Dynamic Fine-Grain Scheduling of Pipeline Parallelism

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Executive Summary

- Pipeline-parallel applications are hard to schedule
  - Existing techniques either ignore pipeline parallelism, cannot handle its dependences, or suffer from load imbalance

- Contributions:
  - Design a runtime that dynamically schedules pipeline-parallel applications efficiently
  - Show it outperforms typical scheduling techniques from multicore, GPGPU and Streaming programming models

Outline

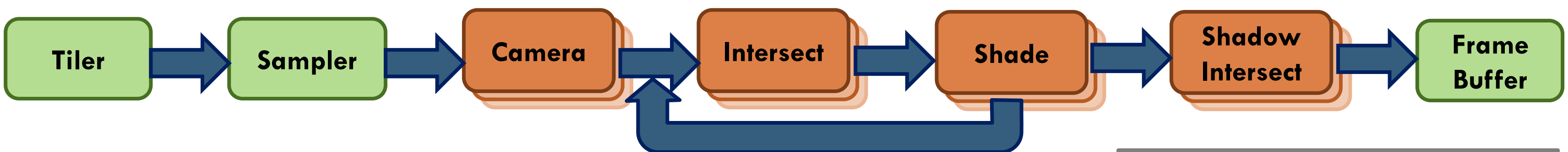
- Introduction
- GRAMPS Programming Model
- GRAMPS Runtime
- Evaluation

High-Level Programming Models

- High-level parallel programming models provide:
  - Simple, safe constructs to express parallelism
  - Automatic resource management and scheduling
- Many aspects; we focus on scheduling
  - Model, scheduler and architecture often intimately related
- In terms of scheduling, three main types of models:
  - Task-parallel models, typical in multicore (Cilk, X10)
  - Data-parallel models, typical in GPU (CUDA, OpenCL)
  - Streaming models, typical in streaming architectures (StreamIt, StreamC)

Pipeline-Parallel Applications

- Some models (e.g. streaming) define applications as a graph of stages that communicate explicitly through queues
  - Each stage can be sequential or data-parallel
  - Arbitrary graphs allowed (multiple inputs/outputs, loops)



Ray tracing pipeline

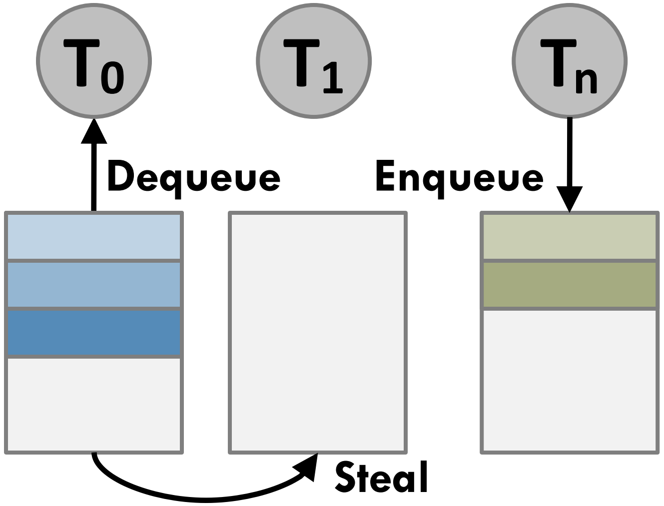
- ✓ Well suited to many algorithms
- ✓ Producer-consumer communication is explicit → Easier to exploit to improve locality
- × Traditional scheduling techniques have issues dynamically scheduling pipeline-parallel applications

Task-Parallel – Task-Stealing

- Model: Task-parallel with fork-join dependences or independent tasks (Cilk, X10, TBB, OpenMP, …)
- Task-Stealing Scheduler:
  - Worker threads enqueue/dequeue tasks from local queue
  - Steal from another queue if out of tasks

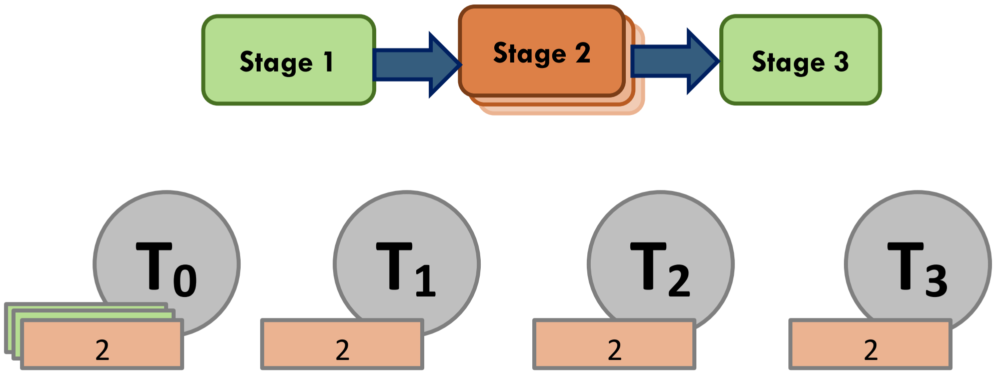
✓ Efficient load-balancing

× Unable to handle dependences of pipeline-parallel programs



Data-Parallel – Breadth-First

- Model: Sequence of data-parallel kernels (CUDA, OpenCL)
- Breadth-First Scheduler: Execute one stage at a time in breadth-first order (source to sink)



