Application parallelization for multi-core Android devices

Jos van Eijndhoven
jos@vectorfabrics.com

Bits&Chips 2012 Embedded Systems
Nov. 8, 2012, ’s-Hertogenbosch

Vector Fabrics

android

Multi-core ARM and Android conquer the world

Google Nexus 10
2-core Samsung A15

Asus Transformer Prime
“4”-core Nvidia Tegra3

HTC J Butterfly
4-core Qualcomm

Samsung Galaxy SIII
4-core Samsung

Sony Experia P
2-core ST-Ericsson

Huawei Honor2
4-core Huawei

Multi-core usage in Mobile

- 2 core processors:
  Assume the OS has multiple processes and/or kernel threads to occupy the two cores. Easy!
- 4 core processors (and beyond):
  Requires multi-threaded applications Hard!
  - To obtain sufficient concurrent workload
  - To obtain top user experience

Who makes such applications??

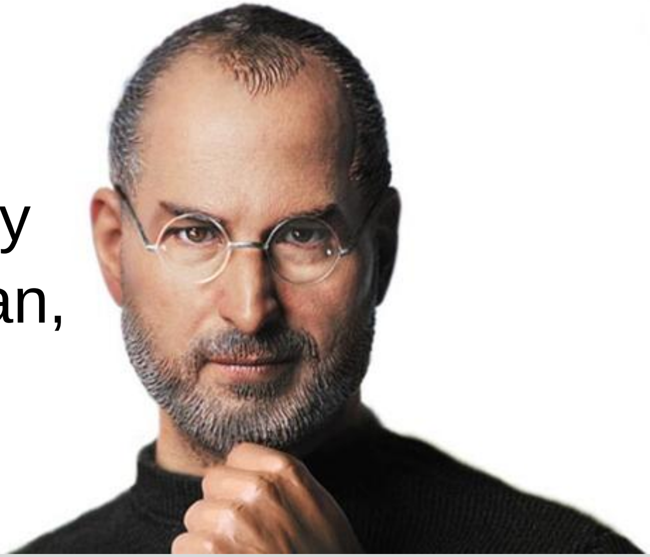
Creating parallel programs is hard…

Herb Sutter, chair of the ISO C++ standards committee, Microsoft:

“Everybody who learns concurrency thinks they understand it, ends up finding mysterious races they thought weren’t possible, and discovers that they didn’t actually understand it yet after all”

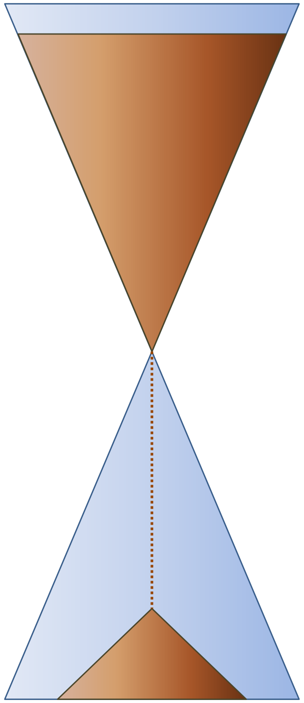
Steve Jobs, Apple:

“The way the processor industry is going, is to add more and more cores, but nobody knows how to program those things. I mean, two yeah; four not really; eight, forget it.”



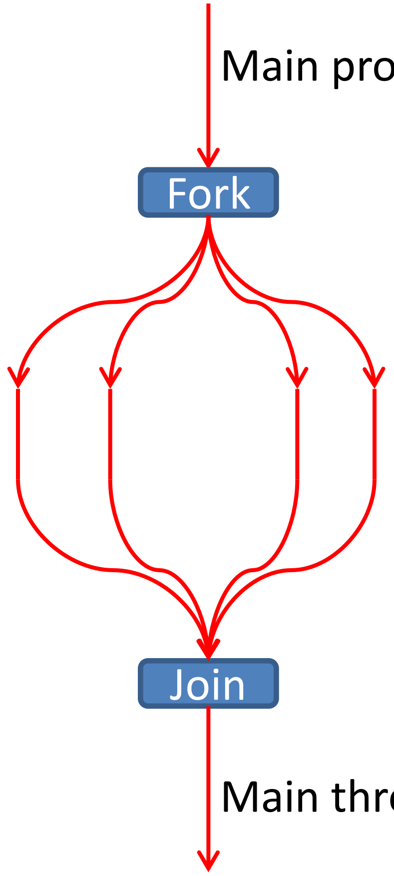
Presentation index

- Introduction
- Multi-threaded concurrency:
  Data- versus Task-partitioning
- Parallelization with dependencies:
  Reduction expressions or Streaming
- Multi-threading: difficult…
- Android: help from Pareon and Perf
- Conclusion



Creating multi-threaded concurrency

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



Main program thread

Concurrent computation threads

Main thread continues

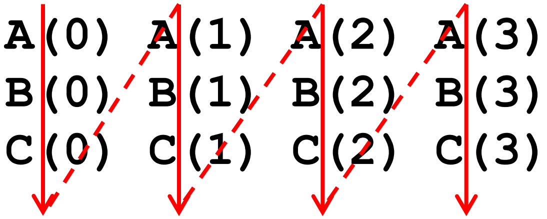
Creation of threads is application responsibility. Operating System handles run-time scheduling across available processors!

Parallelization – two partitioning options

Source code:

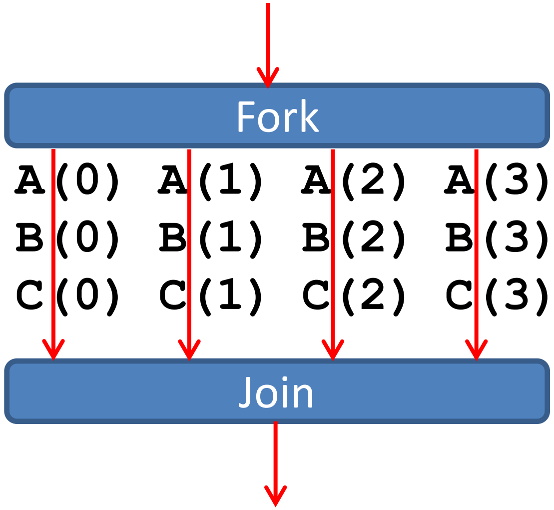
```
for (i=0; i<4; i++) {
    A(i);
    B(i);
    C(i);
}
```

Sequential execution order:



A(0) A(1) A(2) A(3)
B(0) B(1) B(2) B(3)
C(0) C(1) C(2) C(3)

Data partitioning:

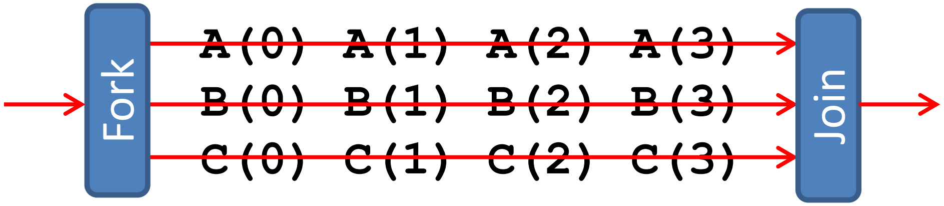


Fork

A(0) A(1) A(2) A(3)
B(0) B(1) B(2) B(3)
C(0) C(1) C(2) C(3)

Join

Task partitioning:

