# Design Principles for End-to-End Multicore Schedulers

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HotPar'10

# Context: Barrelfish Multikernel operating system

- Developed at ETHZ and Microsoft Research
- Scalable research OS on heterogeneous multicore hardware
  - Operating system principles and structure
  - Programming models and language runtime systems
- Other scalable OS approaches are similar
  - Tessellation, Corey, ROS, fos, ...
  - Ideas in this talk more widely applicable

# Today's talk topic

**OS Scheduler architecture for today's (and tomorrow's) multicore machines**

- General-purpose setting:
  - Dynamic workload mix
  - Multiple parallel apps
  - Interactive parallel apps

# Why this is a problem

## A simple example

- Run 2 OpenMP applications concurrently
- On 16-core AMD Shanghai system
- Intel OpenMP library
- Linux OS

# Why this is a problem

## Example: 2x OpenMP on 16-core Linux

- One app is CPU-Bound:

```
#pragma omp parallel
for(;;) iterations[omp_get_thread_num()]++;
```

- Other is synchronization intensive (eg. BARRIER):

```
#pragma omp parallel
for(;;) {
  #pragma omp barrier
  iterations[omp_get_thread_num()]++;
}
```

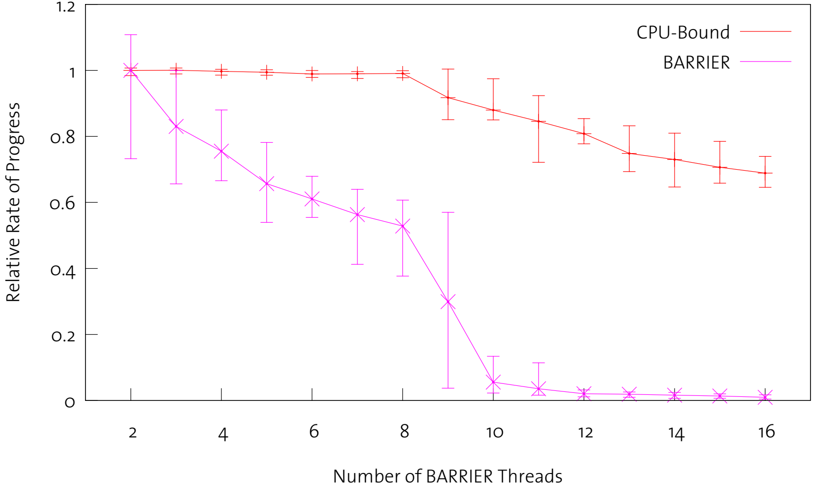
# Why this is a problem

## Example: 2x OpenMP on 16-core Linux

- Run for *x* in [2..16]:
  - `OMP_NUM_THREADS=`*x* `./BARRIER &`
  - `OMP_NUM_THREADS=8 ./cpu_bound &`
  - `sleep 20`
  - `killall BARRIER cpu_bound`
- Plot average `iterations`/thread/s over 20s

# Why this is a problem

## Example: 2x OpenMP on 16-core Linux



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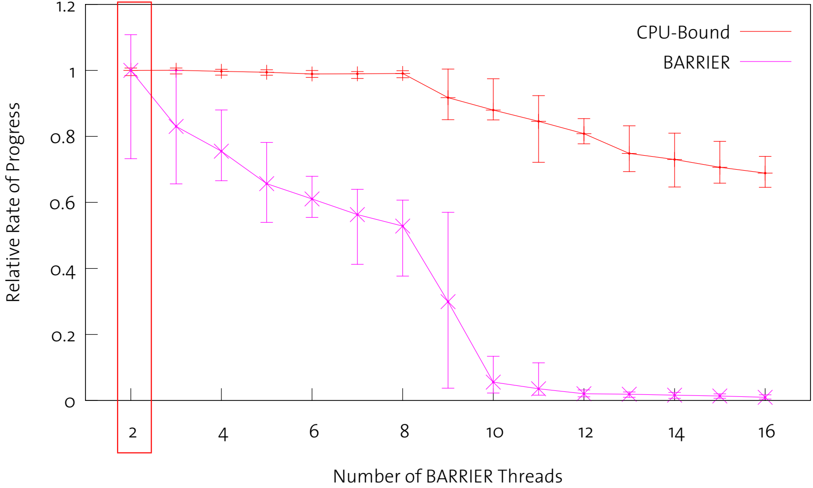