✓ Very simple model

✗ Ignores pipeline parallelism → works poorly with sequential stages, worst-case memory footprint

Streaming – Static Scheduling

- Model: Graph of stages communicating through streams
- Static Scheduler:
  - Assume app and architecture are regular, known in advance
  - Use sophisticated compile-time analysis and scheduling to minimize inter-core communication and memory footprint

✓ Very efficient if application and architecture are regular

✗ Load imbalance with irregular applications or non-predictable architectures (DVFS, multi-threading …)

Summary of Scheduling Techniques

	Supports pipeline-parallel apps	Supports irregular apps/archs
Task-Stealing	✘	✓
Breadth-First	✘	✓
Static	✓	✘
GRAMPS	✓	✓

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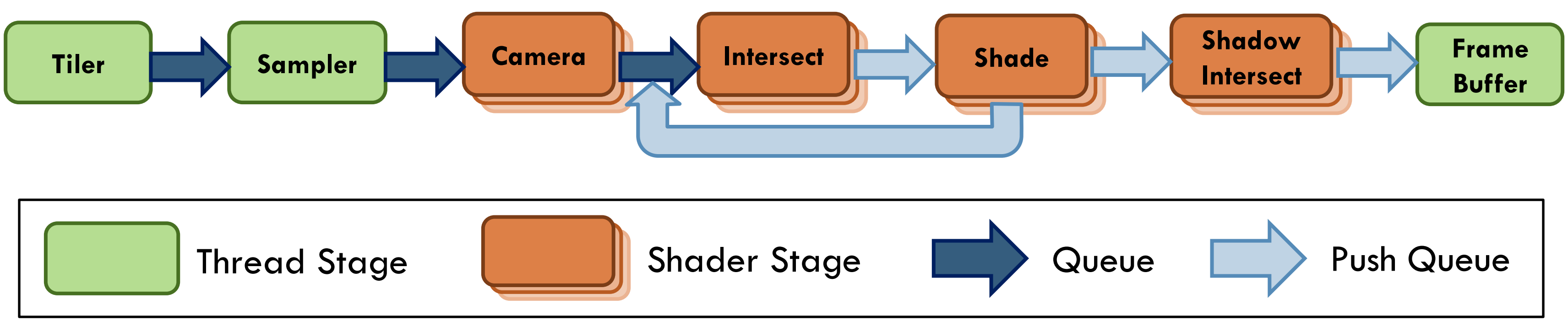
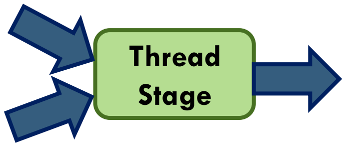
GRAMPS Programming Model

- Programming model for dynamic scheduling of irregular pipeline-parallel workloads
  - Brief overview here, details in [Sugerman 2010]
- Shader (data-parallel) and Thread (sequential) stages
- Stages send packets through fixed-size data queues
  - Queues can be ordered or unordered
  - Can enqueue full packets or push elements (coalesced by runtime)

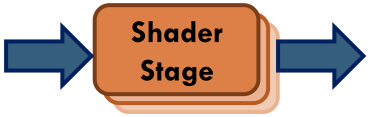


GRAMPS: Threads vs Shaders

- Threads are stateful, instanced by the programmer
  - Arbitrary number of input and output queues
  - Blocks on empty input/full output queue
  - Can be preempted by the scheduler



- Shaders are stateless, automatically instanced
  - Single input queue, one or more outputs
  - Each instance processes an input packet
  - Does not block



GRAMPS Scheduling

- Similar model to Streaming, but features ease dynamic scheduling of irregular applications:
  - Packet granularity → reduce scheduling overheads
  - Stages can produce variable output (e.g., push queues)
  - Data parallel stages, queue ordering are explicit
- Static requires applications to have a steady state; GRAMPS can schedule apps with no steady state
- GRAMPS was evaluated with an idealized scheduler when proposed; we implement a real multicore runtime

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GRAMPS Runtime Overview

- Runtime = Scheduler + Buffer Manager

- Scheduler: Decide what to run where
  - Dynamic, low-overhead, keeps bounded footprint
  - Based on task-stealing with multiple task queues/thread

- Buffer Manager: Provide dynamic allocation of packets
  - Generic memory allocators are too slow for communication-intensive applications
  - Low-overhead solution, based on packet-stealing

