Towards Fair and Efficient SMP Virtual Machine Scheduling

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Executive Summary

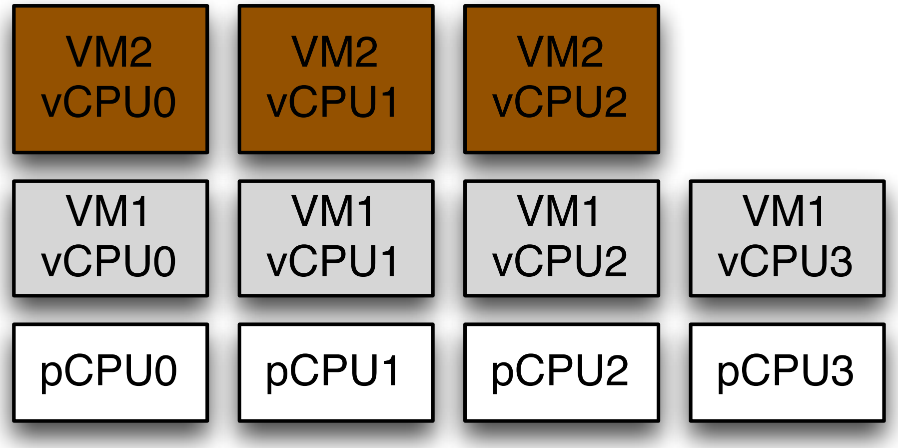
- **Problem**: **unfairness** and **inefficiency** in consolidating SMP VMs
  - Existing VM schedulers favor VMs w/ more virtual CPUs
  - Fairness mechanisms hurt parallel performance
- **Flex** is a scheduling framework that:
  - Adaptively adjusts vCPU weights for VM-level fairness
  - Flexibly schedules vCPUs to minimize unnecessary spinning
  - **Results**: 5% error to the ideally fair allocation, 30%+ performance improvement for parallel workloads, ~1% overhead in Xen

SMP VM Consolidation

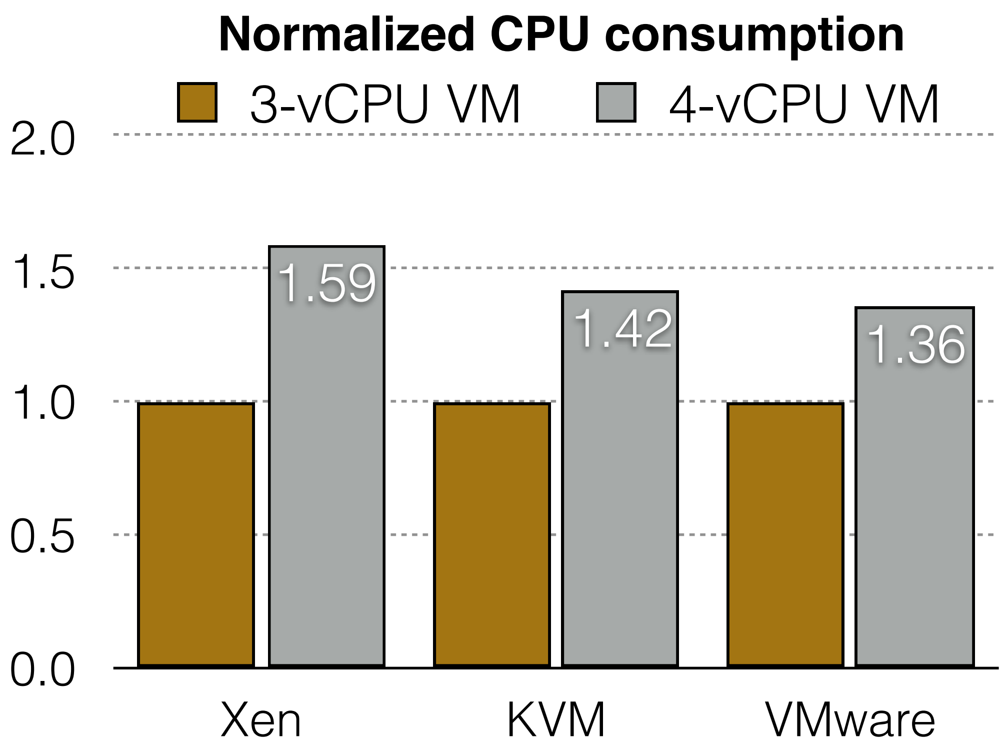
- Abundant hardware parallelism in DC
- SMP VMs are **prevalent** in the cloud
  - 26 out of 29 instance types in Amazon EC2 have more than two vCPUs
  - Support parallel applications
  - Heterogeneous consolidation is **common**, e.g., Amazon EC2

Unfair VM CPU Allocation

- CPU allocation
  - **NOT** proportional to VM weights
  - VMs w/ more vCPUs gain advantage
  - **Common** issue in all hypervisors