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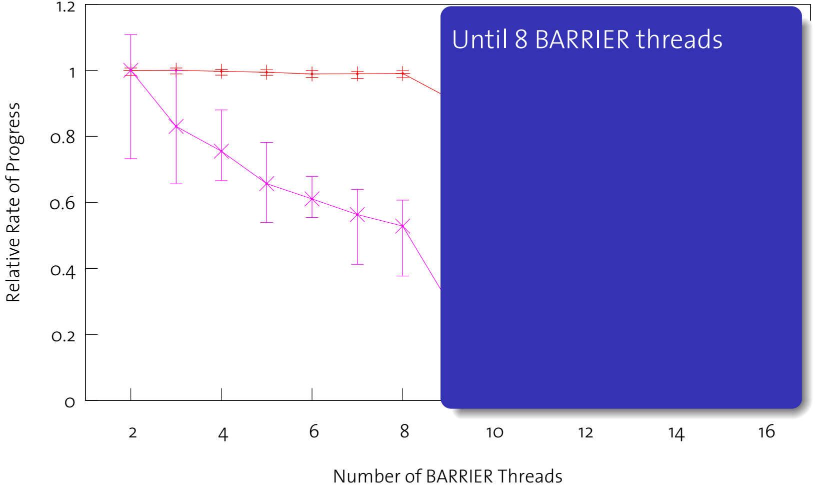

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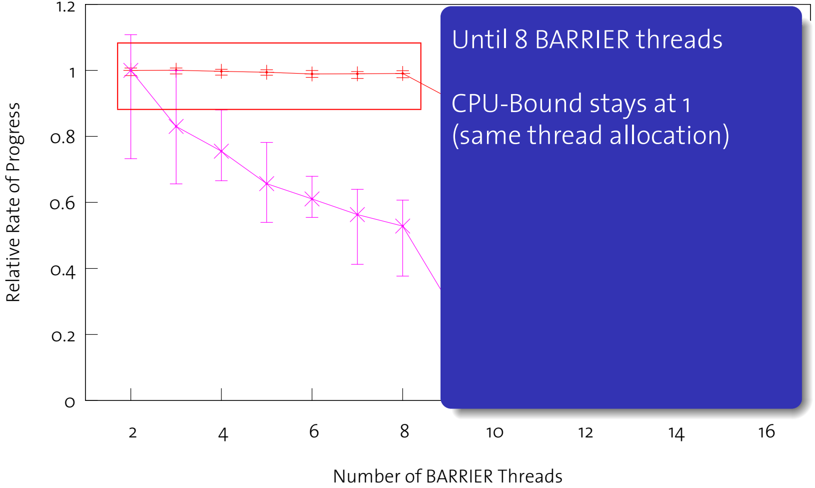

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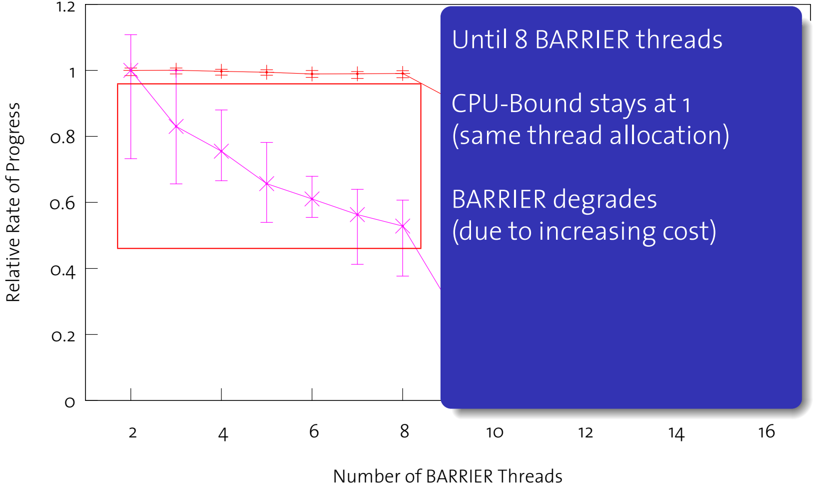