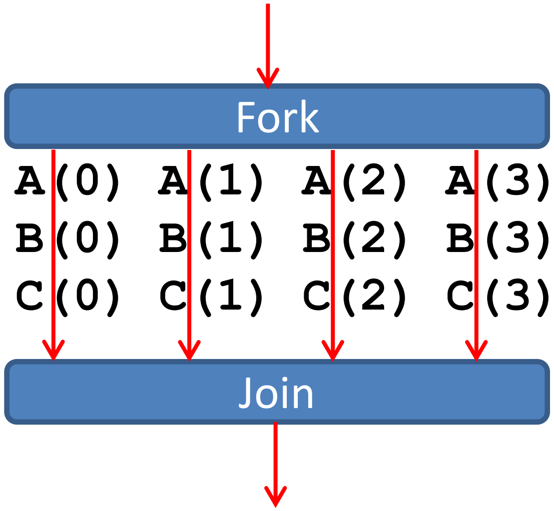


Fork

A(0) A(1) A(2) A(3)
B(0) B(1) B(2) B(3)
C(0) C(1) C(2) C(3)

Join

Issue: Data dependencies



Fork

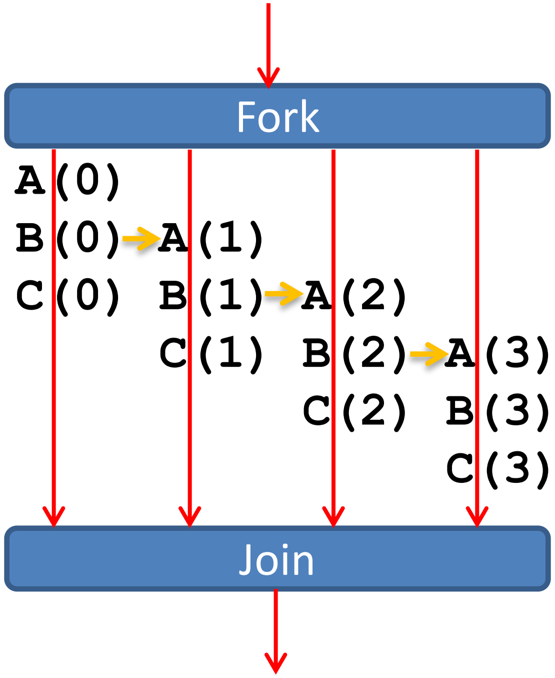
`A(0)` `A(1)` `A(2)` `A(3)`

`B(0)` `B(1)` `B(2)` `B(3)`

`C(0)` `C(1)` `C(2)` `C(3)`

Join

Maybe, **`B(i)`** produces a value that is used by **`A(i+1)`**…



Fork

`A(0)`

`B(0)` → `A(1)`

`C(0)` `B(1)` → `A(2)`

`C(1)` `B(2)` → `A(3)`

`C(2)` `B(3)`

`C(3)`

Join

Adjust program source for parallelization:

- When feasible, remove inter-thread data dependencies
- Implement required data synchronization

Example Data dependencies

Variable assigned in loop body, used in later iteration

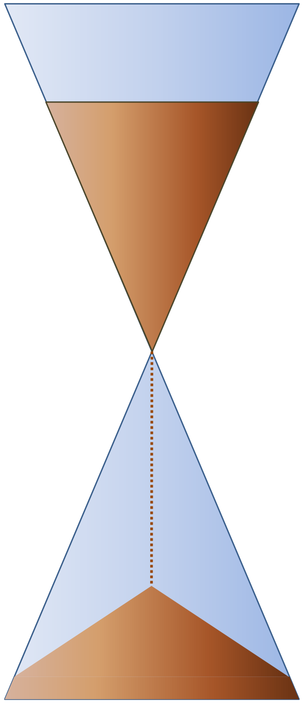
```
// search linked-list for matching items
// save matches in ‘found’ array of pointers
for (p = head, n_found = 0; p; p = p->next)
  if (match_criterion(p))
    found[n_found++] = p;
```

Cannot (easily/trivially) spawn data-parrallel tasks!

- No direct parallel access to list members `*p`
- No direct way to assign index to matched item `n_found`
- Maybe more problems hidden in `match_criterion()`

Presentation index

- Introduction
- Multi-threaded concurrency:
  Data- versus Task-partitioning
- Parallelization with dependencies:
  Reduction expressions or Streaming
- Multi-threading: difficult…
- Android: help from Pareon and Perf
- Conclusion



Can do: reduction data dependencies

- Reduction expressions: accumulate results of loop bodies with commutative operations
- Freedom of re-ordering allows to break sequential constraints

```
// conditionally accumulate results
int acc = 0;
for (i=0; i<N; i++)
{
  int result = some_work(i);
  if (some condition(i))
     acc += result;
}
...use of acc ...
```

- Commutative operations are basic math like +, *, &&, &, ||, but also more complex operations like ‘*add item to set*’.
- Three(?) different methods to handle these ...

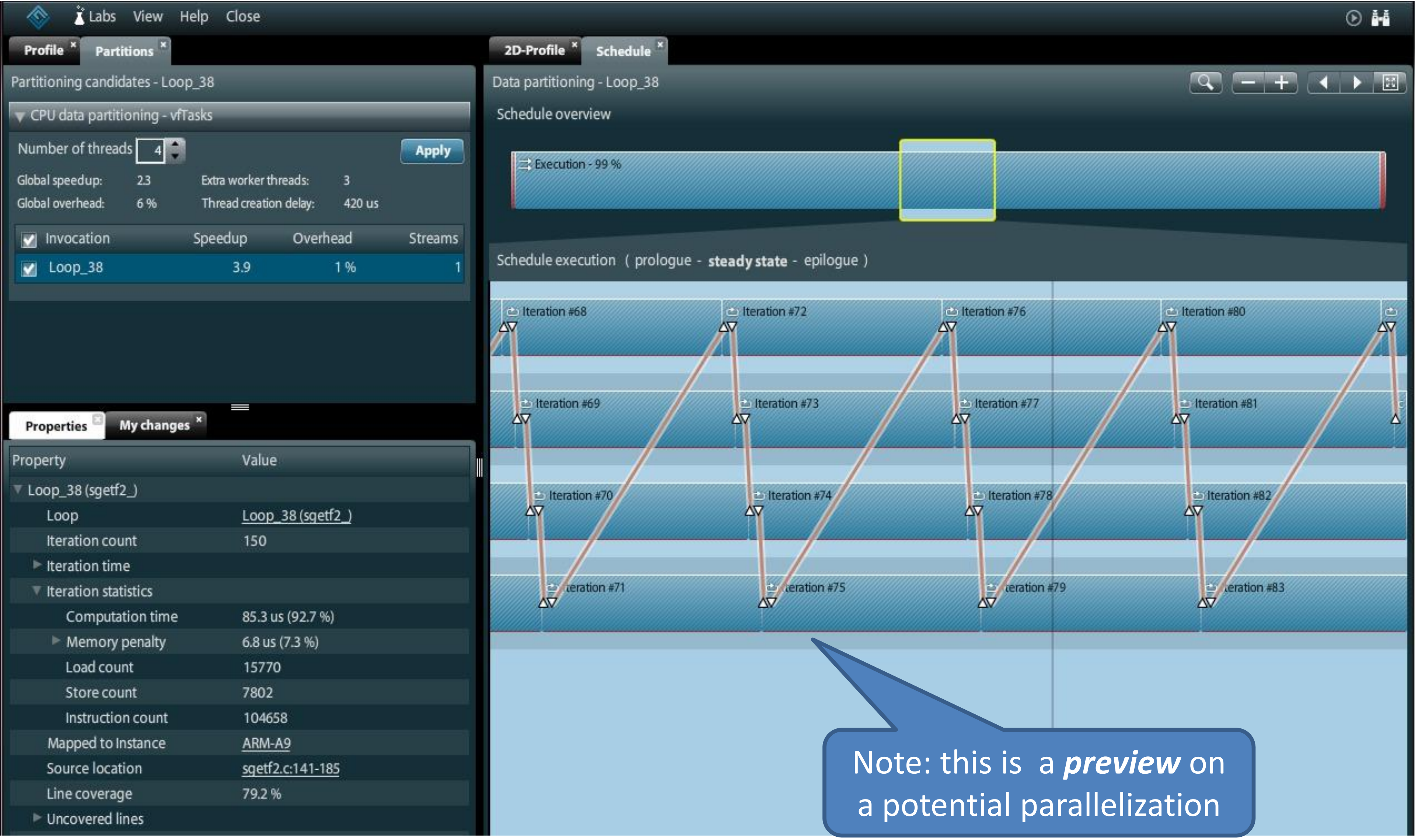
Three methods for reduction dependencies

