Scalable Identification of Load Imbalance in Parallel Executions Using Call Path Profiles

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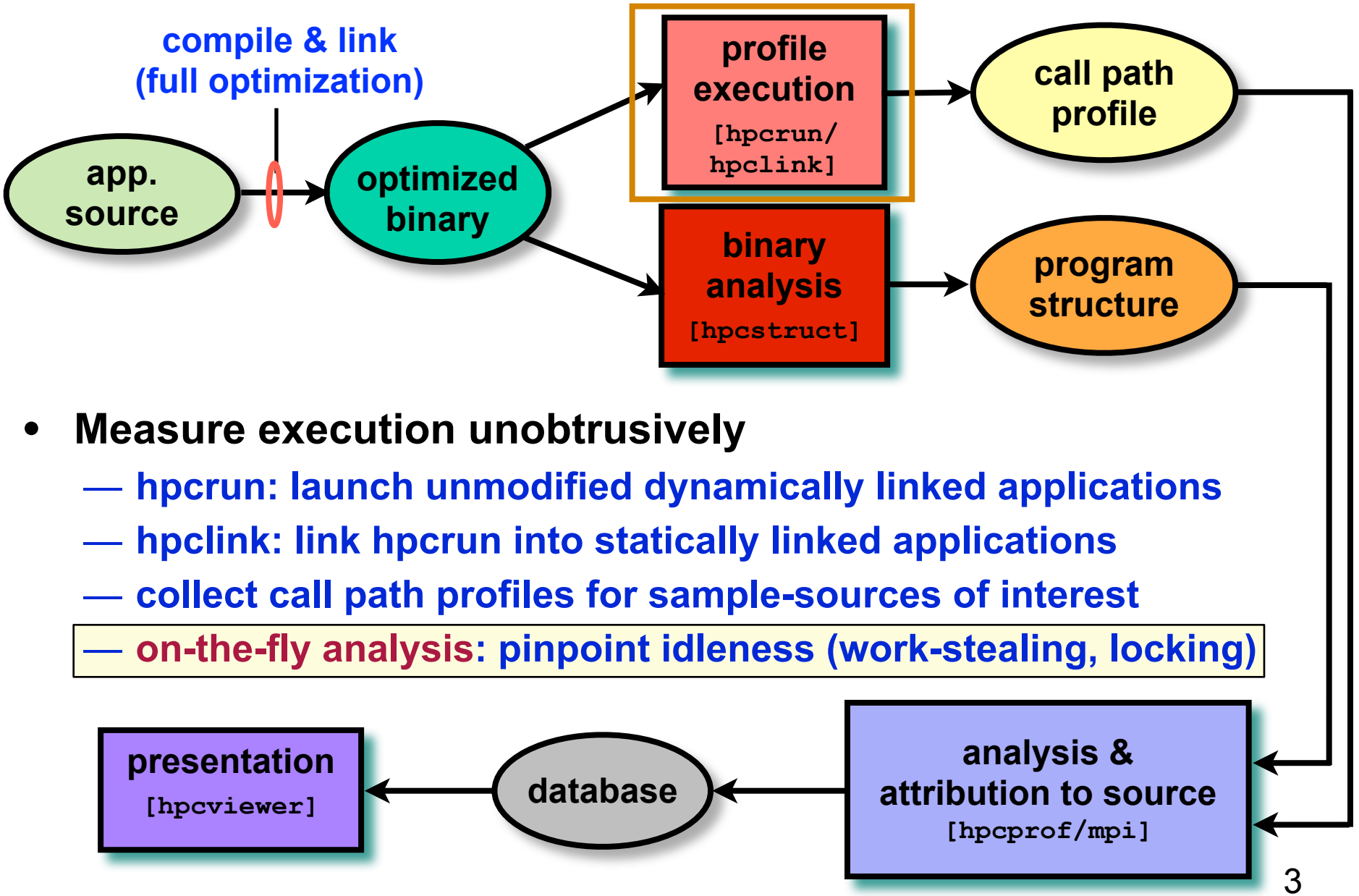
HPCToolkit Performance Tools

- Work at binary level for language independence
  - unmodified, fully optimized codes w/ binary-only libraries
- Asynchronous-sampling-based measurement
  - minimize overhead and distortion; avoid blind spots
  - compact data: well-suited for large-scale parallelism
- Collect and correlate multiple performance metrics
  - diagnosis requires more than one species of metric
  - derived metrics: "unused bandwidth" rather than "cycles"
  - 'third-party' metrics: if thread *x* affects *y*, then blame *x*
- Associate metrics with both static and dynamic context
  - loop nests, procedures, inlined code, calling context
- Support top-down performance analysis
  - avoid overwhelming with the details