Until 8 BARRIER threads

CPU-Bound stays at 1
(same thread allocation)

BARRIER degrades
(due to increasing cost)

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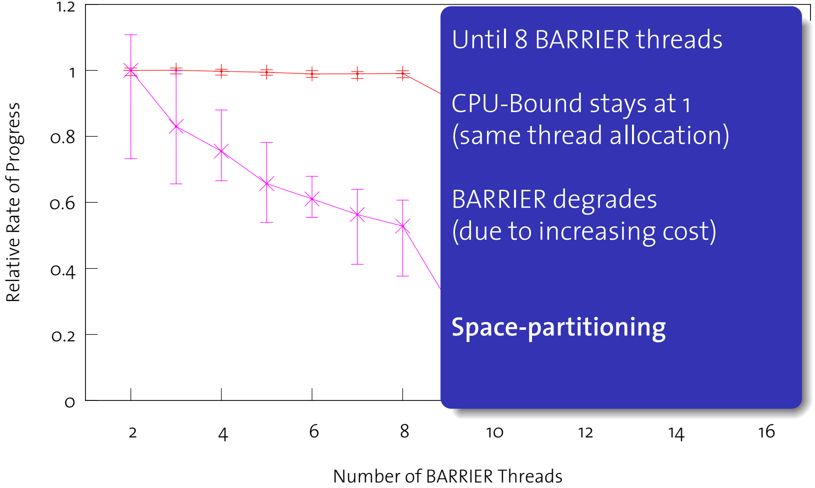


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**Space-partitioning**

# Why this is a problem

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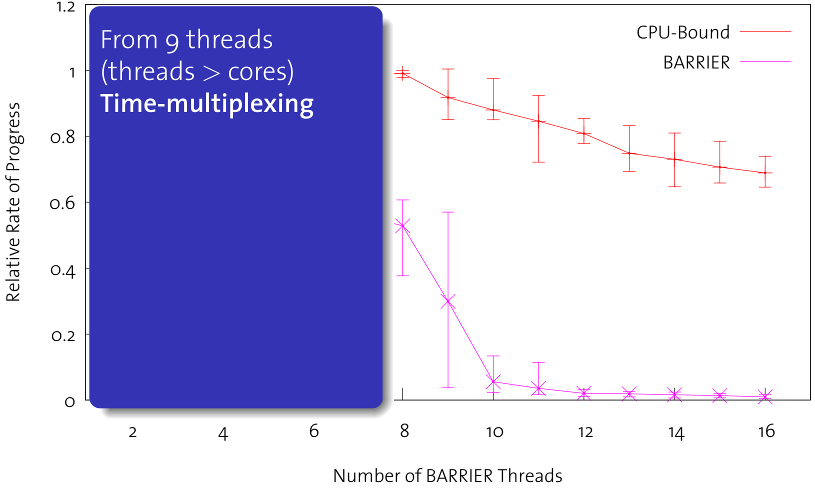
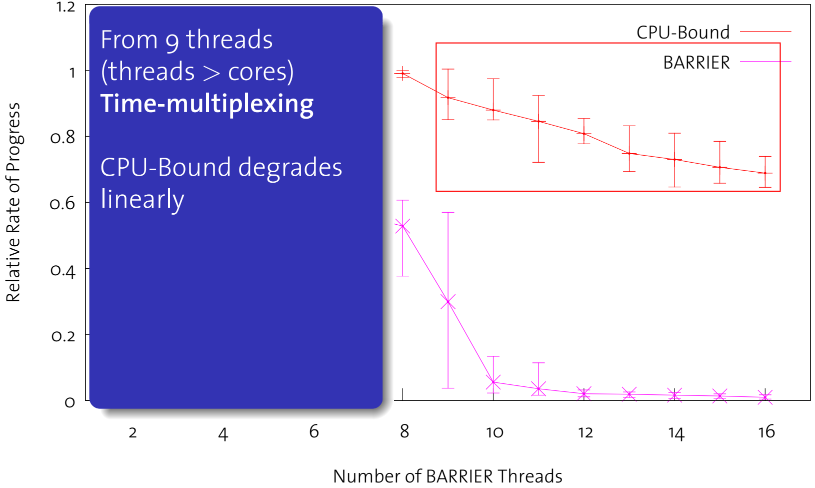