- Create thread-local copies of the accumulator. Accumulate over local copy in each thread. Merge the partial accumulators after thread-join. Eg. created automatically by:
  `#pragma omp parallel for reduction(...)`

- Maintain single accumulator, synchronize updates through atomic operations. Eg. in C11 or C++11:
  ```
  atomic_add_fetch( &acc, result);
  std::atomic<int> acc;
  acc += result;
  ```

- Maintain single accumulator, synchronize updates through protection by acquiring and releasing semaphores.
  Eg. Used by Intel “Threaded Building Blocks” (C++):
  ```
  concurrent_unordered_set<...> s;
  s.insert(...);
  ```

PAREON: Schedule data dependencies



Partitioning candidates - Loop_38

CPU data partitioning - vfTasks

Number of threads 4

Global speedup: 2.3
Extra worker threads: 3
Global overhead: 6 %
Thread creation delay: 420 us

☑ Invocation	Speedup	Overhead	Streams
☑ Loop_38	3.9	1 %	1

Data partitioning - Loop_38

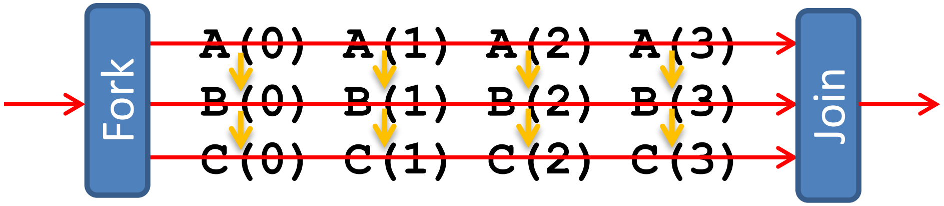
Schedule execution (prologue - **steady state** - epilogue)

Property	Value
Loop_38 (sgetf2_)	
Loop	Loop_38 (sgetf2_)
Iteration count	150
Iteration time	
Iteration statistics	
Computation time	85.3 us (92.7 %)
Memory penalty	6.8 us (7.3 %)
Load count	15770
Store count	7802
Instruction count	104658
Mapped to Instance	ARM-A9
Source location	sgetf2.c:141-185
Line coverage	79.2 %
Uncovered lines	

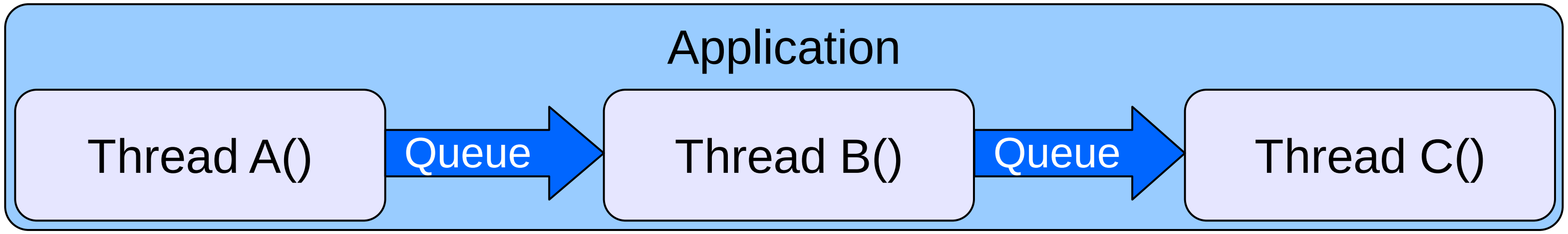
Note: this is a ***preview*** on a potential parallelization

Pipelining: Data deps and task partitioning

Task partitioning with inter-thread dependencies:



Producer-Consumer pattern:

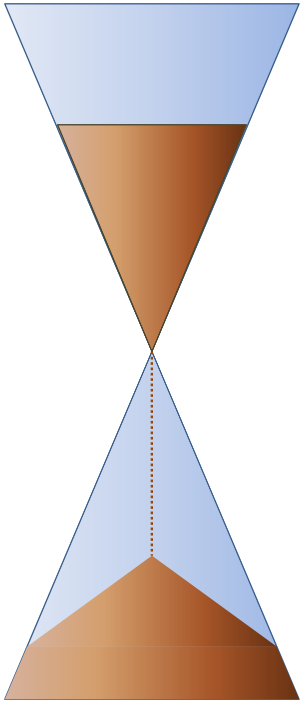


Queue implementation solves dependencies:

- **Solve Data dependencies**: Consumer thread waits for available data (stalls until queue is non-empty)
- **Solve Anti dependencies**: Producer thread creates next item in next memory location (prevents overwriting previous value)

Presentation index

- Introduction
- Multi-threaded concurrency:
  Data- versus Task-partitioning
- Parallelization with dependencies:
  Reduction expressions or Streaming
- Multi-threading: difficult…
- Android: help from Pareon and Perf
- Conclusion



Concurrent C/C++ programming: Pitfalls

Risc introduction of functional errors:

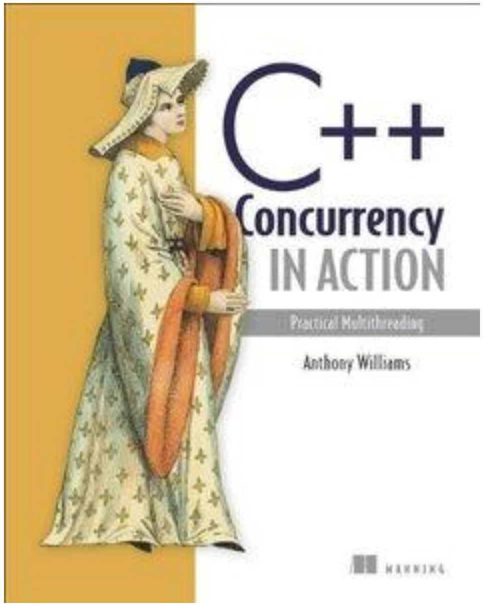
- Overlooking use of shared/global variables
  (deep down inside called functions, or inside 3rd party library)
- Overlooking exceptions that are raised and catched outside studied scope
- Incorrect use of semaphores: flawed protection, deadlocks

Unexpected performance issues:

- Underestimation of time spent in added multi-threading or synchronization code and libraries
- Underestimation of other penalties in OS and HW
  (inter-core cache penalties, context switches, clock-frequency reductions)

Parallel programming remains hard!