HPCToolkit Workflow

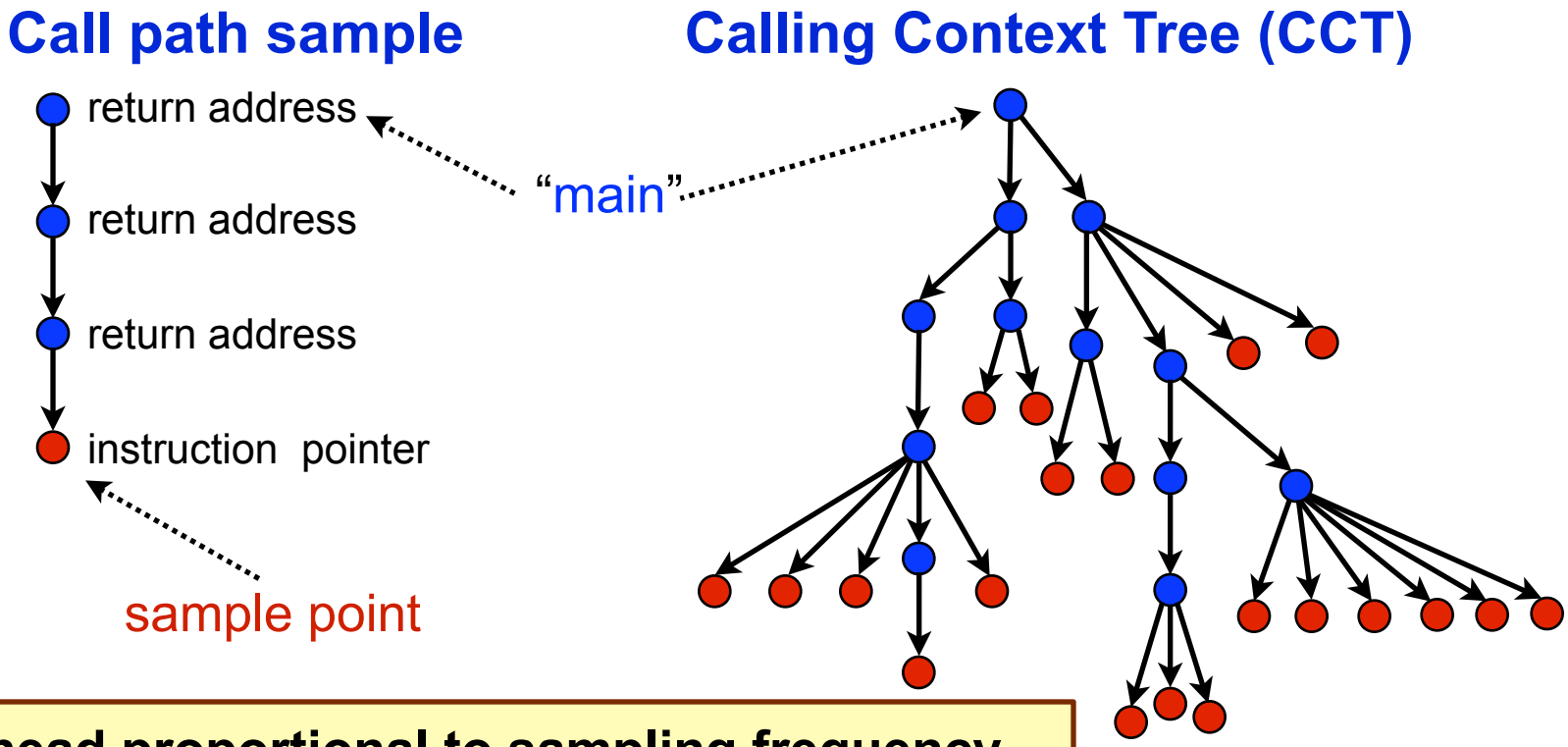


- **Measure execution unobtrusively**
  - hpcrun: launch unmodified dynamically linked applications
  - hpclink: link hpcrun into statically linked applications
  - collect call path profiles for sample-sources of interest
  - on-the-fly analysis: pinpoint idleness (work-stealing, locking)

Call Path Profiling

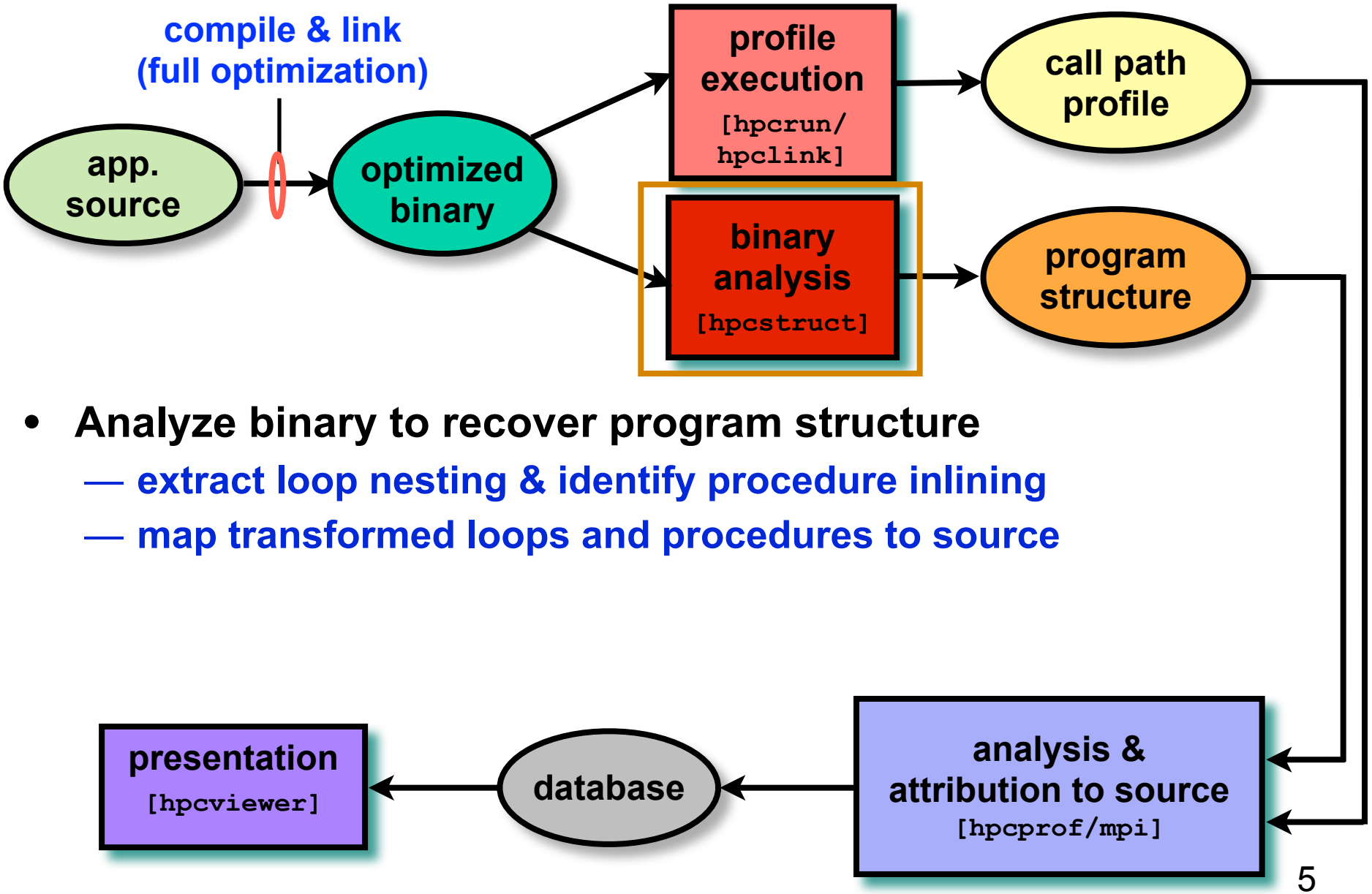
Measure and attribute costs in their *calling* context

