorfabrics.com for a free trial of concurrency analysis