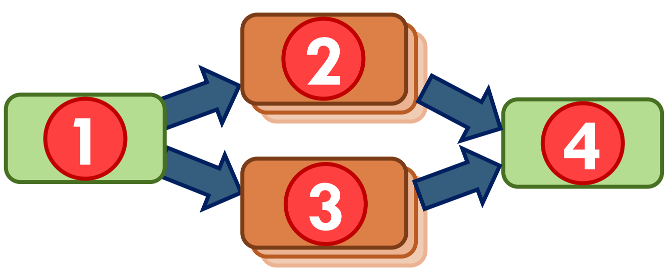
Scheduler organization

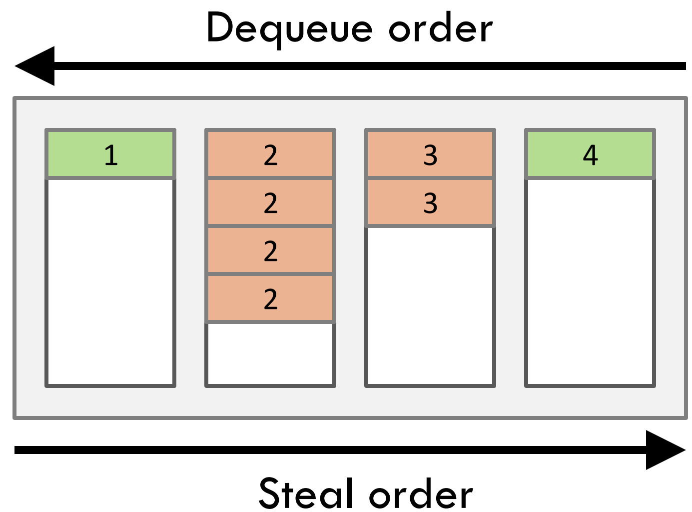
- As many worker pthreads as hardware threads
- Work is represented with tasks

- Shader stages are function calls (stateless, non-preemptive)
  - One task per runnable shader instance
- Thread stages are user-level threads (stateful, preemptive)
  - User-level threads enable fast context-switching (100 cycles)
  - One task per runnable thread

Scheduler: Task Queues

- Load-balancing with task stealing
  - Each thread has one LIFO task queue per stage
  - Stages sorted by breadth-first order (higher priority to consumers)
  - Dequeue from high-priority first, steal low-priority first
    - Higher priority tasks drain the pipeline, improve locality
    - Lower priority tasks produce more work (less stealing)