- **Sample timer or hardware counter overflows**
- **Gather calling context using stack unwinding**



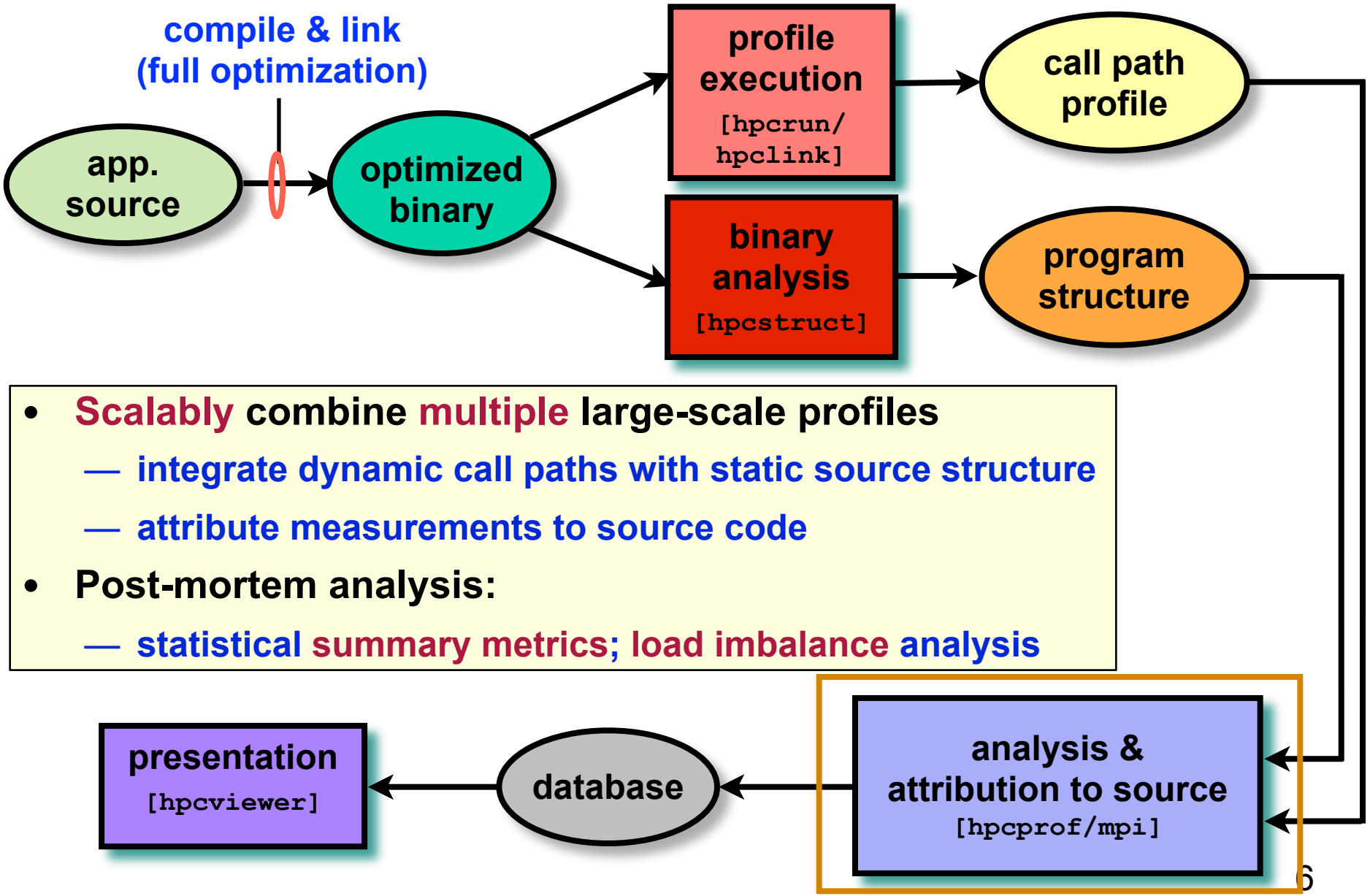
Overhead proportional to sampling frequency...
...not call frequency

HPCToolkit Workflow



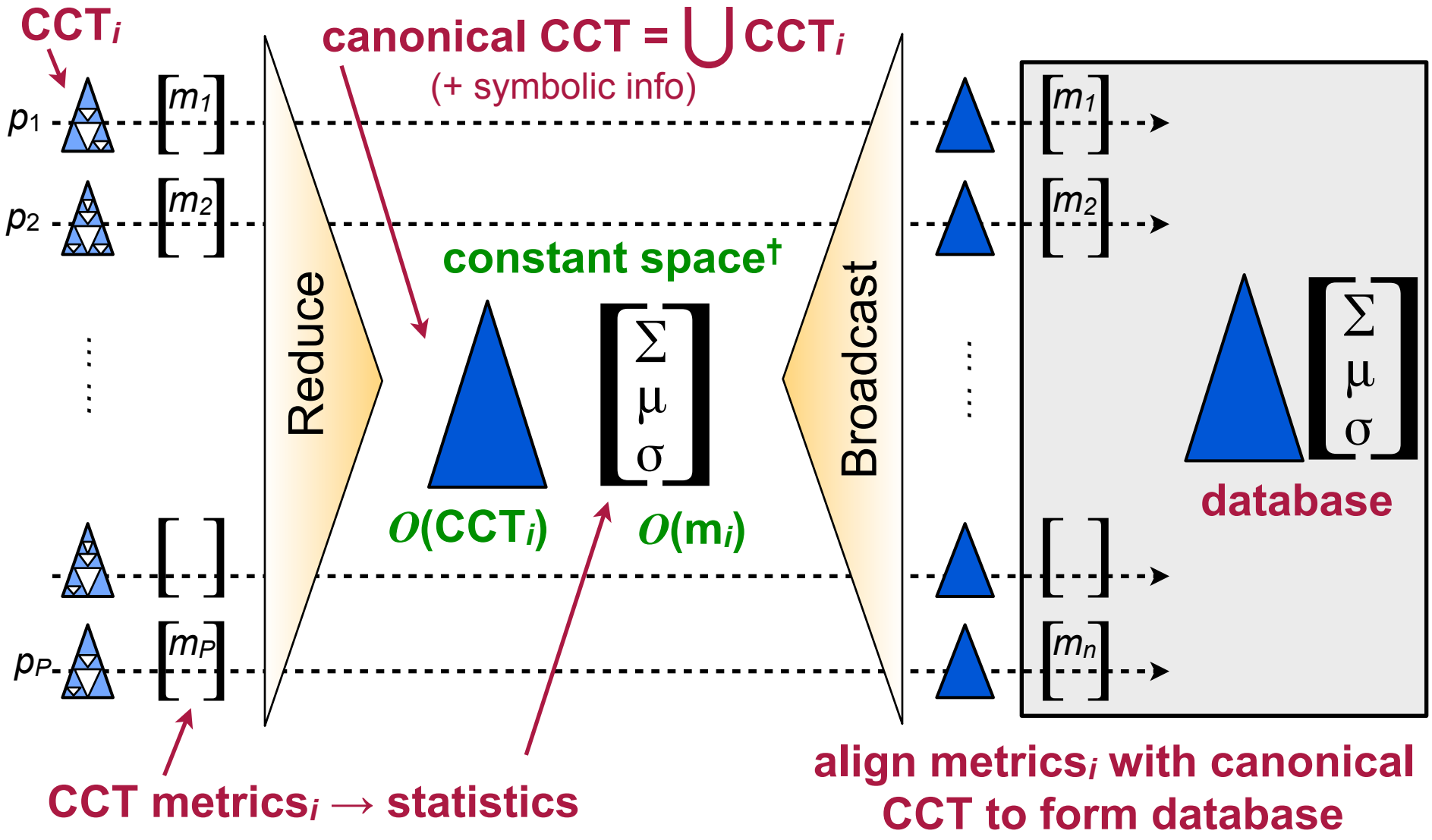
- Analyze binary to recover program structure
  - extract loop nesting & identify procedure inlining
  - map transformed loops and procedures to source