# Why this is a problem

## Example: 2x OpenMP on 16-core Linux

From 9 threads
(threads > cores)
**Time-multiplexing**

CPU-Bound degrades linearly



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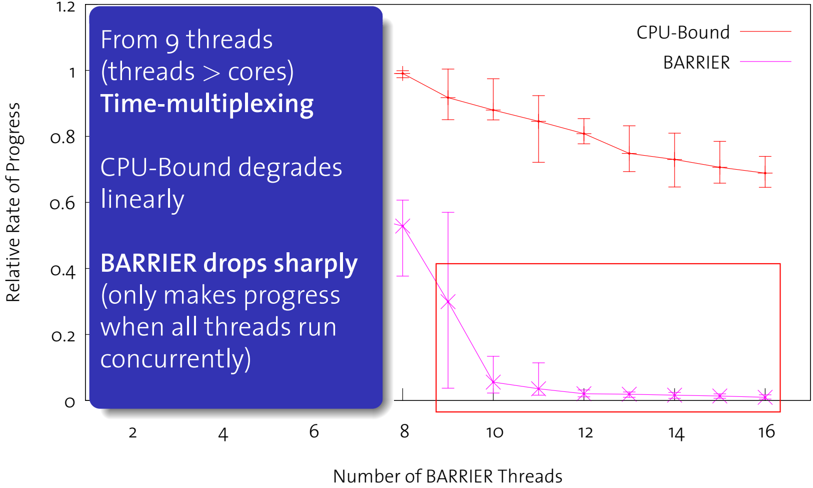



From 9 threads
(threads > cores)
**Time-multiplexing**

CPU-Bound degrades linearly

**BARRIER drops sharply**
(only makes progress when all threads run concurrently)

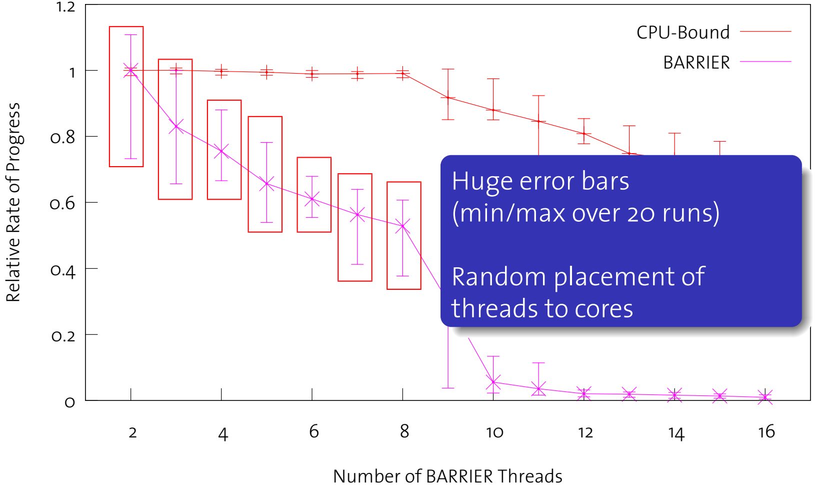
# Why this is a problem

## Example: 2x OpenMP on 16-core Linux

- Gang scheduling or smart core allocation would help
- Gang scheduling:
  - OS unaware of apps' requirements
  - The run-time system could've known
    - Eg. via annotations or compiler
- Smart core allocation:
  - OS knows general system state
  - Run-time system chooses number of threads
- Information and mechanisms in the wrong place

# Why this is a problem

## Example: 2x OpenMP on 16-core Linux

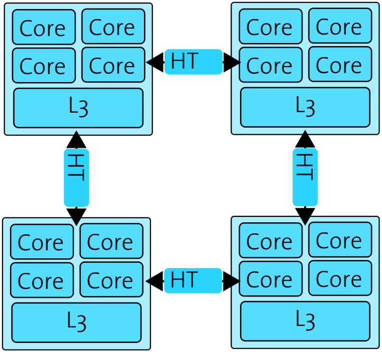



Huge error bars (min/max over 20 runs)

Random placement of threads to cores

# Why this is a problem

## 16-core AMD Shanghai system




- Same-die L3 access twice as fast as cross-die
- OpenMP run-time does not know about this machine