Concurrent programming remains hard



- C++11 standardizes valuable primitives
- Provides good insight in C++ concurrency
- Warns for many subtle problems

Development of parallel code

Guidelines:

- Base upon a sequential program:
  functional and performance reference
- Apply higher-level parallelization patterns and primitives:
  clear semantics, re-use code, reduce risk
- Use tooling for analysis and verification
  - Prevent introduction of hard-to-find bugs
  - Prevent recoding effort that does not perform

Managable development process!

PAREON tool workflow

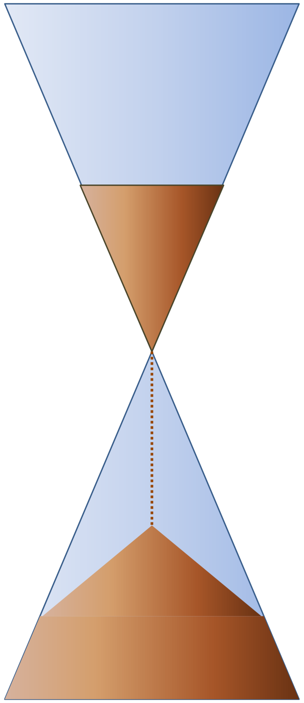
1 Developer builds C/C++ application with Pareon's compiler
Compiler creates instrumented code

2 Execute application with input data set
Pareon captures trace with call stack and ld/st memory traffic
Pareon analyzes data dependency patterns

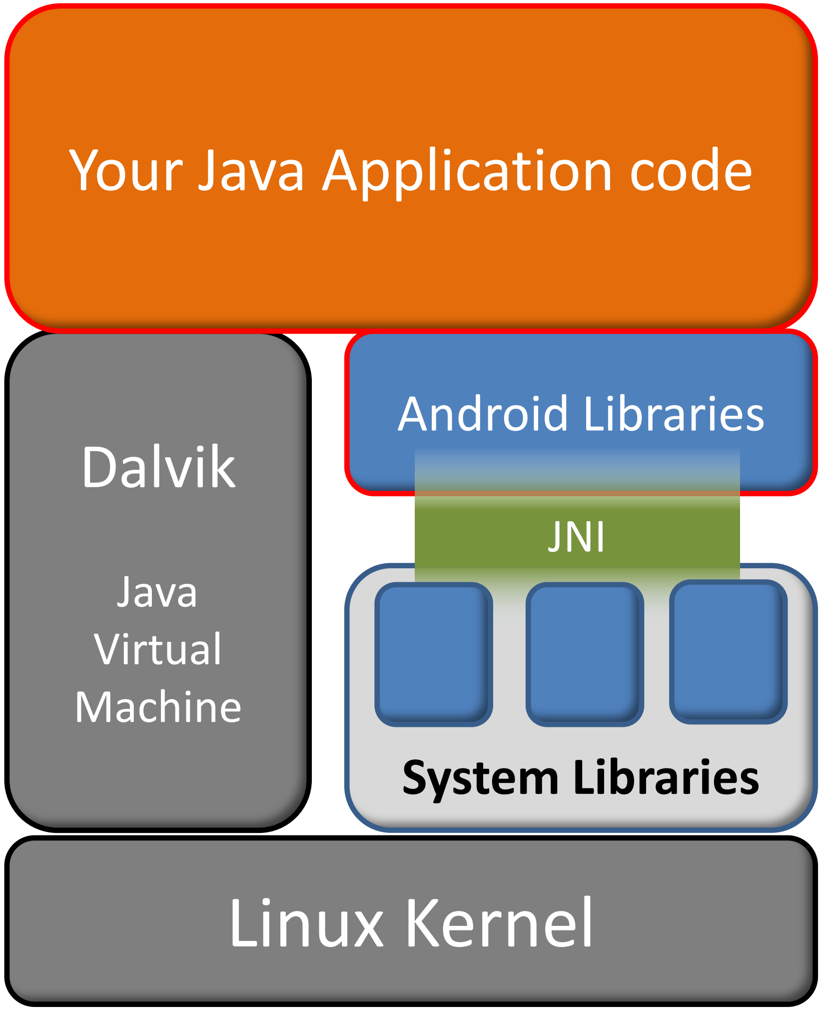
3 Developer browses application model
Selects loops for parallelization from performance estimate
Performs source-code transformation

Presentation index

- Introduction
- Multi-threaded concurrency:
  Data- versus Task-partitioning
- Parallelization with dependencies:
  Reduction expressions or Streaming
- Multi-threading: difficult…
- Android: help from Pareon and Perf
- Conclusion