HPCToolkit Workflow



- Scalably combine multiple large-scale profiles
  - integrate dynamic call paths with static source structure
  - attribute measurements to source code
- Post-mortem analysis:
  - statistical summary metrics; load imbalance analysis

Scalably* Combining A Large-Scale Profile

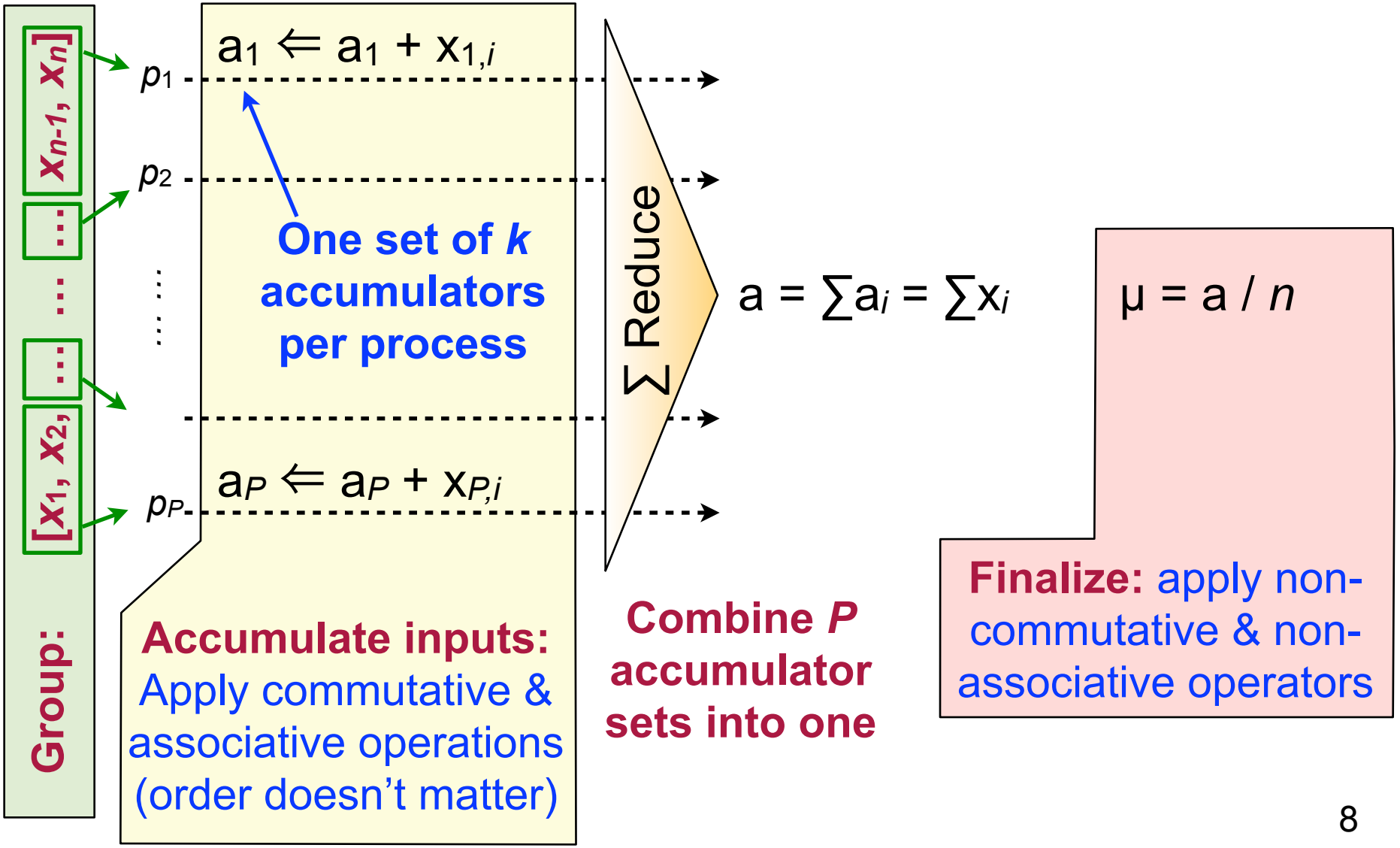


* Yes, I know 'scalably' is not a word — but it should be.