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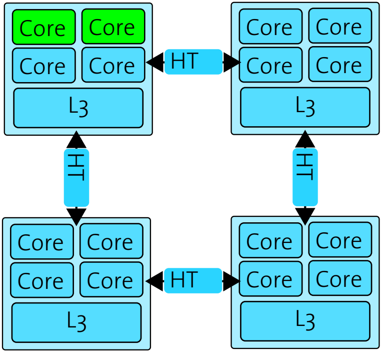


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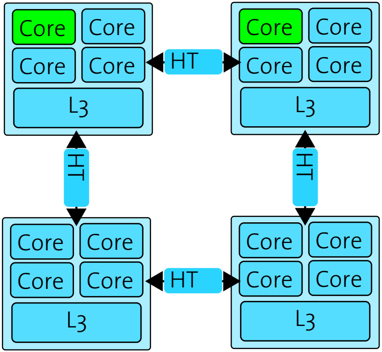


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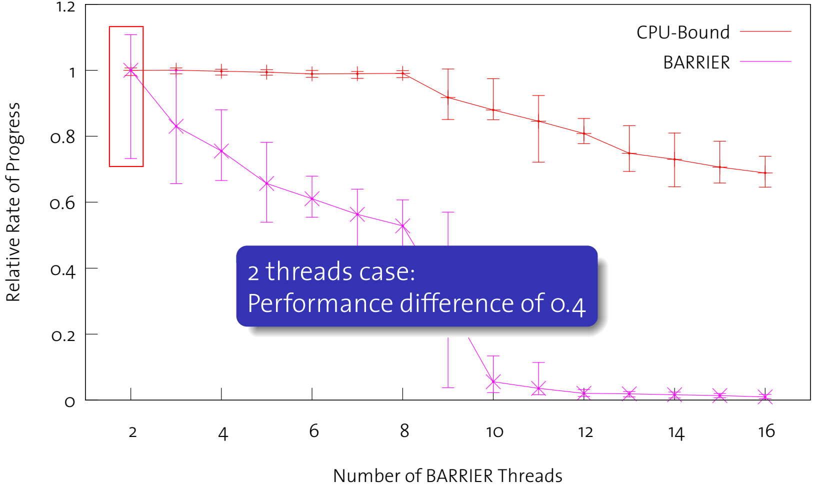
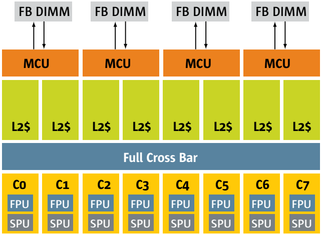



2 threads case:
Performance difference of 0.4

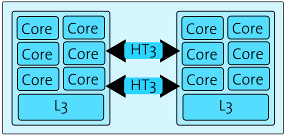
# Why this is a problem

## System diversity



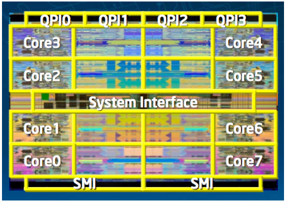

Sun Niagara T2

- Flat, fast cache hierarchy




AMD Opteron (Magny-Cours)

- On-chip interconnect




Intel Nehalem (Beckton)

- On-die ring network

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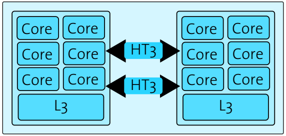


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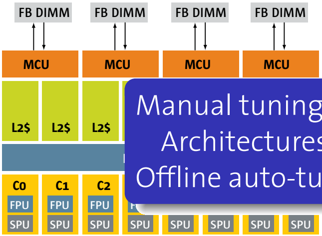
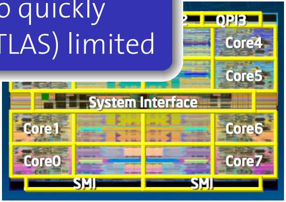
connect




Sun Niagara T2

- Flat, fast cache hierarchy

Manual tuning increasingly difficult
Architectures change too quickly
Offline auto-tuning (eg. ATLAS) limited

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# Online adaptation

- Online adaptation remains viable
- Easier with contemporary runtime systems
  - OpenMP, Grand Central Dispatch, ConcRT, MPI, ...
  - Synchronization patterns are more explicit
- But needs information at right places