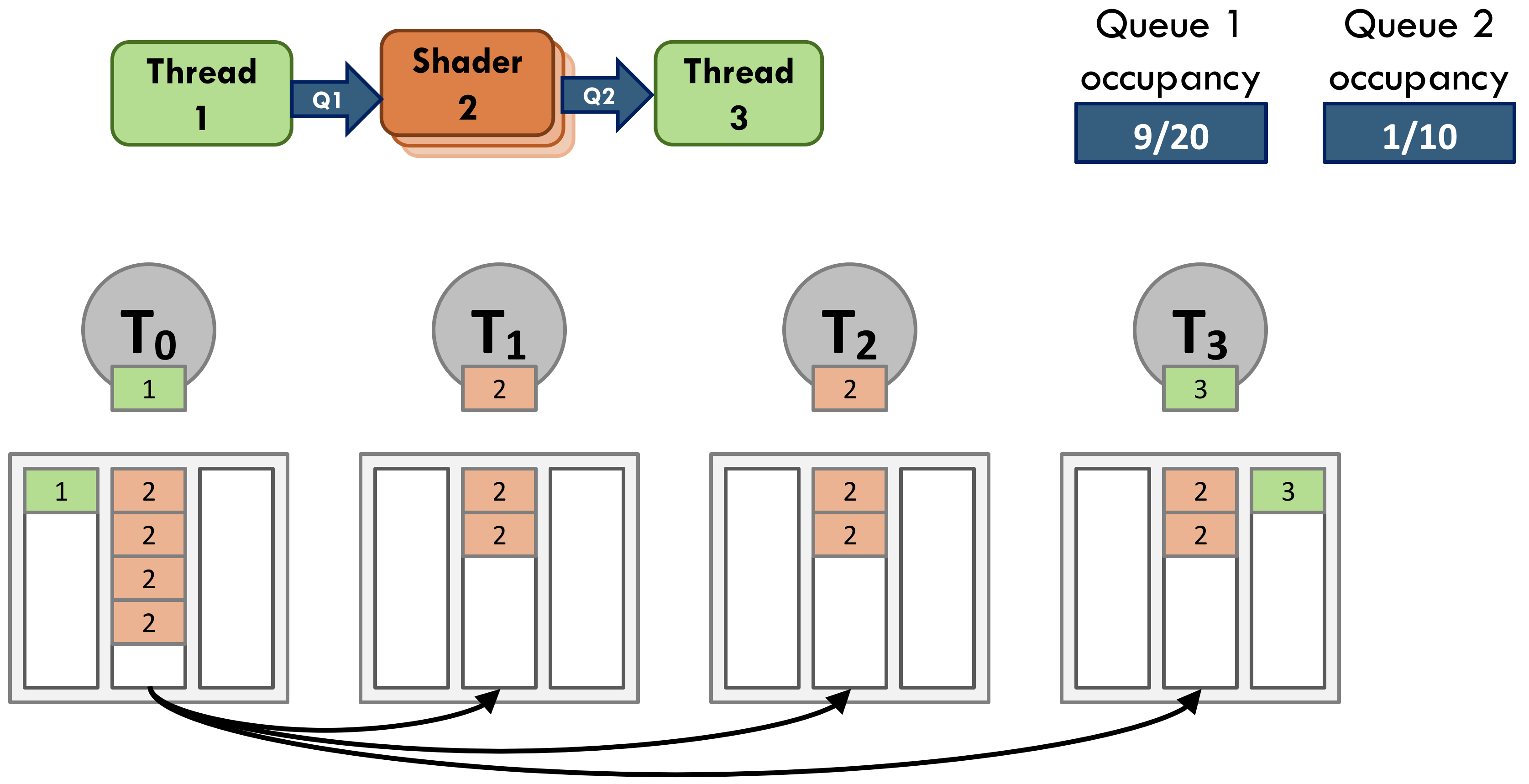




Scheduler: Data Queues

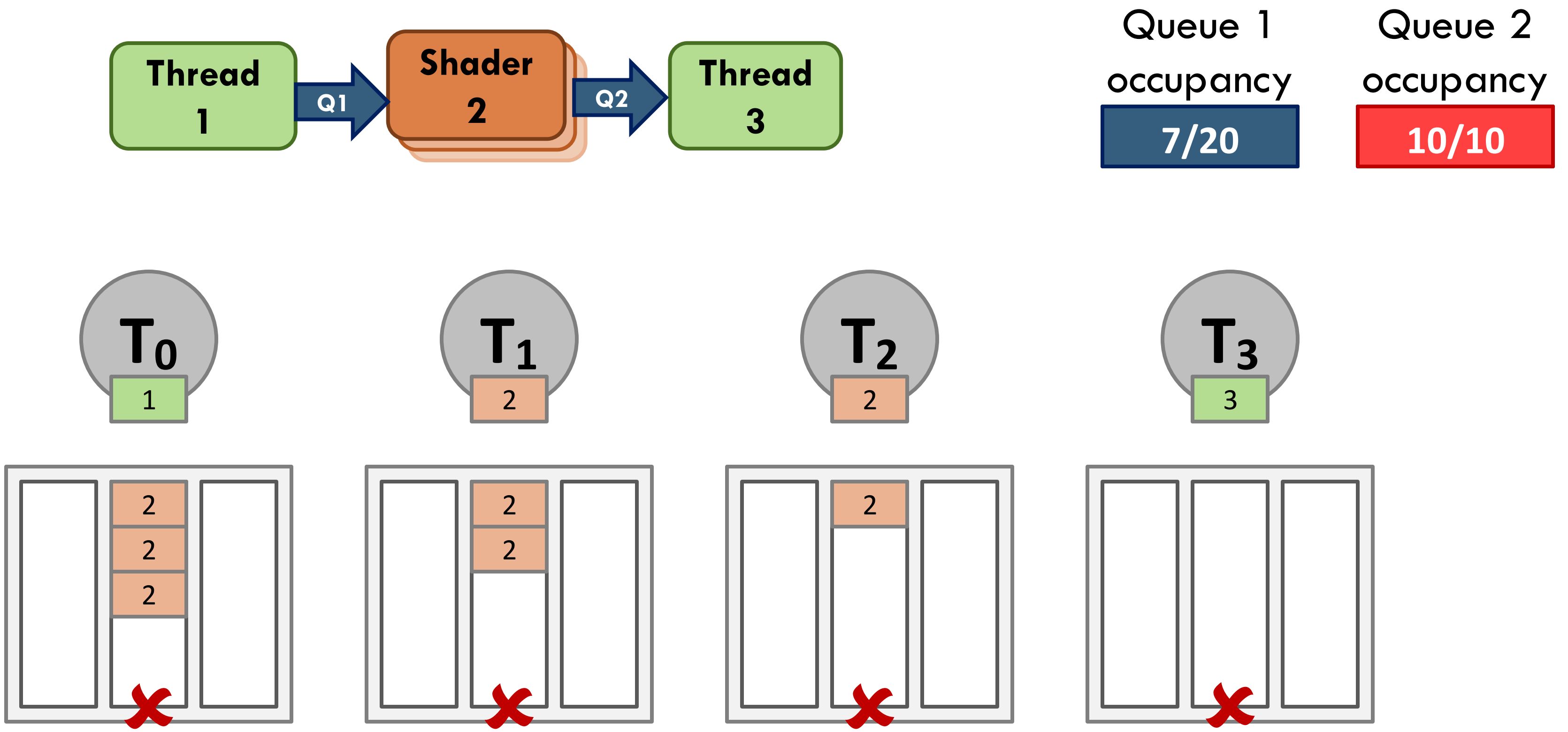
- Thread input queues maintained as linked lists
- Shader input queues implicitly maintained in task queues
  - Each shader task includes a pointer to its input packet
- Queue occupancy tracked for all queues
- Backpressure: When a queue fills up, disable dequeues and steals from queue producers
  - Producers remain stalled until packets are consumed, workers shift to other stages
  - Queues never exceed capacity → bounded footprint
- Queues are optionally ordered (see paper for details)

Example



Thread 1
Q1
Shader 2
Q2
Thread 3
Queue 1 occupancy
9/20
Queue 2 occupancy
1/10
T_0
1
T_1
2
T_2
2
T_3
3
1
2
2
2
2
2
2
2
2
2
2
3

Example (cont.)



Queue 2 full → disable dequeues and steals from Stage 2

Packet-Stealing Buffer Manager

- Packets pre-allocated to a set of pools
  - Each pool has packets of a specific size

- Each worker thread maintains a LIFO queue per pool
  - Release used input packets to local queue
  - Allocate new output packets from local queue, if empty, steal
  - Due to bounded queue sizes, no need to dynamically allocate packets
  - LIFO policy results in high locality and reuse