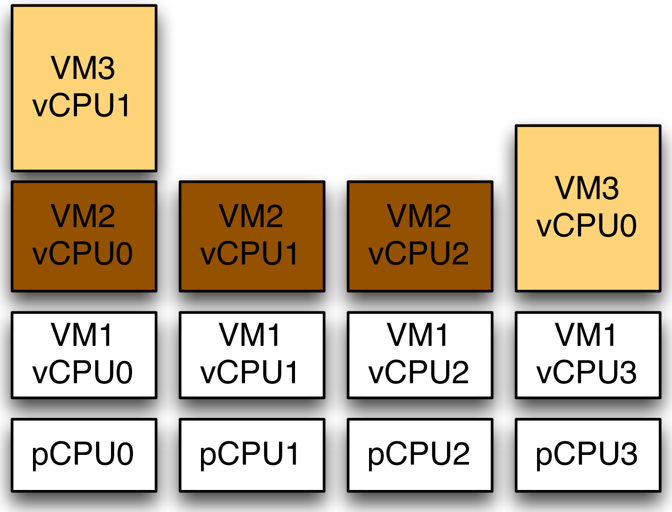


Fair share = two CPU cores



Causes of Unfairness

- Per-CPU scheduling
  - Independent scheduler on each CPU
  - Each allocates CPU based on relative vCPU weights
  - Per-vCPU weight dependent on VM weight and the **number** of vCPUs
  - Scalable but **hard** for **VM-level fairness**



Equal weight VMs
Box size reflects per-vCPU weight

Allocations on vCPU => VM-level fairness
IFF
Same total weight on each CPU

Existing Solutions

- Capping VM CPU consumption (Cap)
  - Requires pre-calculation of the fair share
  - Non-

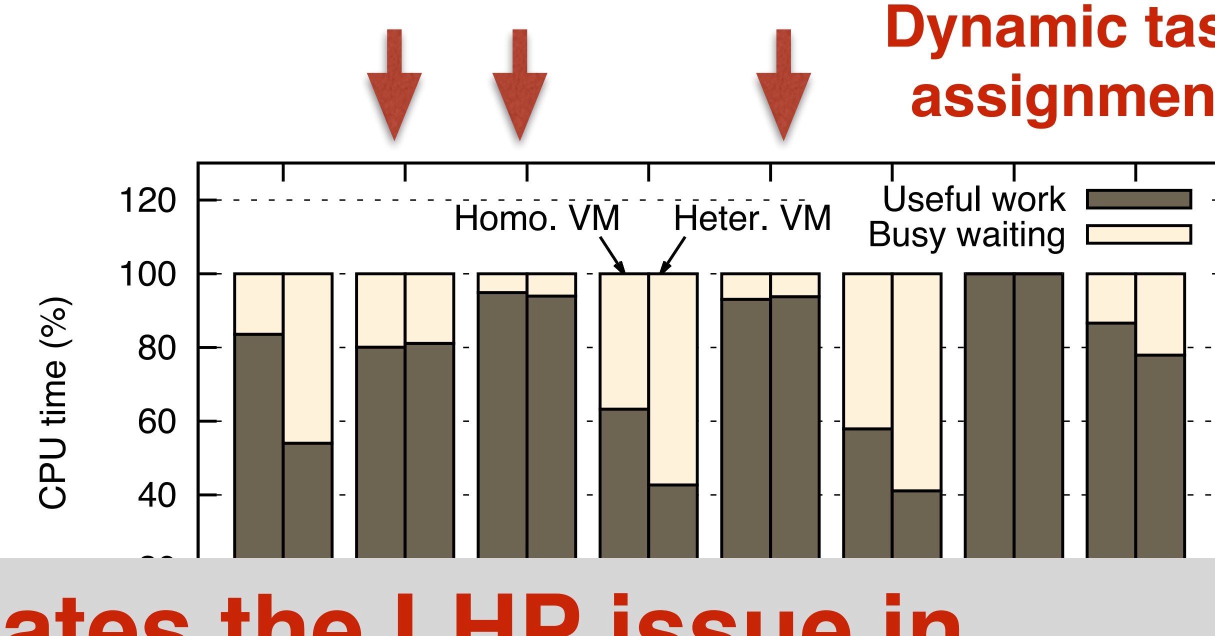
Introduce significant inefficiencies to parallel applications

- Load balancing (LB)
  - Tries to achieve equal weights on CPUs
  - Balance weight vs. balance run queue length

Cap on Busy-waiting-based Workloads

- Busy-waiting synchronization
  - Tasks stay in a busy loop waiting for lock release
  - Avoids contexts switches