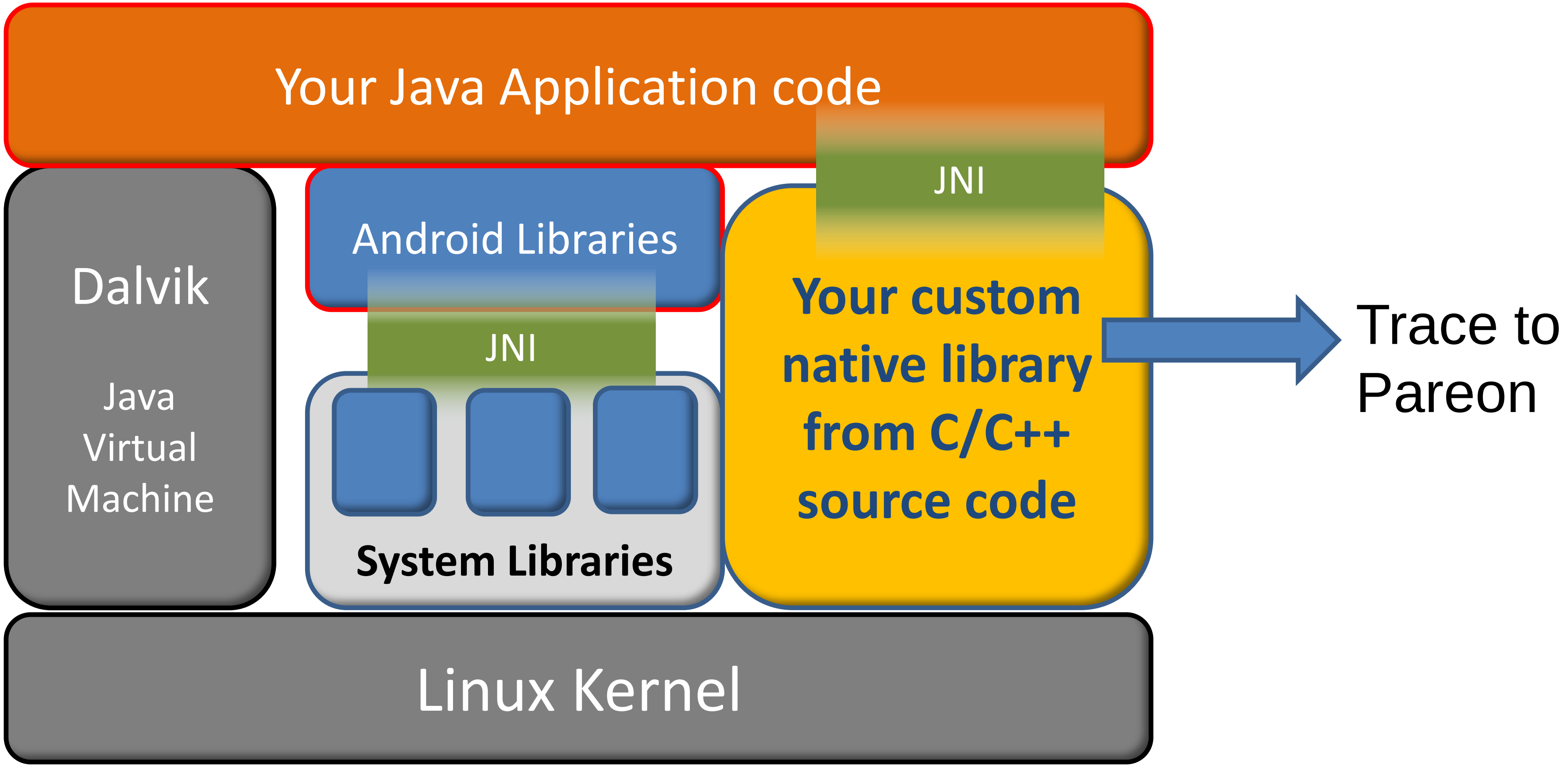
Android Application 1: Plain, just Java



Many apps have no critical CPU load
For now, no Java support in Pareon

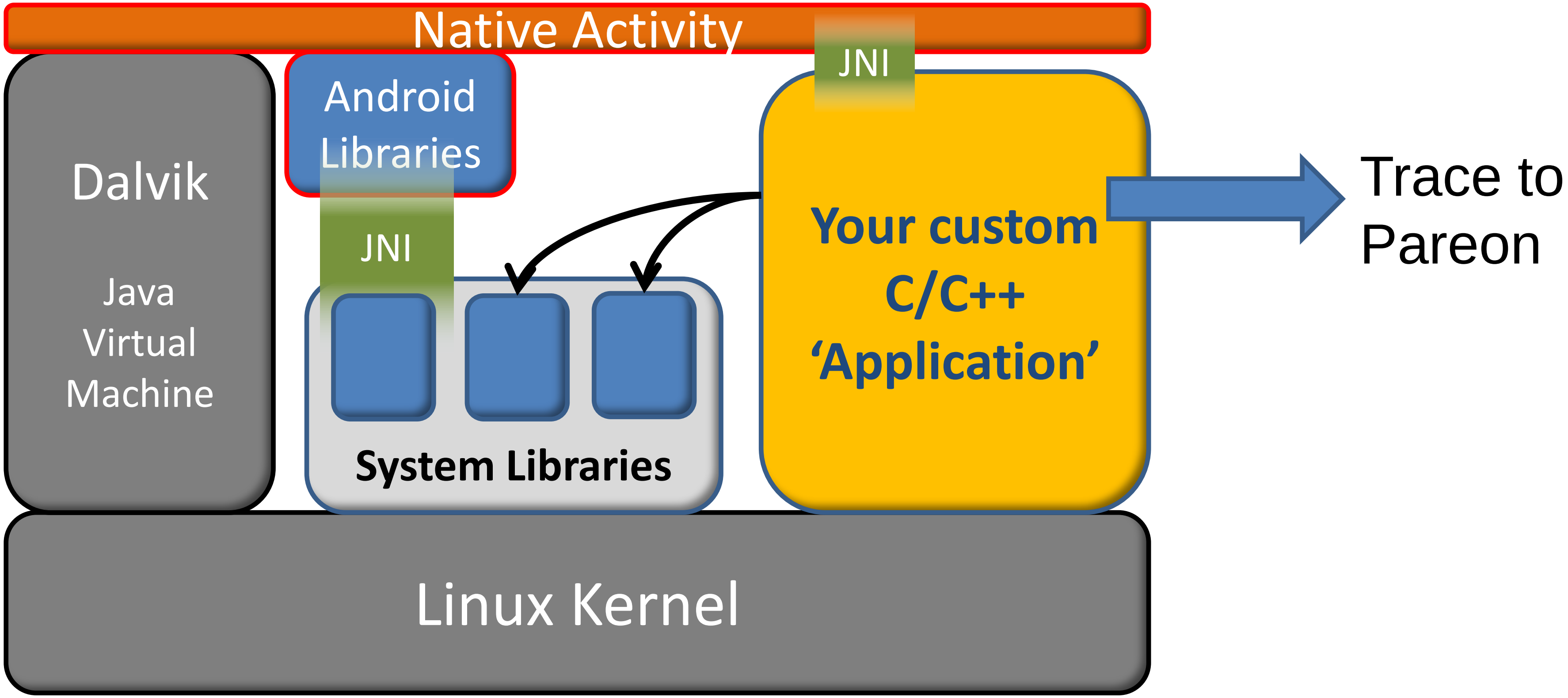
Android Application 2: with native libraries