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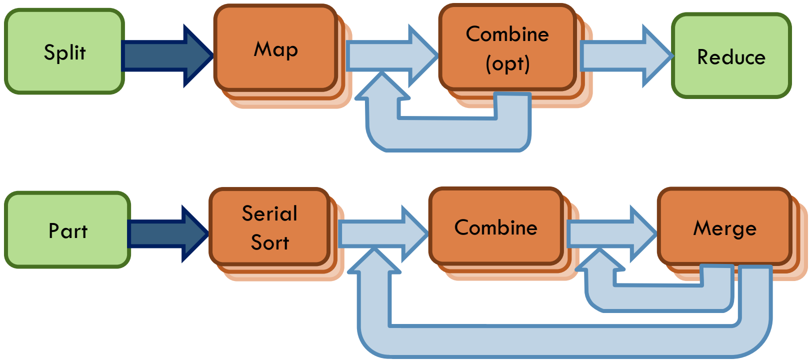
Methodology

- Test system: 2-socket, 12-core, 24-thread Westmere
  - 32KB L1I+D, 256KB private L2, 12MB per-socket L3
  - 48GB 1333MHz DDR3 memory, 21GB/s peak BW

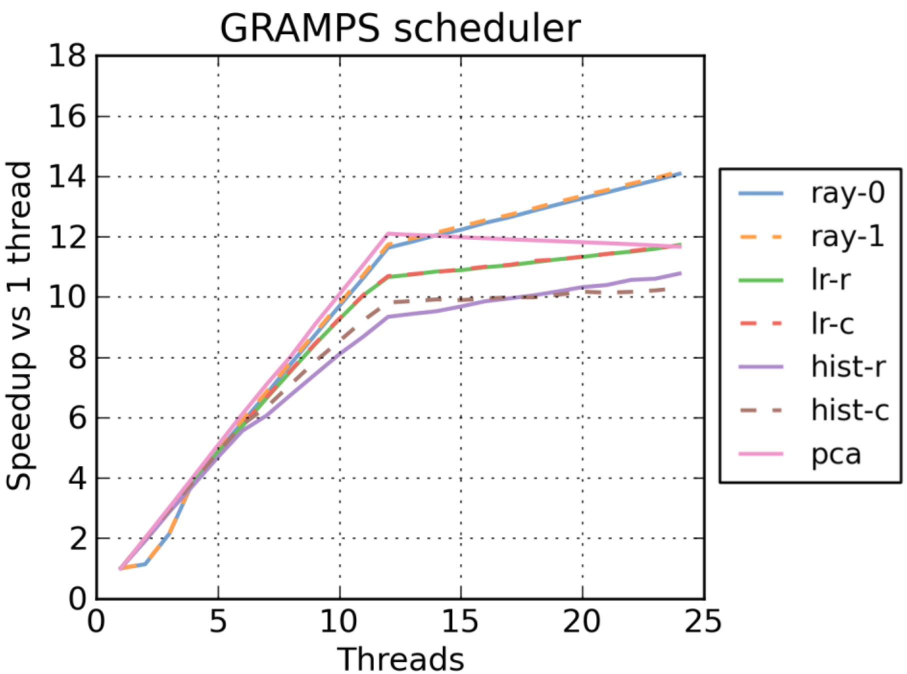
- Benchmarks from different programming models:
  - GRAMPS: raytracer
  - MapReduce: histogram, lr, pca
  - Cilk: mergesort
  - StreamIt: fm, tde, fft2, serpent
  - CUDA: srad, recursiveGaussian

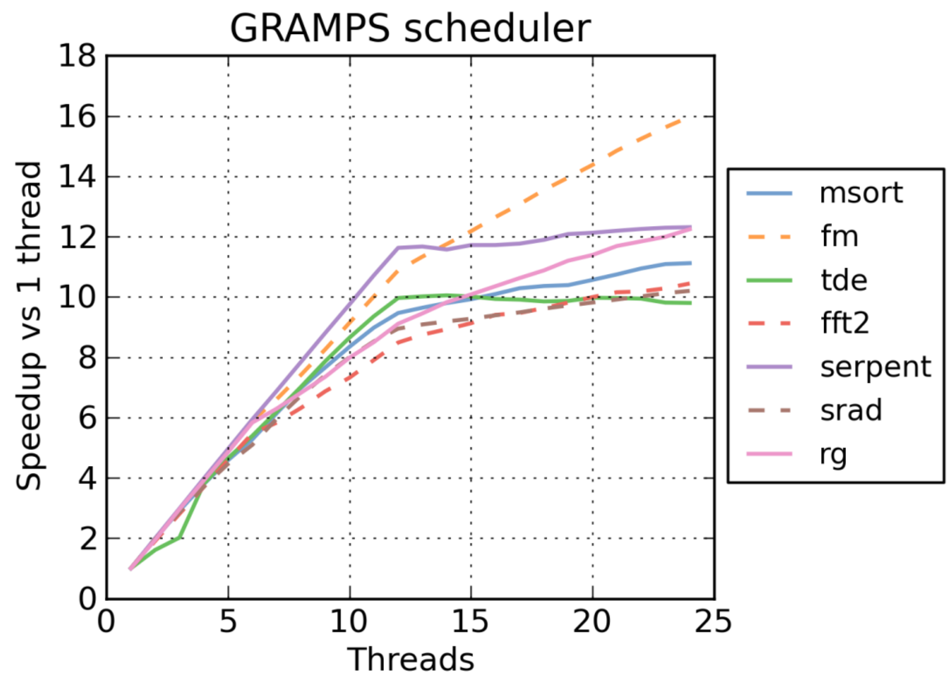


Alternative Schedulers

- GRAMPS scheduler can be substituted with other implementations to compare scheduling approaches
- Task-Stealing: Single LIFO task queue per thread, no backpressure
- Breadth-First: One stage at a time, may do multiple passes due to loops, no backpressure
- Static: Application is profiled first, then partitioned using METIS, and scheduled using a min-latency schedule, using per-thread data queues