† SPMD apps

Scalably Computing Statistics

Simple example: Given $x_1, \ldots, x_n$, compute arithmetic mean μ



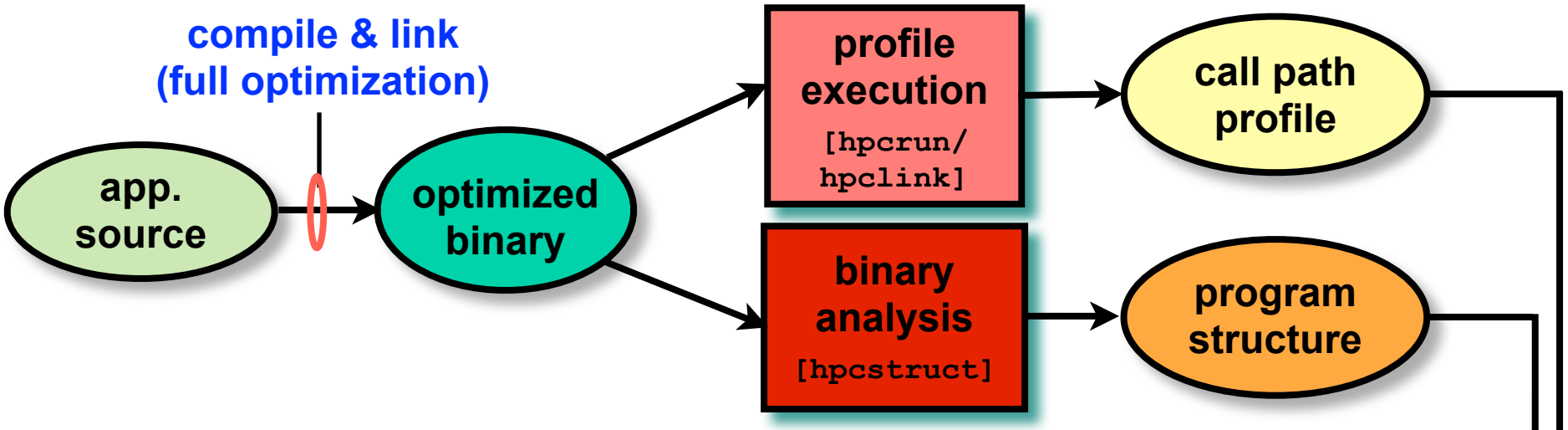
Details: PFLOTRAN @ 8K cores, JaguarPF

- **hpcrun generates a (binary) file per-thread**
  - size of output: 7.2 GB (0.9 MB/process)
  - overhead: 3% (230 smpl/sec)
    - relative to unmonitored execution of 15.3 minutes
  - todo:
    - use parallel I/O (e.g., SIONlib)
    - apply sampling at multiple levels
- **hpcprof-mpi**
  - size of data: 3.6 GB
  - execution times: →

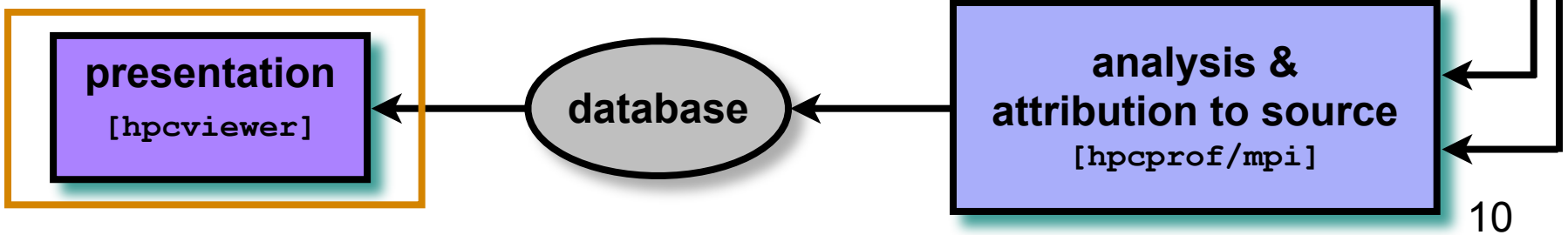
24 cores:	13.0 minutes
48 cores:	8.0 minutes
96 cores:	5.5 minutes

  - filters 'uninteresting' CCT paths
    - filter CCT node *n* if for all (additive) metrics m and all threads *t*:
      - $\sum_{t \in \text{threads}} \mathrm{m}_I(n,t) < .001\% \sum_{t \in \text{threads}} \mathrm{m}_I(root,t)$ (I: inclusive)
  - todo: exploit sparsity of thread-level metric database