Apps can include “native” binary code for best performance

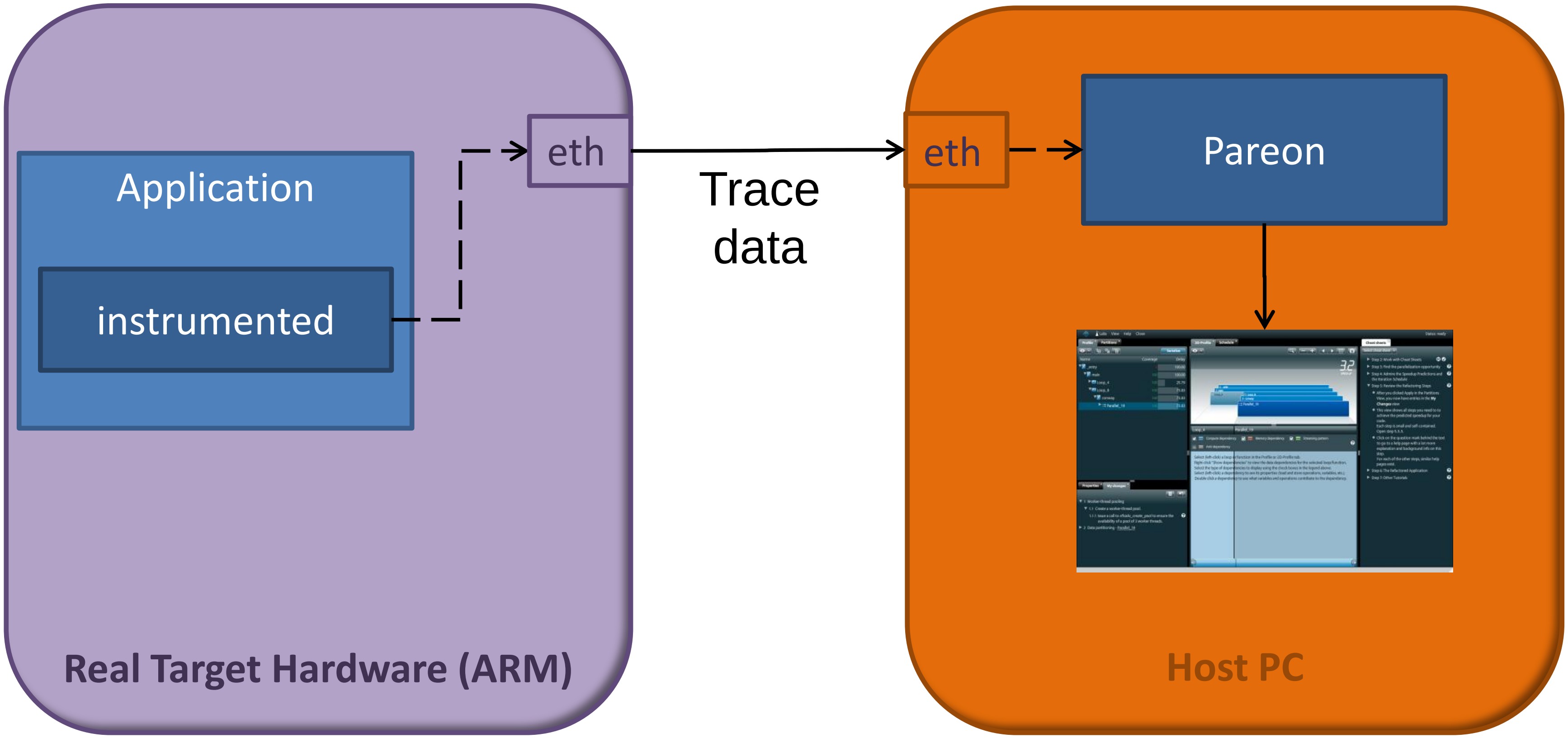


Android Application 3: NativeActivity

“Native activities” are created without Java source code



Application Analysis on Android target



Application

instrumented

eth

Trace data

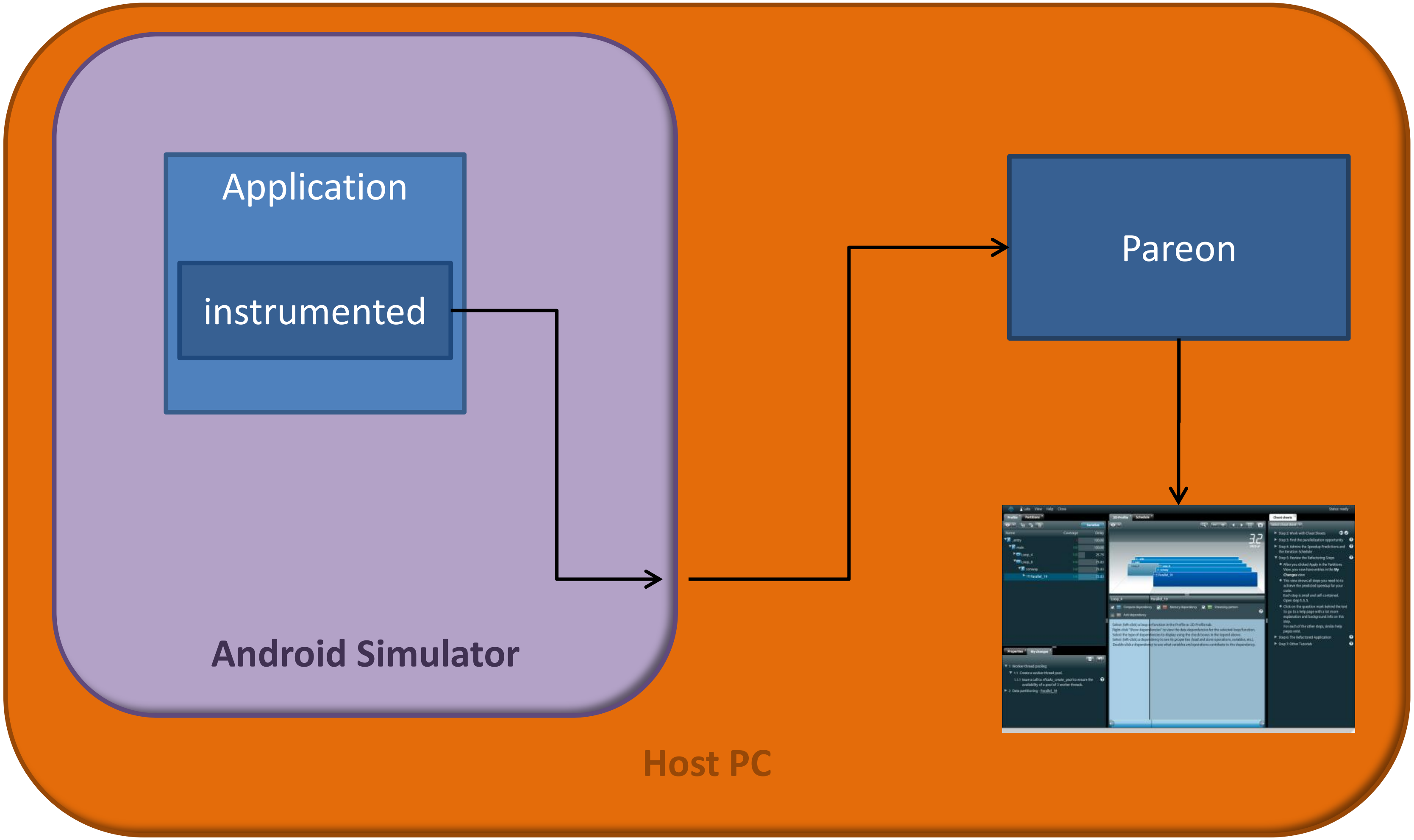
eth

Pareon

Real Target Hardware (ARM)