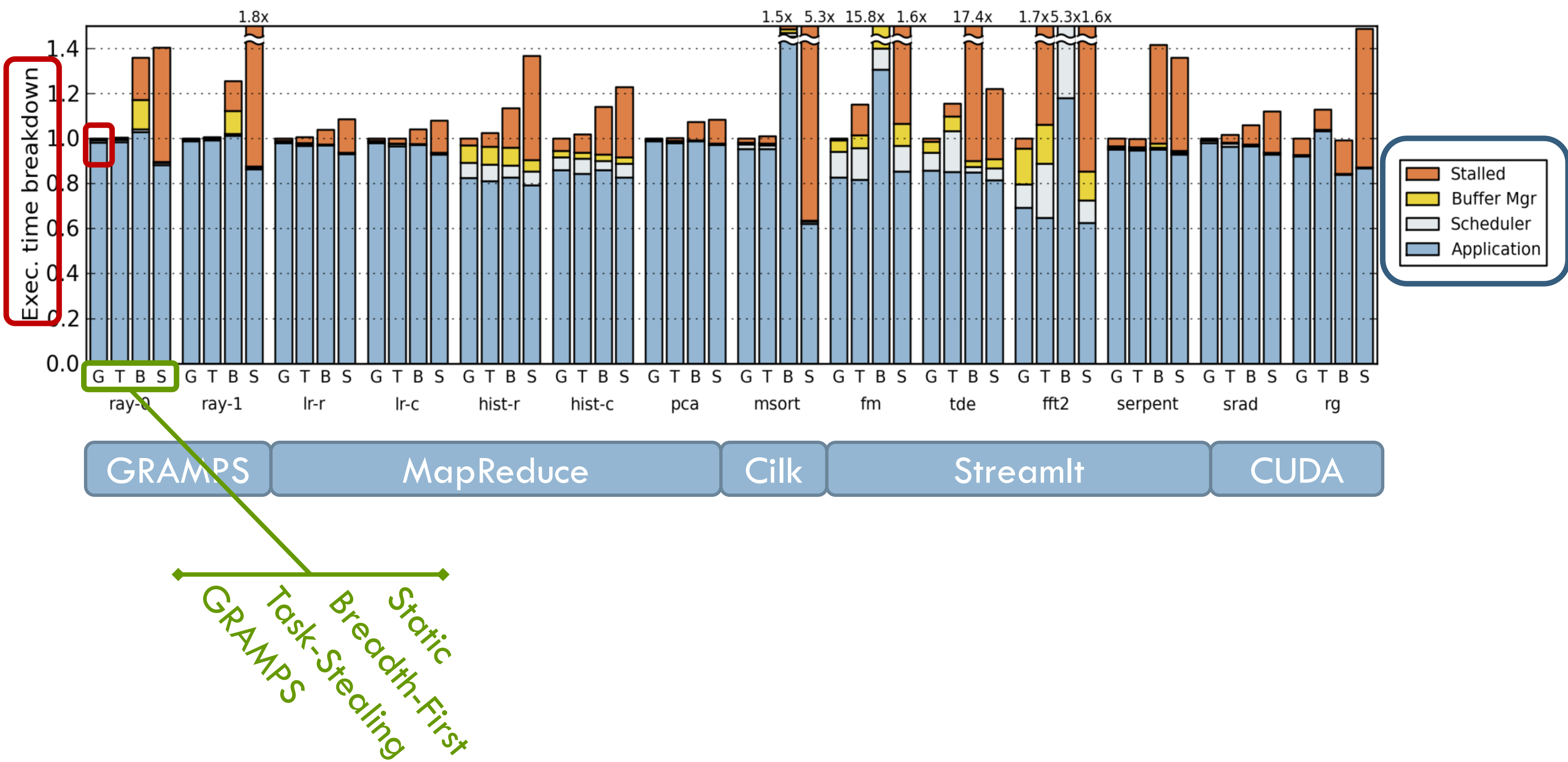
GRAMPS Scheduler Scalability



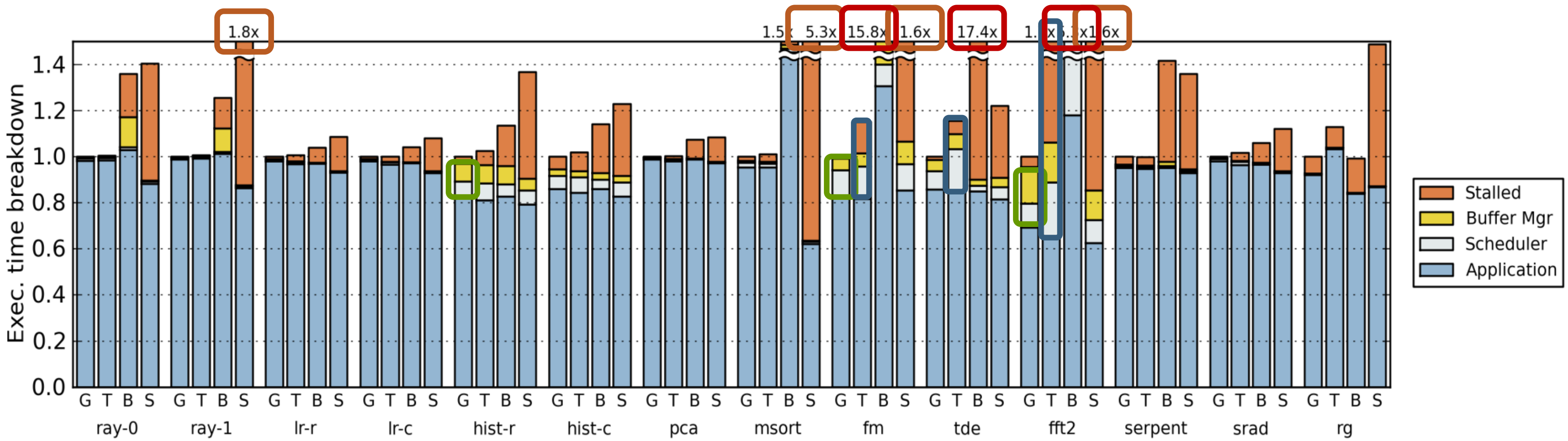


- All applications scale well
- Knee at 12 threads due to HW multithreading
- Sublinear scaling due to memory bandwidth (hist, CUDA)