Dynamic task assignment



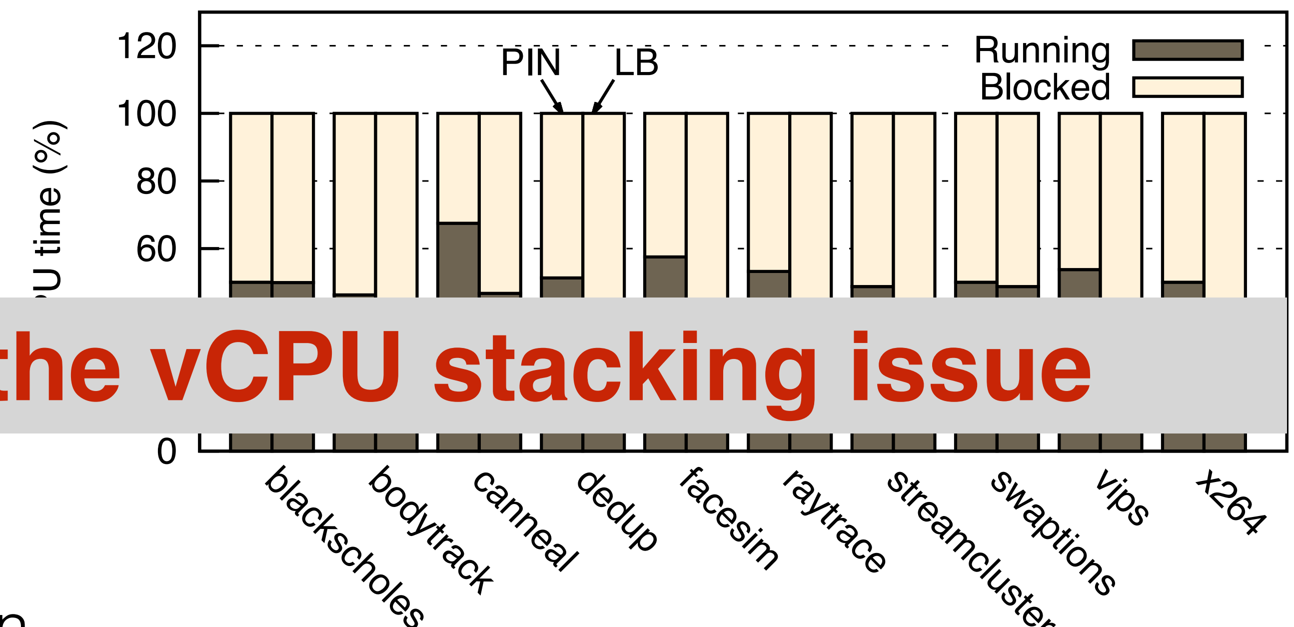
Capping exacerbates the LHP issue in virtualized environments

- Lc
  - Preemption of vCPU holding locks
  - Long synchronization latency

capping may mistakenly preempt vCPUs that are doing useful work.

LB on Blocking-based Workloads

- Blocking synchronization
  - Tasks go to sleep if failing to acquire the lock
  - Avoids wasted CPU cycles
- vCPU stacking
  - vCPUs belonging to one VM pile on the same CPU
  - No parallelism + Long sync latency



LB exacerbates the vCPU stacking issue

Since blocking vCPUs frequently switch between READY and RUNNING states, they are more likely "victims" of work-stealing based load balancing.

Gradually, stolen vCPUs pile on a few CPUs

Related Work

- Fairness in multicore systems
  - **[Li-PPoPP09]** - no VM-level fairness
- Minimizing sync latency in SMP VMs

Flex: non-intrusive, lightweight and applicable to different implementations

  - **Pause loop exit (PLE)** - needs hardware support
- Spin detection
  - **[Wells-PACT06]** - store-based spin detection, not accurate to apps with different store rates, e.g., LU in NAS parallel benchmark

Flex for Fairness and Efficiency

- Flexible vCPU weight (**FlexW**)
  - Monitors VM CPU consumption
  - Calculates fair shares based on VM weights
  - Adjusts vCPU weights to compensate the difference
- Flexible vCPU scheduling (**FlexS**)
  - Stops spinning vCPUs to avoid wasted CPU cycles
  - Switches the preempted vCPU with one on another CPU that is doing useful work
  - Ensures that no vCPUs from the same VM stack on one CPU

FlexW Design

- Determine the fair share
  - *P* - number of shared CPUs, w_i - VM weight
  - Ideally fair share according to generalized processor sharing (GPS)