Host PC

System Setup using Android Simulator



Application

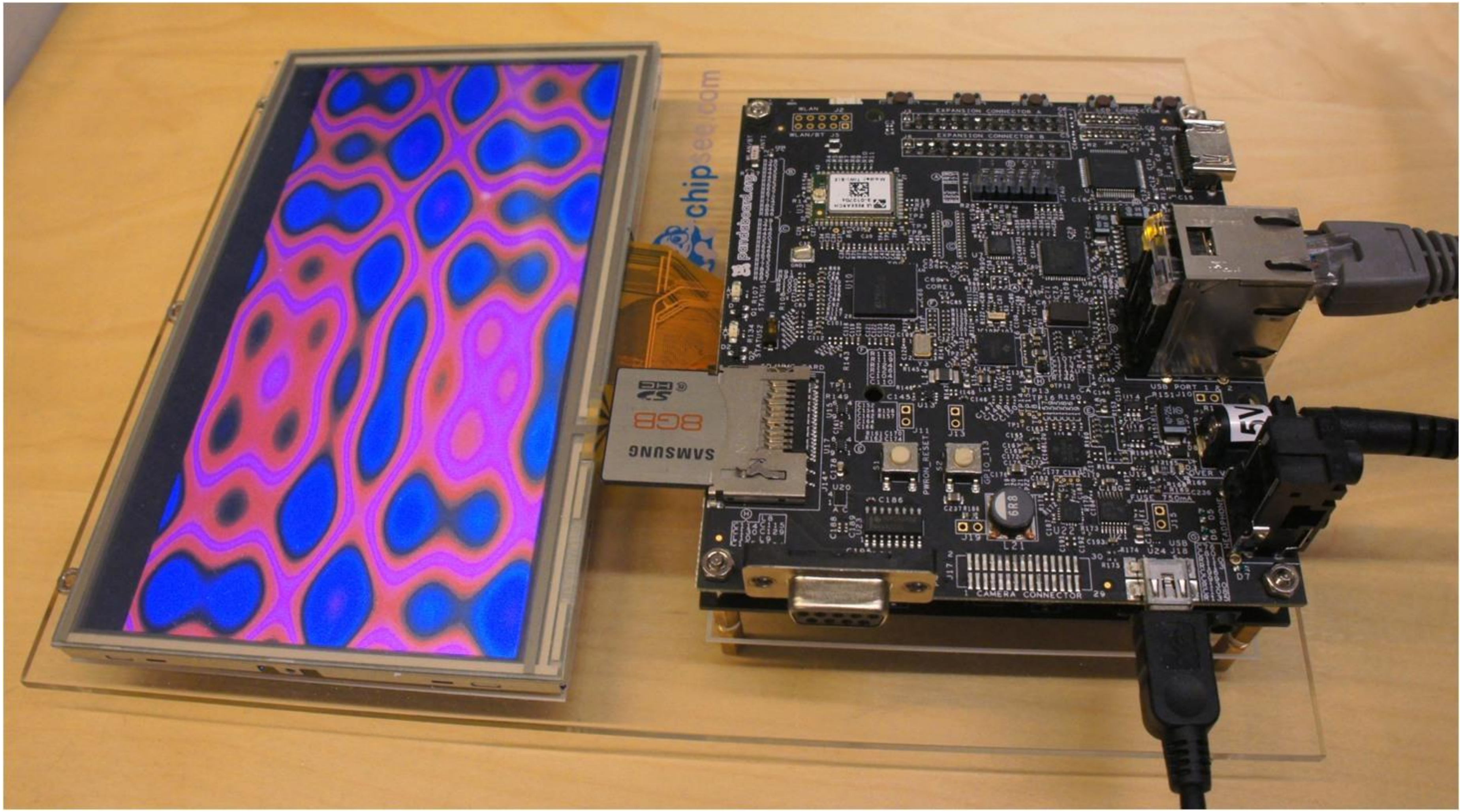
instrumented

Android Simulator

Pareon

Host PC

NDK plasma demo app analyzed on Android



Finding data parallelism on Android

Partitioning candidates - Loop_313

CPU data partitioning - vfTasks

Number of threads 4

Global speedup:	2.4	Extra worker threads:	3
Global overhead:	1 %	Thread creation delay:	420 us

☑ Invocation	Speedup	Overhead	Streams
☑ Loop_120	4.0	1 %	0
☑ Loop_189	4.0	1 %	0
☑ Loop_313	3.9	1 %	0

Property	Value
Compute dependency 313.46	
Ignore with data partitioning	induction expression
Source	
Operation (+)	Loop_313 (fill_plasma)
Location	plasma.c:211
Destinations	
#loop-carried transfers	68.2 Ki transfers/s
Loop carried	yes

☑ Compute dependency ☑ Memory dependency ☑ Streaming pattern

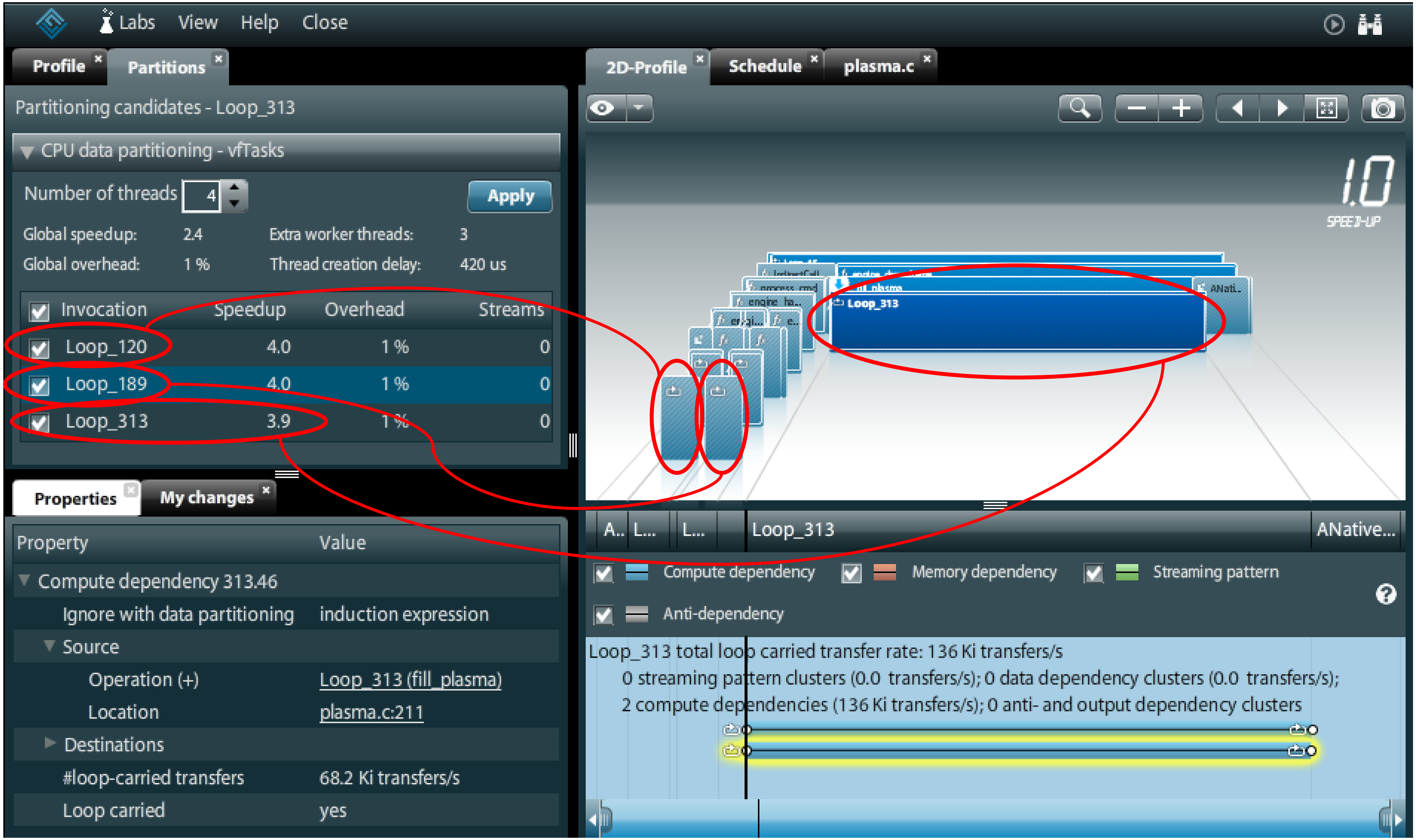
☑ Anti-dependency

Loop_313 total loop carried transfer rate: 136 Ki transfers/s

0 streaming pattern clusters (0.0 transfers/s); 0 data dependency clusters (0.0 transfers/s);

2 compute dependencies (136 Ki transfers/s); 0 anti- and output dependency clusters

Finding data parallelism on Android



Partitioning candidates - Loop_313

CPU data partitioning - vfTasks

Number of threads: 4

Global speedup: 2.4

Extra worker threads: 3

Global overhead: 1 %

Thread creation delay: 420 us

☑ Invocation	Speedup	Overhead	Streams
☑ Loop_120	4.0	1 %	0
☑ Loop_189	4.0	1 %	0
☑ Loop_313	3.9	1 %	0

Property	Value
Compute dependency 313.46	
Ignore with data partitioning	induction expression
Source	
Operation (+)	Loop_313 (fill_plasma)
Location	plasma.c:211
Destinations	
#loop-carried transfers	68.2 Ki transfers/s
Loop carried	yes