# The end-to-end approach

- The system stack:

| Component | Related work |
|---|---|
| Hardware | Heterogeneous, ... |
| OS scheduler | CAMP, HASS, ... |
| Runtime systems | OpenMP, MPI, ConcRT, McRT, ... |
| Compilers | Auto-parallel., ... |
| Programming paradigms | MapReduce, ICC, ... |
| Applications | annotations, ... |

- Involve all components, top to bottom
- Need to cut through classical OS abstractions
- Here we focus on OS / runtime system integration

# Design Principles

# Design principles

## 1. Time-multiplexing cores is still needed

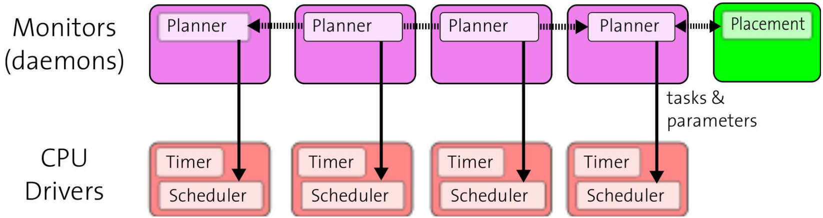
- Resource abundance $\neq$ scheduler freedom
- Asymmetric multi-core architectures
  - Contention for “big” cores
- Provide real-time QoS to interactive apps, not wasting cores
  - Avoid power wasted through over-provisioning

# Design principles

## 2. Schedule at multiple timescales

- Interactive workloads are now parallel
  - Requirements might change abruptly
  - Eg. parallel web browser
- Much shorter, interactive time scales
- Thus need small overhead when scheduling
  - Synchronized scheduling on every time-slice won't scale

# Implementation in Barrelfish




- Combination of techniques at different time granularities
  - Long-term placement of apps on cores
  - Medium-term resource allocation
  - Short-term per-core scheduling

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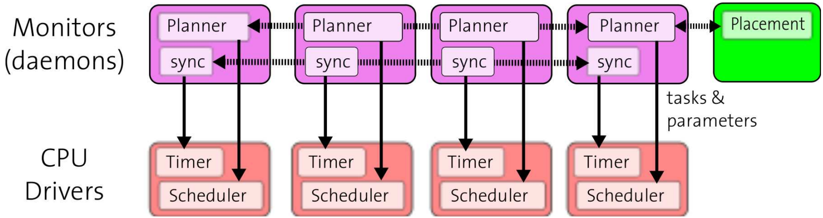
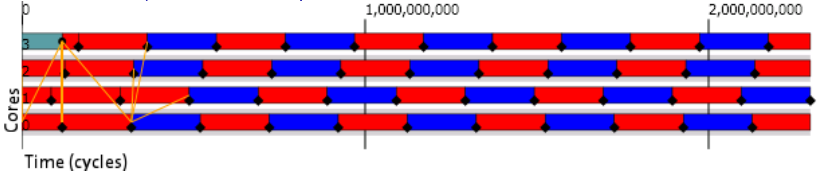



- Combination of techniques at different time granularities
  - Long-term placement of apps on cores
  - Medium-term resource allocation
  - Short-term per-core scheduling
- Phase-locked gang scheduling
  - Gang scheduling over interactive timescales

# Phase-locked gang scheduling

- Decouple schedule synchronization from dispatch


Best-effort (actual trace):

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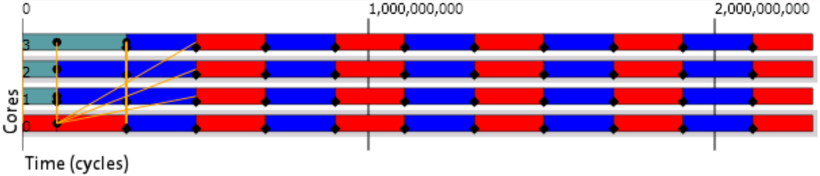