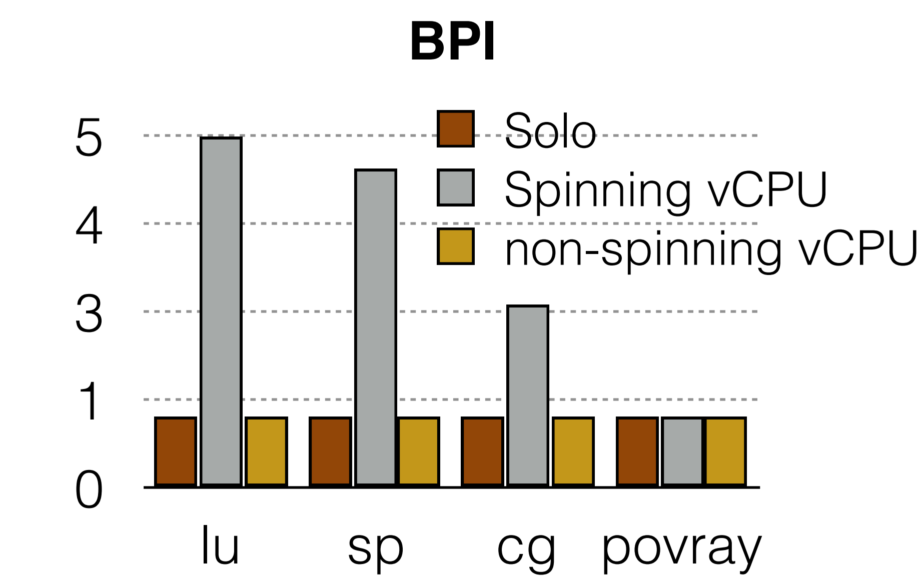
$$S_{i,GPS}(t_1, t_2) = \frac{w_i}{\sum w_j}(t_2 - t_1) \cdot P$$

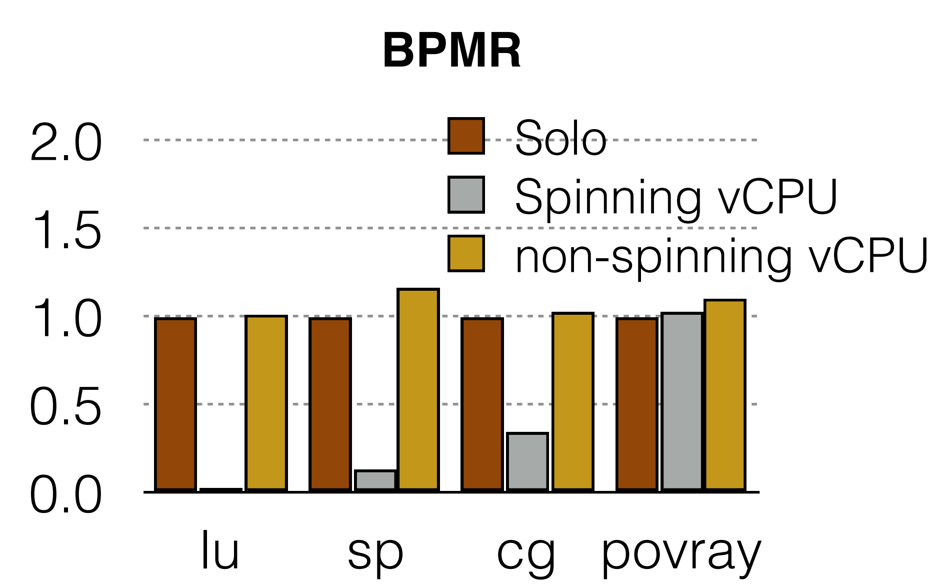
- Adjust VM weights
  - w_i^r - VM weight
  - calculate the lag $lag_i(t_1, t_2) = \frac{S_{i,GPS}(t_1,t_2) - S_i(t_1,t_2)}{S_{i,GPS}(t_1,t_2)}$
  - compensate the lag with real-time weights

$$w_i^r = w_i^r + w_i \cdot lag_i(t_1, t_2)$$

FlexS Design

- Identifying busy-waiting vCPU
  - Non-intrusive identification without application knowledge
  - Common pattern in different spin implementations
    - Spin loops contain a few instructions
    - Spin loops are executed many times
  - Spin loops show **high** branch per instruction (BPI) and **low** branch miss prediction rate (BMPR)





FlexS Design (cont')

- Eliminating busy-waiting time
  - Periodically update a vCPU's BPI and BMPR
  - Busy-waiting vCPU voluntarily yields CPU
  - Find a sibling vCPU to complete the unfinished time slice
  - **Switch** the two vCPU to avoid vCPU stacking and run queue weight changes

Practical Considerations

- Starvation
  - VMs demanding less than its share will have ever increasing real-time weight
  - **Solution**: reset real-time weight every 10s
- Infeasible weight -> peak CPU demand less than the fair share
  - **Solution**: peak demand as the fair share
- False positive in identifying spinning vCPU
  - **Solution**: reset BPI and BMPR every 10s
- Inter-CPU locking overhead due to vCPU migrations
  - **Solution**: only try twice when looking for siblings to switch- the *power of two choices*

Implementation

- Implement Flex in Xen's credit scheduler
  - weight -> credit
  - **FlexW** in the system-wide csched_acct() routine, adjusts VM credit refill based on real-time weights, invoked every 30ms
  - **FlexS** in the per-CPU schedule() function, adds load_balance_switch() to exchange work with sibling vCPUs
  - Identify spinning vCPU in vcpu_acct() when Xen charges credit to the current running vCPU