☑ Compute dependency ☑ Memory dependency ☑ Streaming pattern ☑ Anti-dependency

Loop_313 total loop carried transfer rate: 136 Ki transfers/s

0 streaming pattern clusters (0.0 transfers/s); 0 data dependency clusters (0.0 transfers/s);

2 compute dependencies (136 Ki transfers/s); 0 anti- and output dependency clusters

Finding data parallelism on Android

Partitioning candidates - Loop_313

CPU data partitioning - vfTasks

Number of threads: 4

Global speedup: 2.4
Extra worker threads: 3
Global overhead: 1 %
Thread creation delay: 420 us

☑ Invocation	Speedup	Overhead	Streams
☑ Loop_120	4.0	1 %	0
☑ Loop_189	4.0	1 %	0
☑ Loop_313	3.9	1 %	0

Property	Value
Compute dependency 313.46	
Ignore with data partitioning	induction expression
Source	
Operation (+)	Loop_313 (fill_plasma)
Location	plasma.c:211
Destinations	
#loop-carried transfers	68.2 Ki transfers/s
Loop carried	yes

☑ Compute dependency ☑ Memory dependency ☑ Streaming pattern

☑ Anti-dependency

Loop_313 total loop carried transfer rate: 136 Ki transfers/s

0 streaming pattern clusters (0.0 transfers/s); 0 data dependency clusters (0.0 transfers/s);

2 compute dependencies (136 Ki transfers/s); 0 anti- and output dependency clusters

Not parallelized: JNI call to render frame

Name	Cover...	Delay
ANativeWindow_lock		6.05
__android_log_print		0.00
stats_startFrame	100	0.07
clock_gettime		0.23
fill_plasma	70	42.10
Parallel_370	64	42.10
ANativeWindow_unlockAndPost		26.17
stats_endFrame	93	1.61

☑ Compute dependency ☑ Memory dependency ☑ Streaming pattern

☑ Anti-dependency

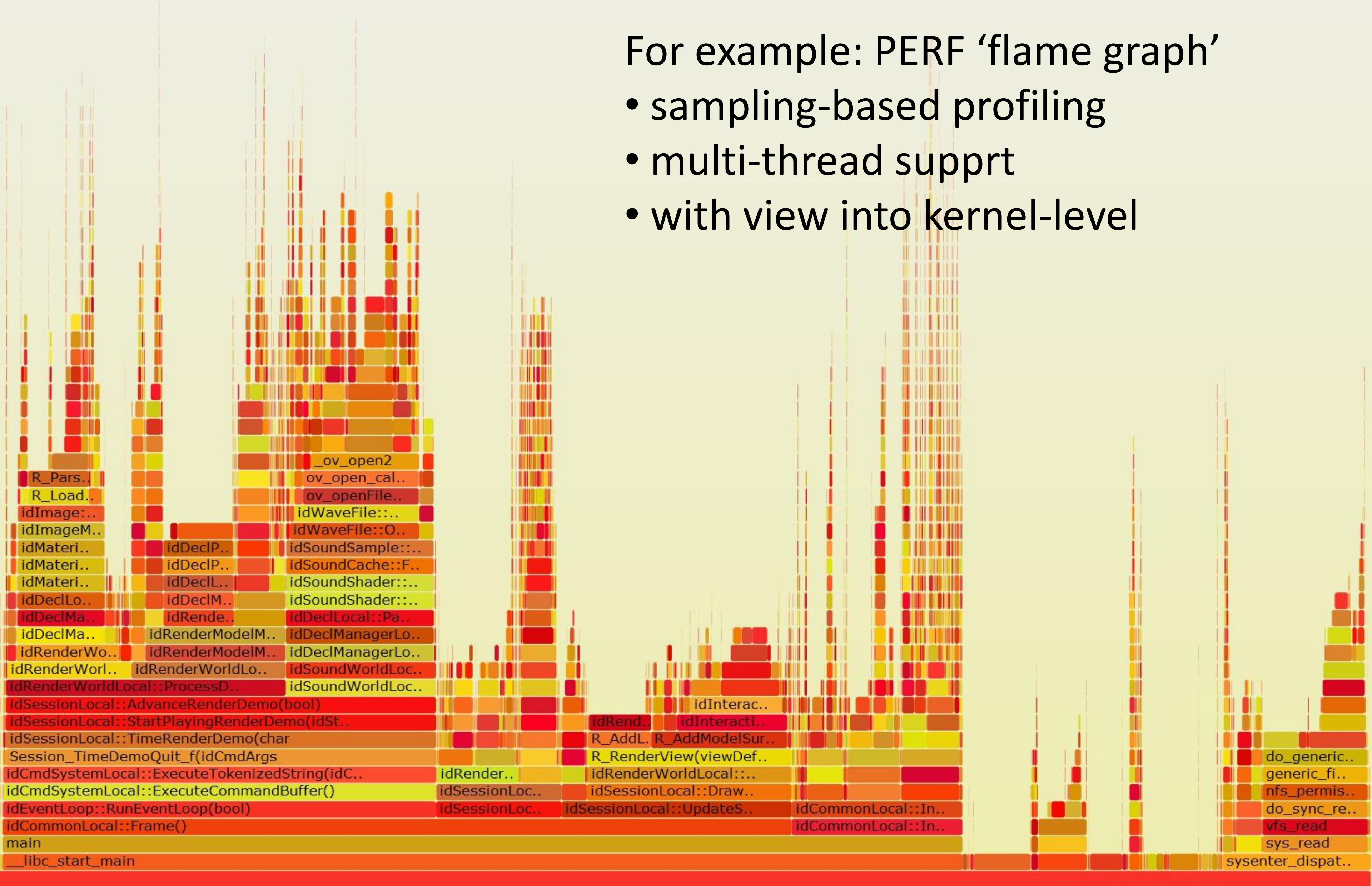
Select (left-click) a loop or function in the Profile or 2D-Profile tab.
Right-click i.e. "Show internal dependencies" to view the internal data dependencies for the selected loop/function.
Select the type of dependencies to display using the check boxes in the legend above.
Select (left-click) a dependency to see its properties (load and store operations, variables, etc.).

Property	Value
ANativeWindow_unlockAndF	
Intrinsic	ANativeWindow_unlockAndPost
Invocation time	
Estimated	1.9 ms
Constraint	<delay> ns
Invocation statistics	
Mapped to Instance	ARM-A9
Call location	plasma.c:407

Performance Verification

For example: PERF ‘flame graph’

- sampling-based profiling
- multi-thread supprt
- with view into kernel-level



Conclusion

Today's gap:

- Multi-core CPUs are everywhere,
- Yet multi-threaded programming remains hard:
  - Risk of creating hard-to-locate bugs regarding dynamic data races and semaphore issues
  - Obtained speedup is lower then expected

- A sequential functional reference implementation ...
  ... helps to set a baseline for parallelization

- Android sets a new record in development complexity
- Proper tooling is needed to save on edit-verify development cycles

Questions?

Today's gap:

- Multi-core CPUs are eve e.
- Yet multi-threaded pro amming mains hard:
  - Risk of creating ha d-to-locat ugs regarding dynamic data races and semaphore issu
  - Obtained speedup is lo hen expected

- A sequential functional reference implementation ...
  ... helps to set a baseline r parallelization

- Android sets a new record in development complexity
- Proper tooling is needed to save on edit-verify development cycles

Check www.vectorfabrics.com for a free demo on concurrency analysis

Thank you!