# Phase-locked gang scheduling

- Decouple schedule synchronization from dispatch

BARRIER
CPU-Bound
◆Timer interrupt

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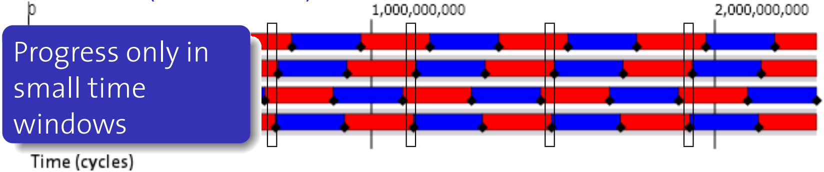


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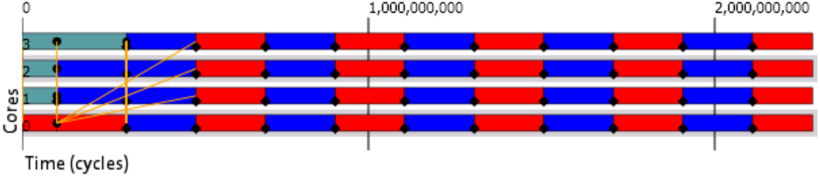

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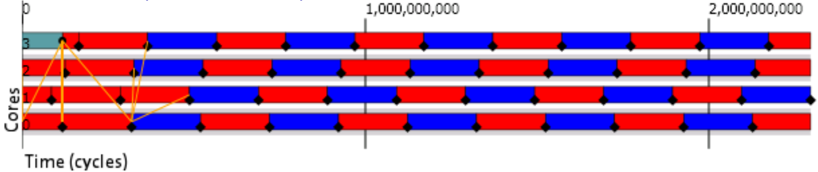


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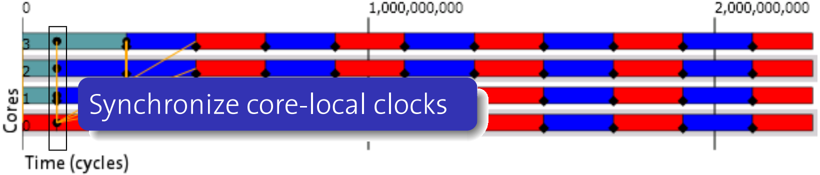

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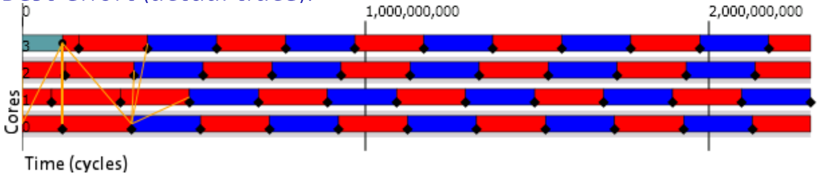


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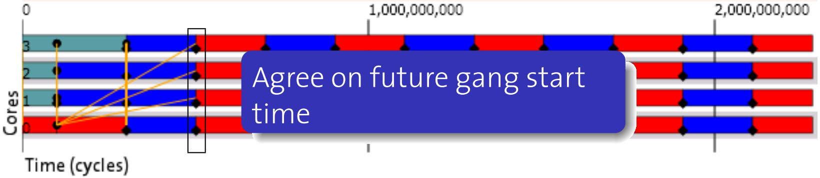

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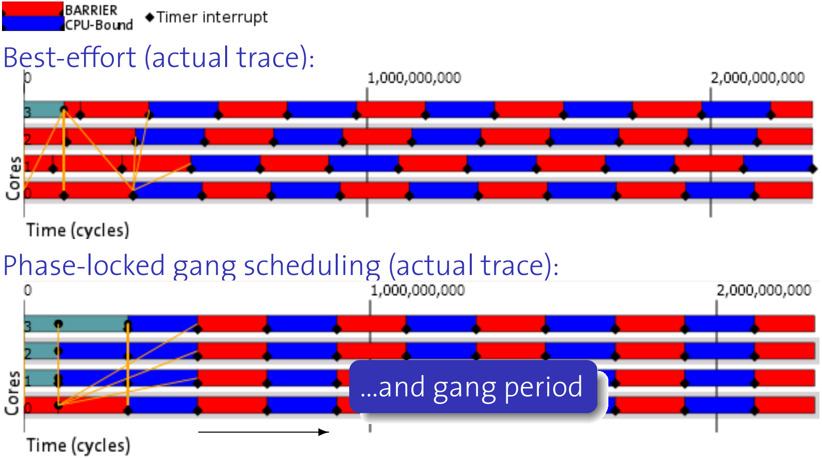