Evaluation Methodology

- **Questions**: ***VM-level fairness?*** and ***parallel performance?***
- Workload
  - **NAS** Parallel benchmark (OpenMP, busy-waiting sync)
  - **PARSEC** (Pthreads, blocking sync)
  - **Background** interfering loops — isolate from cache contention
- Scheduling strategies for comparison
  - **Xen** default credit scheduler
  - **Balance+cap+CO** - [Sukwong-Eurosys11]
  - **Demand+cap** - [Kim-ASPLOS13]

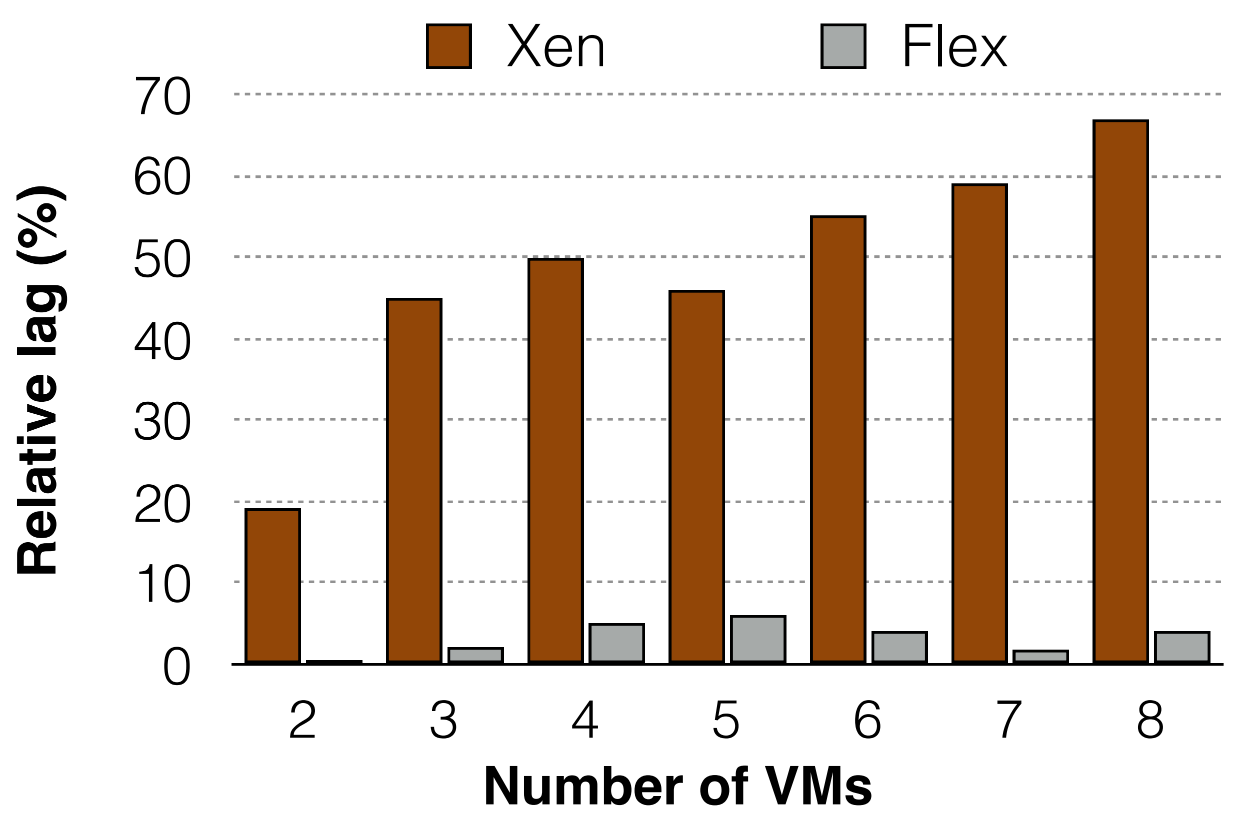
VM-level Fairness

Heterogeneous VMs:
1vCPU, 2vCPU, 3vCPU, 4vCPU

Each running while(1) loop

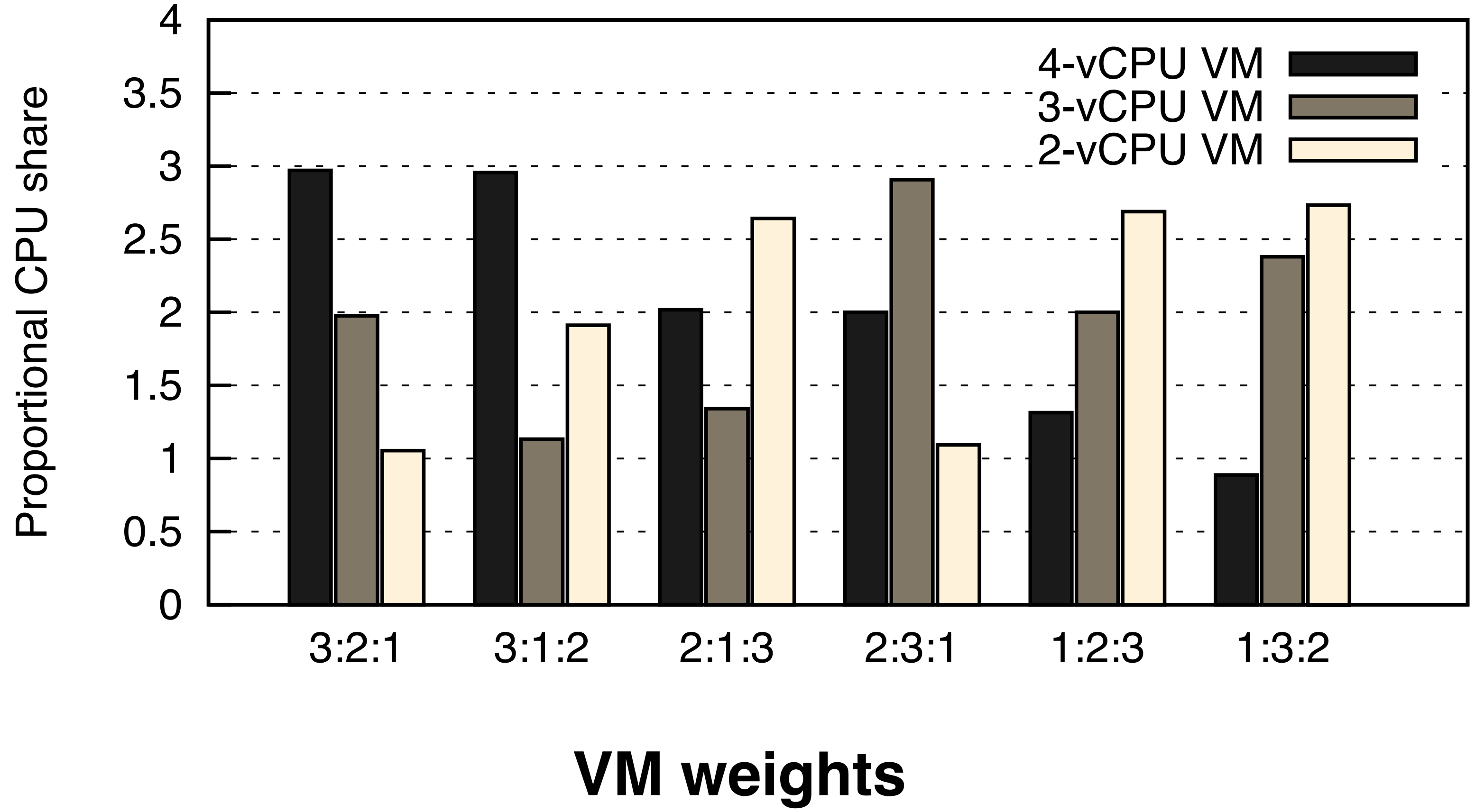
Relative lag = $\left|\frac{S_{i,GPS}(t_1,t_2) - S_i(t_1,t_2)}{S_{i,GPS}(t_1,t_2)}\right|$