HPCToolkit Workflow

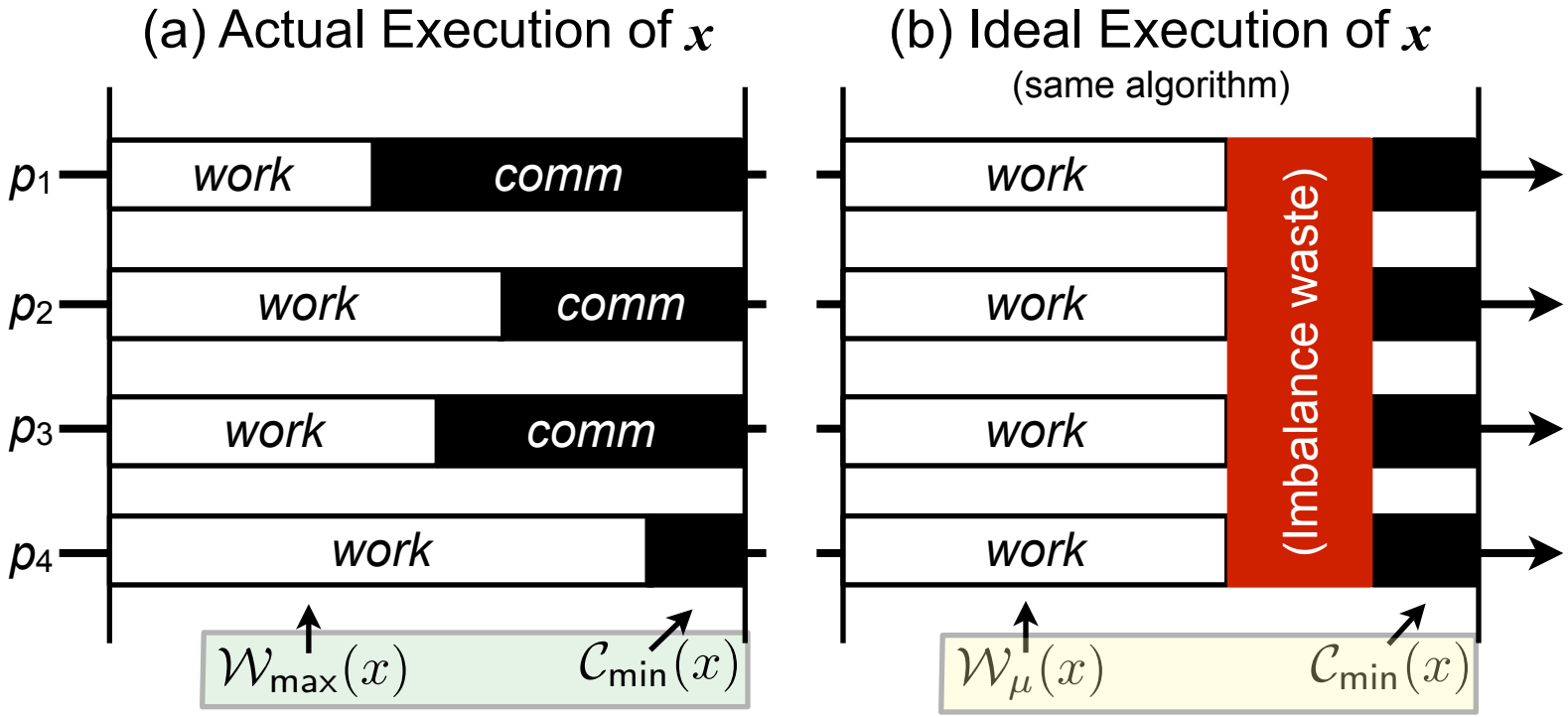


- **Presentation**
  - support top-down analysis with interactive viewer
  - show context-sensitive metrics in three views
  - generate plots of context-sensitive thread-level values
  - analyze results anytime, anywhere



Analyzing Load Imbalance Post-Mortem

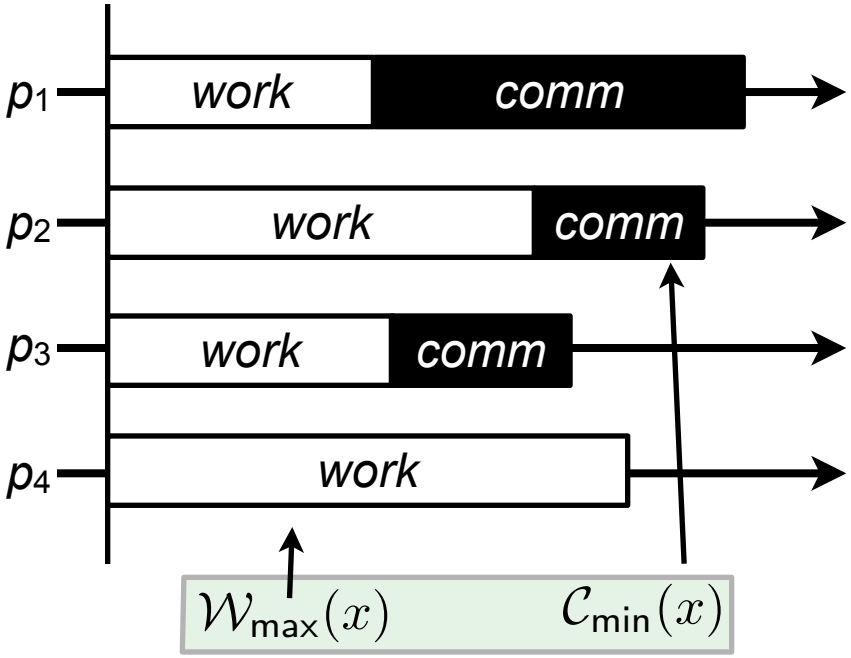
Given a synchronized procedure x, compute imbalance waste, $\overline{\mathcal{B}}(x)$



$$\overline{\mathcal{B}}(x) = \mathcal{W}_{\max}(x) + \mathcal{C}_{\min}(x) - [\mathcal{W}_{\mu}(x) + \mathcal{C}_{\min}(x)] = \mathcal{W}_{\max}(x) - \mathcal{W}_{\mu}(x)$$

(time of actual exe) (time of ideal exe) (imbalance waste)

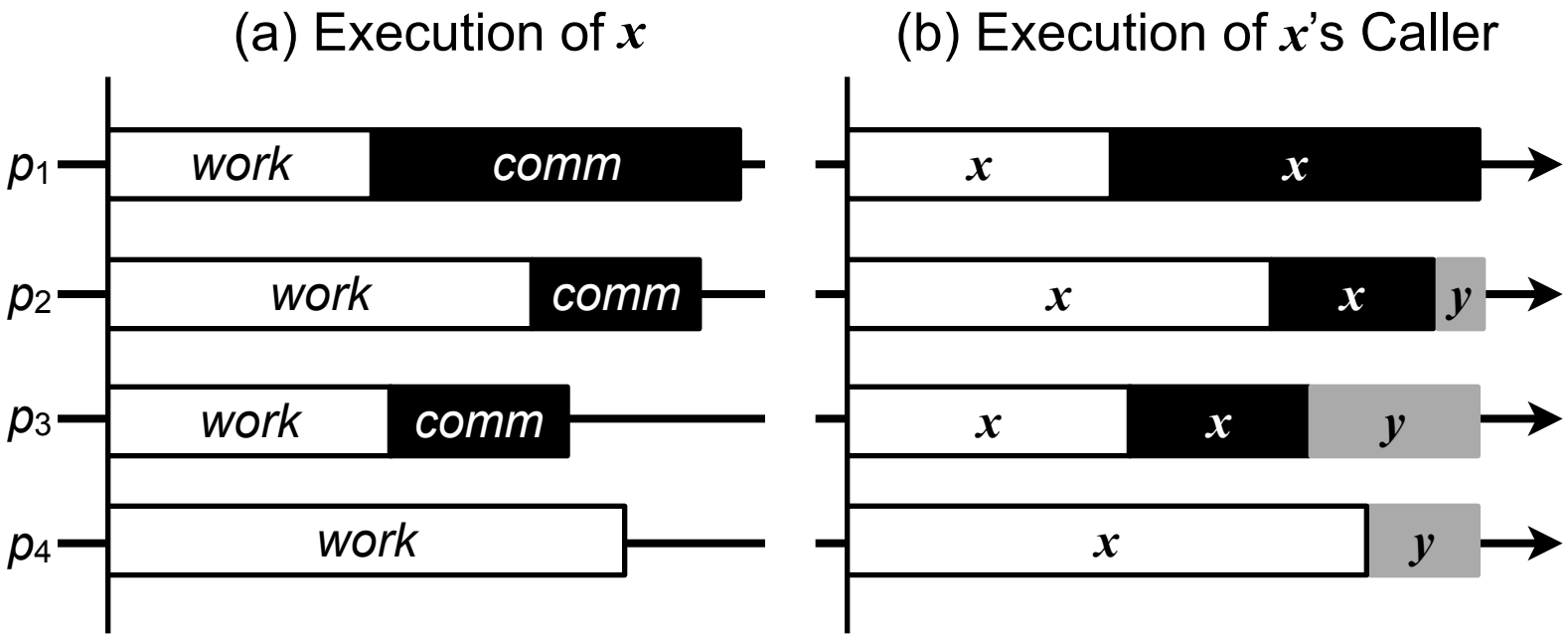
What If Procedure Is Not Synchronized?