Performance Comparison

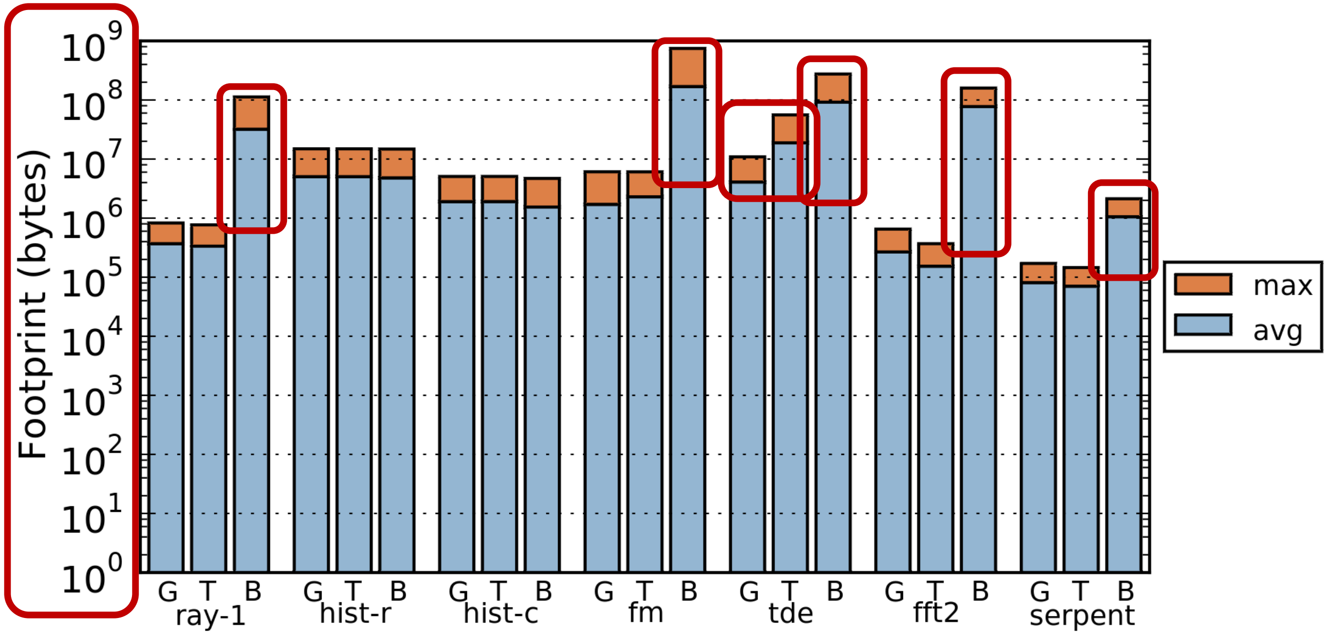


Performance Comparison



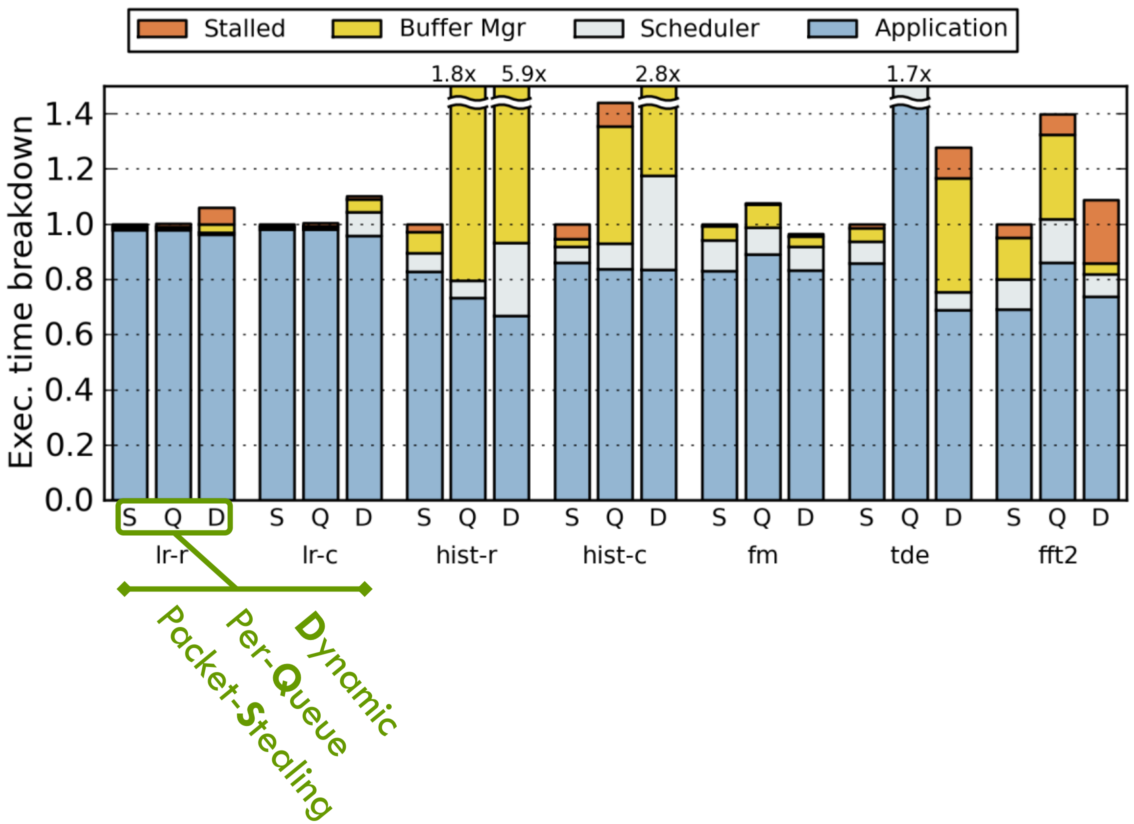
- Dynamic runtime overheads are small in GRAMPS
- Task-Stealing performs worse on complex graphs (fm, tde, fft2)
- Breadth-First does poorly when parallelism comes from pipelining
- Static has no overheads and better locality, but higher stalled time due to load imbalance

Footprint Comparison



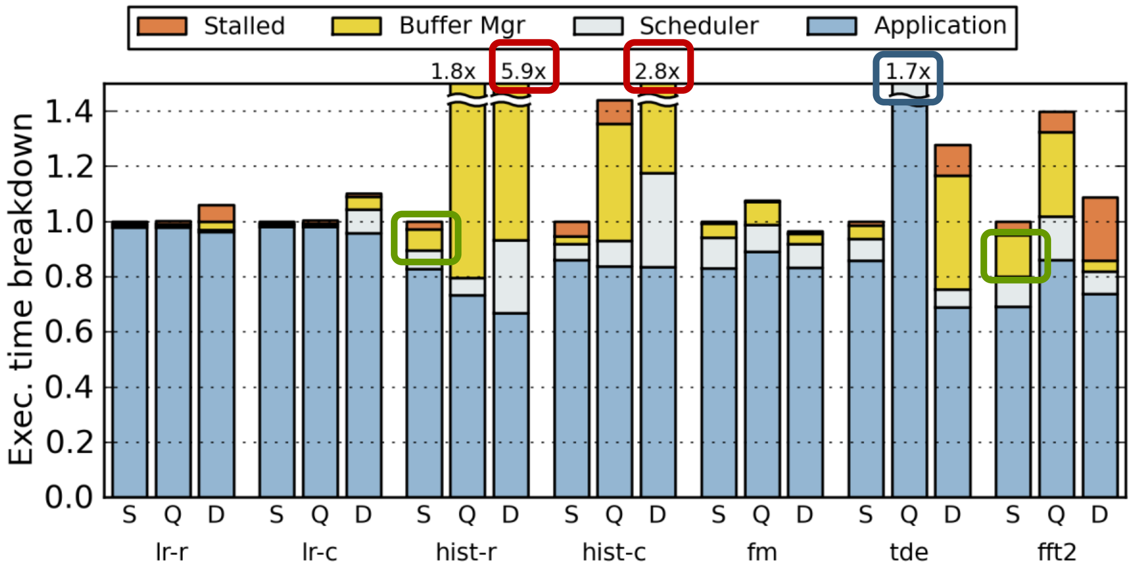
- Task-Stealing fails to keep footprint bounded (tde)
- Breadth-First has worst-case footprints → much higher footprint, memory bandwidth requirements

Buffer Manager Performance



- Dynamic: Allocate packets using malloc/free (tcmalloc)
- Per-Queue: Use per-queue, shared packet buffers

Buffer Manager Performance



- Generic dynamic memory allocator causes up to 6x slowdown on buffer-intensive applications
- Per-queue allocator degrades locality, performance with lots of stages (tde)
- Packet-stealing has low overheads, maintains locality

Conclusions

- Traditional scheduling techniques have problems with pipeline-parallel applications
  - Task-Stealing: fails on complex graphs , ordered queues
  - Breadth-First: no pipeline overlap, terrible footprints
  - Static: load imbalance with any irregularity

- GRAMPS runtime performs dynamic fine-grain scheduling of pipeline-parallel applications efficiently
  - Low scheduler and buffer manager overheads
  - Good locality

THANK YOU FOR YOUR ATTENTION

QUESTIONS?