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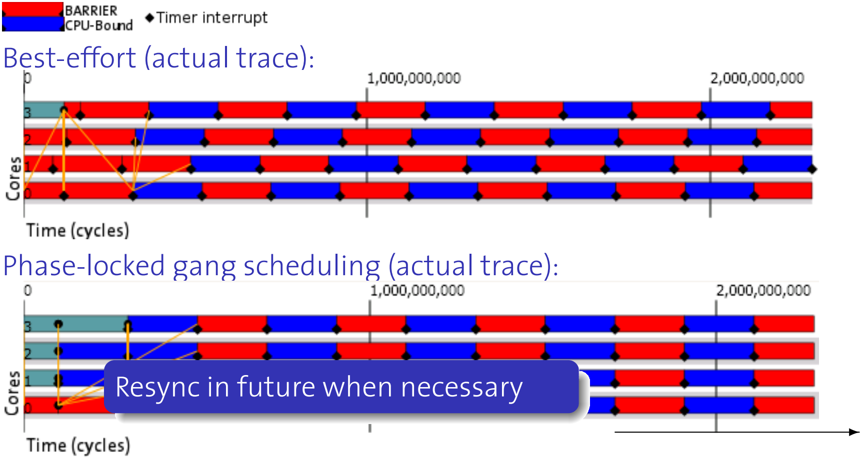


# Design principles

## 3. Reason online about the hardware

- We employ a system knowledge base
  - Contains rich representation of the hardware
  - Queries in subset of first-order logic
  - Logical unification aids dealing with diversity
- Both OS and apps use it

# Design principles

## 4. Reason online about each application

- OS should exploit knowledge about apps for efficiency
  - Eg. gang schedule threads in an OpenMP team
  - But no sense in gang scheduling unrelated threads
- A single app might go through different phases
  - Optimal allocation of resources changes over time

Implementation:

- Apps submit scheduling manifests to planner
  - Contain predicted long-term resource requirements
  - Expressed as constrained cost-functions
  - May make use of any information in the SKB

# Design principles

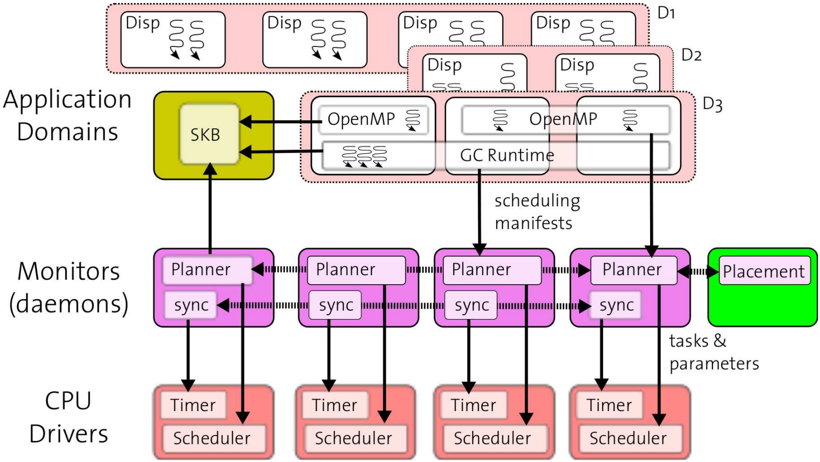
## 5. Applications and OS must communicate

- Implementing the end-to-end principle
- Resource allocation may be renegotiated during runtime

Implementation:

- Hardware threads run user-level dispatchers
  - Cf. Psyche, inheritance scheduling
- Related dispatchers are grouped into dispatcher groups
  - Derived from RTIDs of McRT
  - Used as handles when renegotiating
- Scheduler activations [Anderson 1992] to inform app

# Implementation in the Barrelfish OS



# Open questions

- What are appropriate mechanisms and timescales for inter-core phase synchronization?
- How can programmers provide useful concurrency information to the runtime?
- How efficiently can runtime specify requirements to OS?
- Hidden cost (if any) of decoupling scheduling timescales?
- Tradeoffs between centralized and distributed planners?
- Appropriate level of expressivity for the SKB?