- **Cannot use prior equation to compute imbalance waste**
  - **e.g.:** $\mathcal{W}_{\max}(x) + \mathcal{C}_{\min}(x) \neq$ **time of actual execution**
- **May be *fine* that procedure x is imbalanced!**
  - **E.g.: each process performs different amount of work for x...**
    - **...but is balanced at a x's caller**

Imbalanced vs. Balanced Procedures

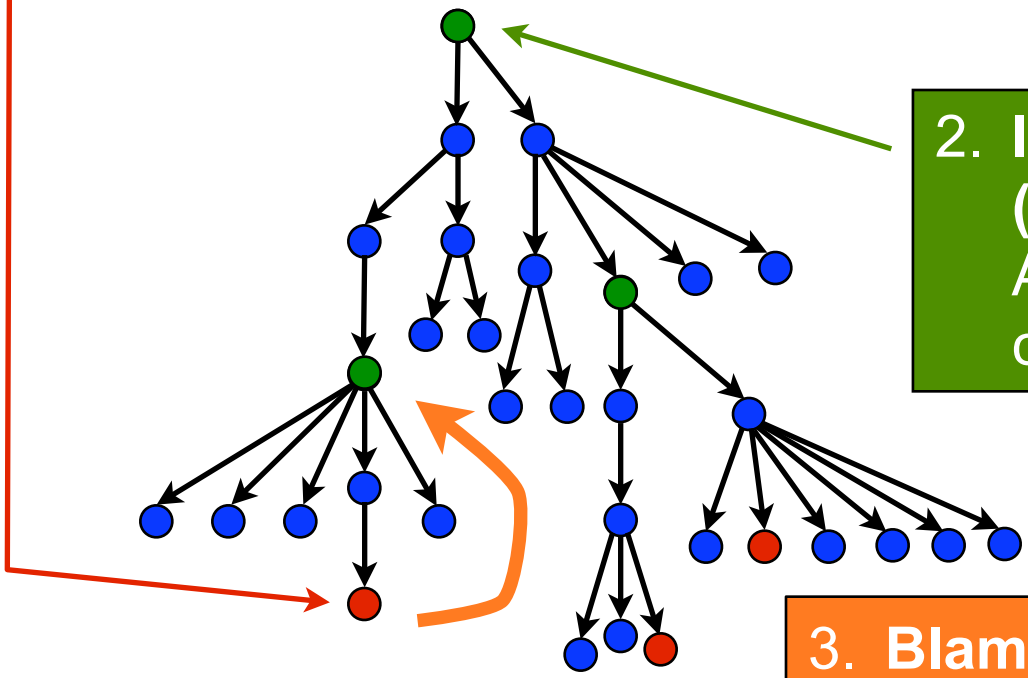
- **Cannot apply prior equation to left (a), but *could* to right (b)**



- **Challenge: compute imbalance waste in its *calling context***
  - **For what contexts can we compute imbalance waste?**
  - **Can we identify waste *more precisely* than using differences in communication time?**

Blame-Shift Idleness in Call Path Profiles

1. **Identify idleness (exposed waiting):** All imbalance is manifested in idleness (e.g., MPI_Cray_Progress_Wait)



2. **Identify balance points (procedures or loops):** A balance point cannot contribute to imbalance

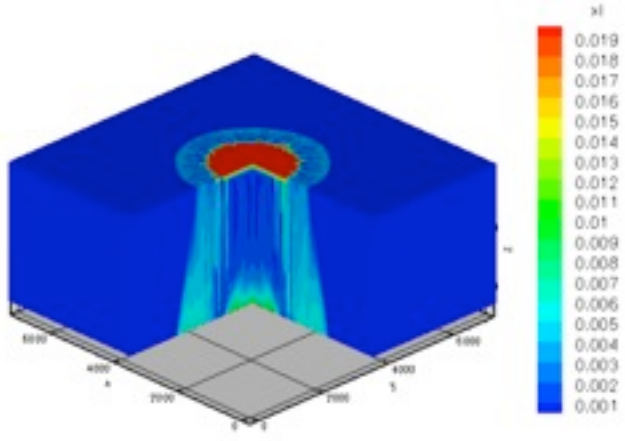
3. **Blame-shift** idleness (effect) on closest ancestor balance point (nearer to cause)