Lower is better



Flex: significant improvement over Xen with no more than 5% unfairness

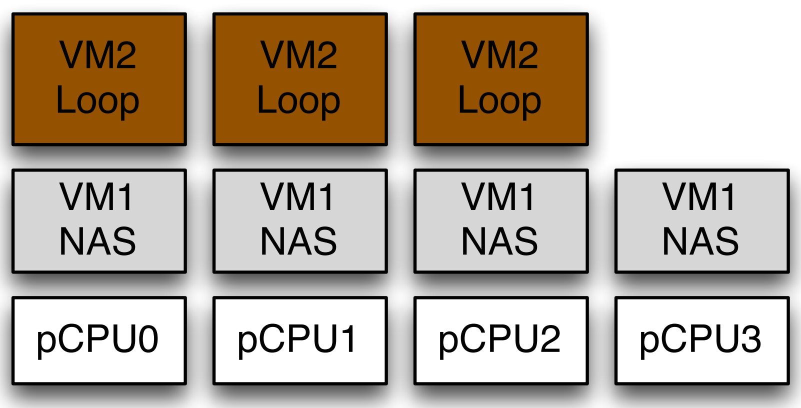
VM Differentiation



Flex realizes proportional share among VMs

Parallel Performance

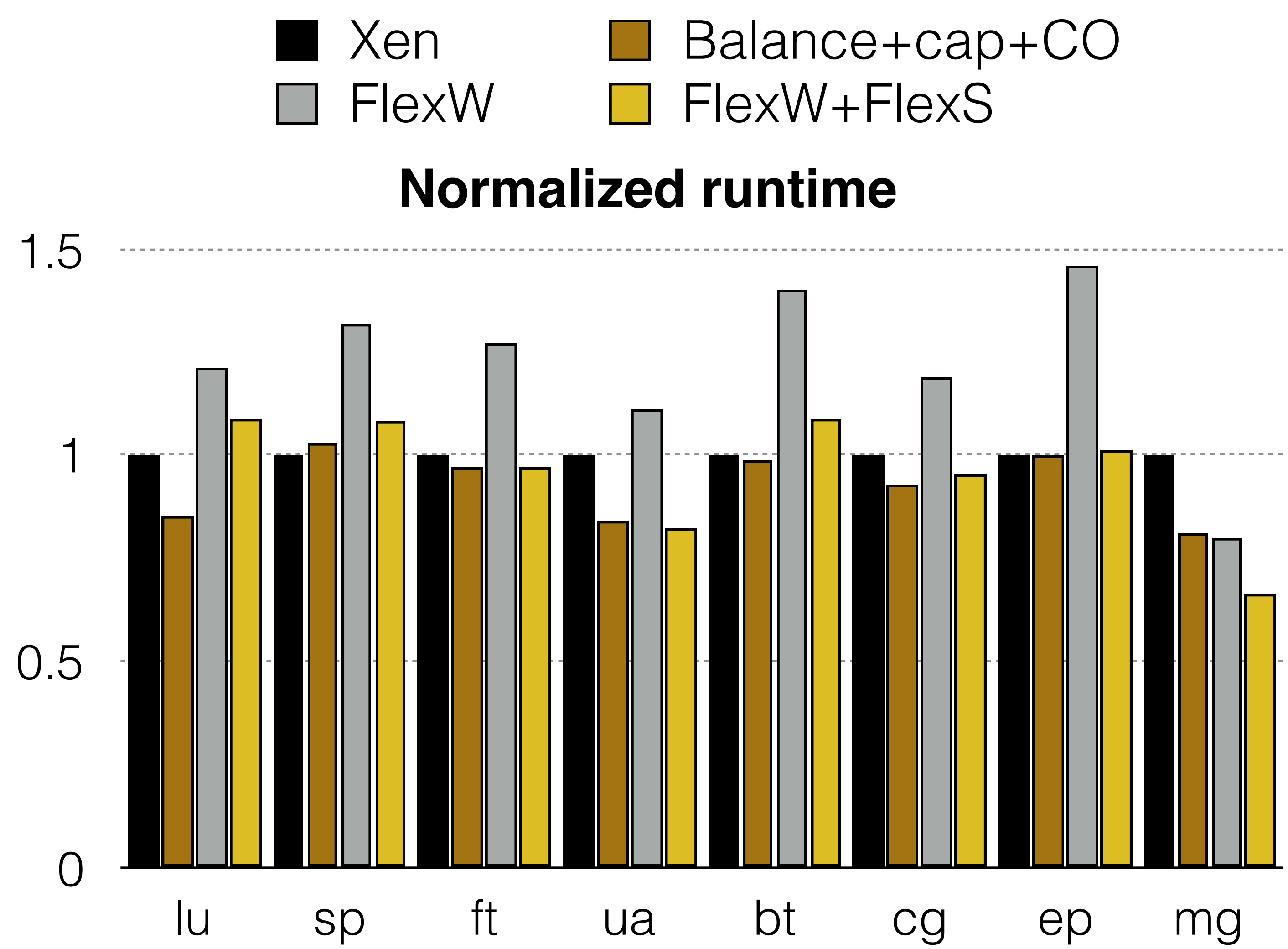
Challenge: Flex allocates less CPU time to the 4vCPU VM than Xen



Observation: FlexW alone does NOT guarantee good perf.