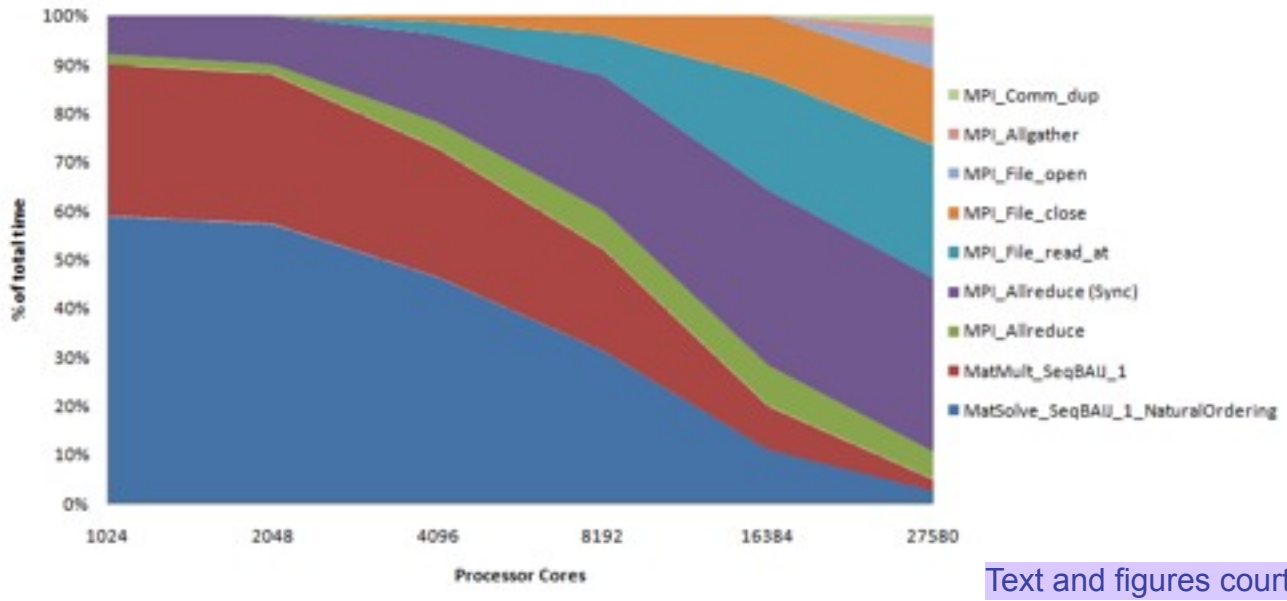
4. Scatter plots of thread-level CCT metrics help expose patterns.

Demo: Load Imbalance

PFLOTRAN: modeling multi-scale, multiphase, multi-component subsurface reactive flows

Example use: modeling sequestration of CO_2 in deep geologic formations, where resolving density-driven fingering patterns is necessary to accurately describe the rate of dissipation of the CO_2 plume





Strong scaling study on Cray XT

Text and figures courtesy of PFLOTRAN Team

PFLOTRAN

8K cores, Cray XT5

1. Drill down 'hot path' to loop (a balance point)

2. Notice top two call sites...

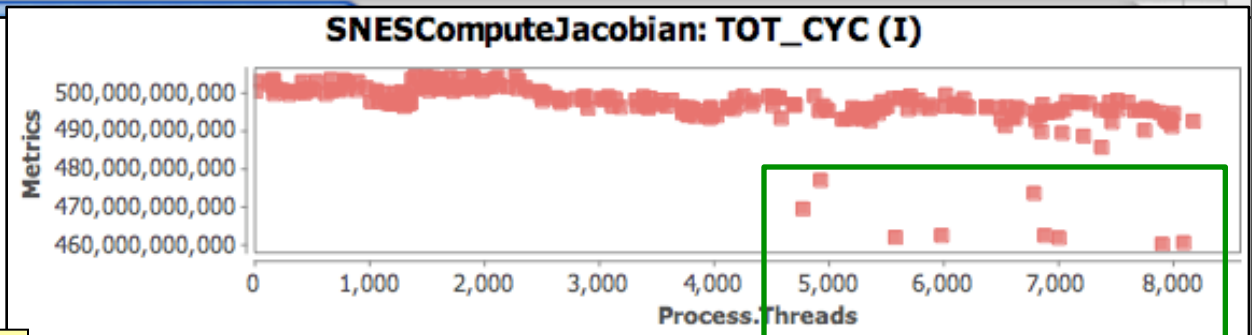
3. Plot the per-process values:

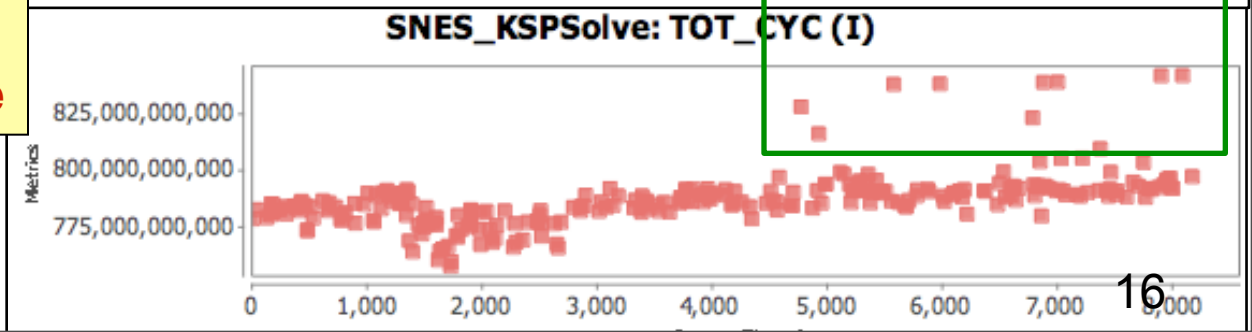
Early finishers...

...become early arrivers at Allreduce

	imbalance (I)	TOT_CYC:Sum (I)	
pflotran	5.28e+15	1.85e+16	100 %
timestepper_module_stepperrun_	5.17e+15	1.82e+16	98.3%
loop at timestepper.F90: 384	5.17e+15	1.82e+16	98.2%
timestepper_module_steppersteptransportdt_	2.22e+15	1.33e+16	72.0%
loop at timestepper.F90: 1230	2.22e+15	1.33e+16	72.0%
loop at timestepper.F90: 1254	2.22e+15	1.32e+16	71.3%
snessolve_	2.22e+15	1.30e+16	70.4%
SNESSolve	2.22e+15	1.30e+16	70.4%
SNESSolve_LS	2.22e+15	1.30e+16	70.4%
loop at ls.c: 181	2.15e+15	1.27e+16	68.8%
SNES_KSPSolve	1.19e+15	6.44e+15	34.8%
SNESComputeJacob	6.21e+14	4.07e+15	22.0%

```
189    ierr = SNESComputeJacobian(snes,X,&snes->jacobian,&snes->jacobian_pre,&
190    ierr = KSPSetOperators(snes->ksp,snes->jacobian,snes->jacobian_pre,flg)
191    ierr = SNES_KSPSolve(snes,snes->ksp,F,Y);CHKERRQ(ierr);
```





The End