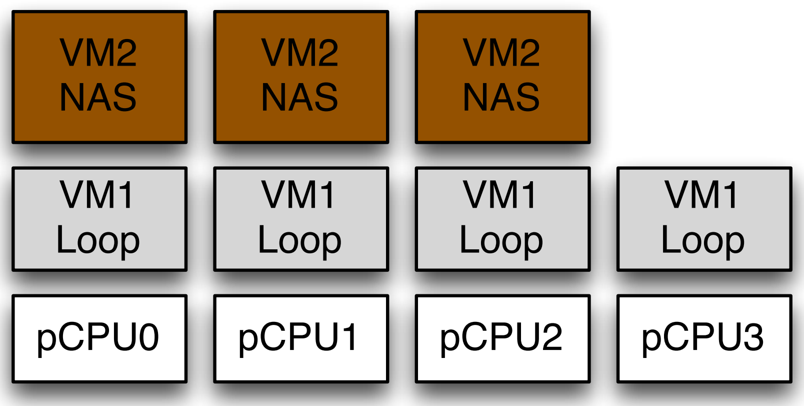
Reason: Imbalance wastes CPU time

Results: FlexW+FlexS performs closely to Xen and balance+cap+CO



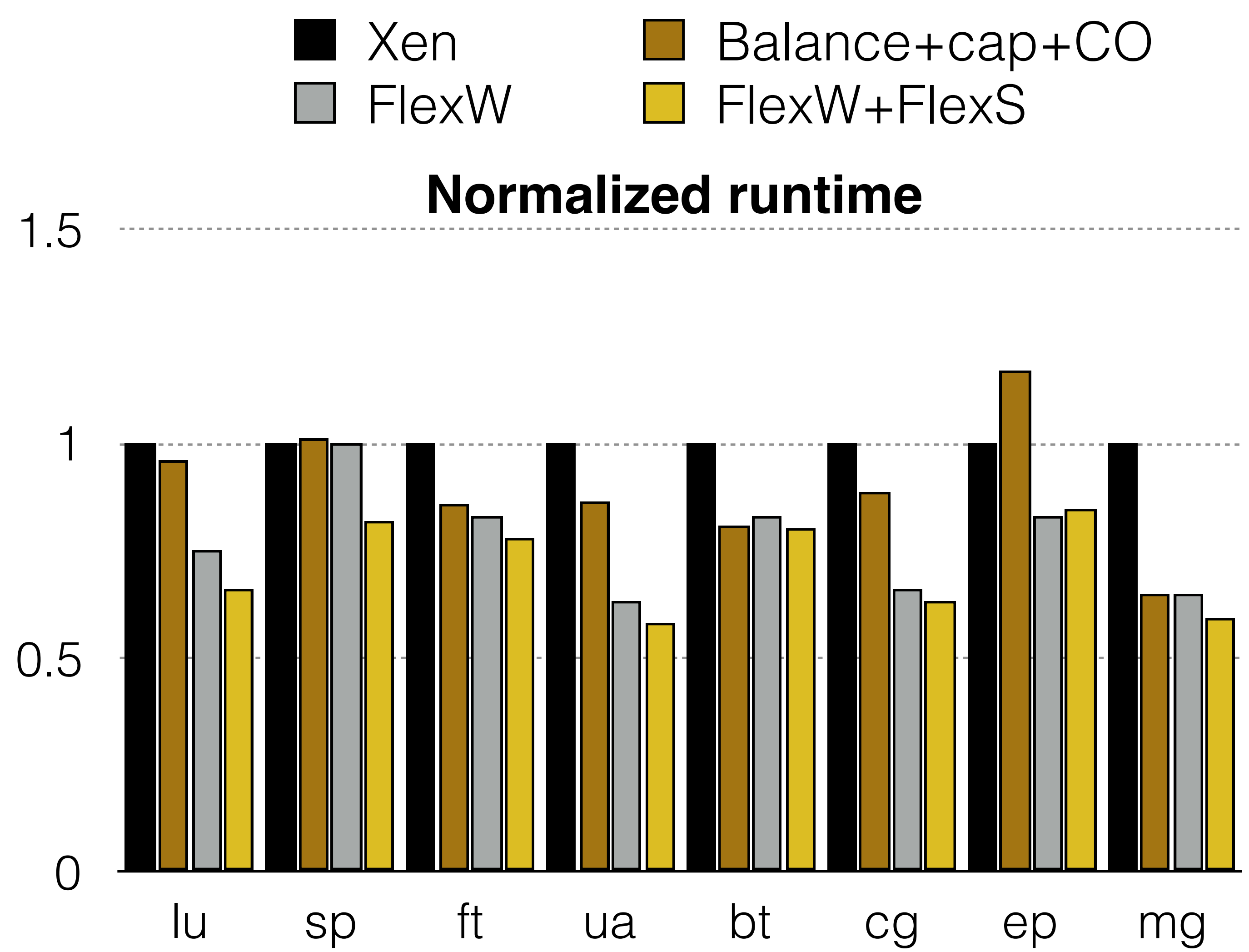
Lower is better

Parallel Performance



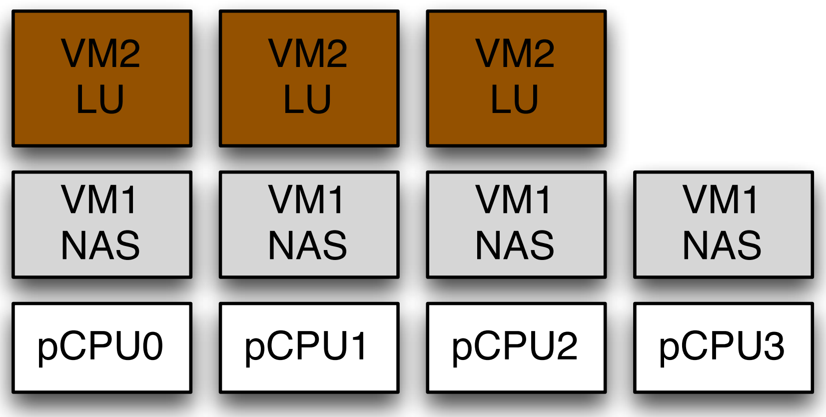
Expected: Flex performs better than Xen

Reason: Flex allocates more CPU time to the 3vCPU VM than Xen

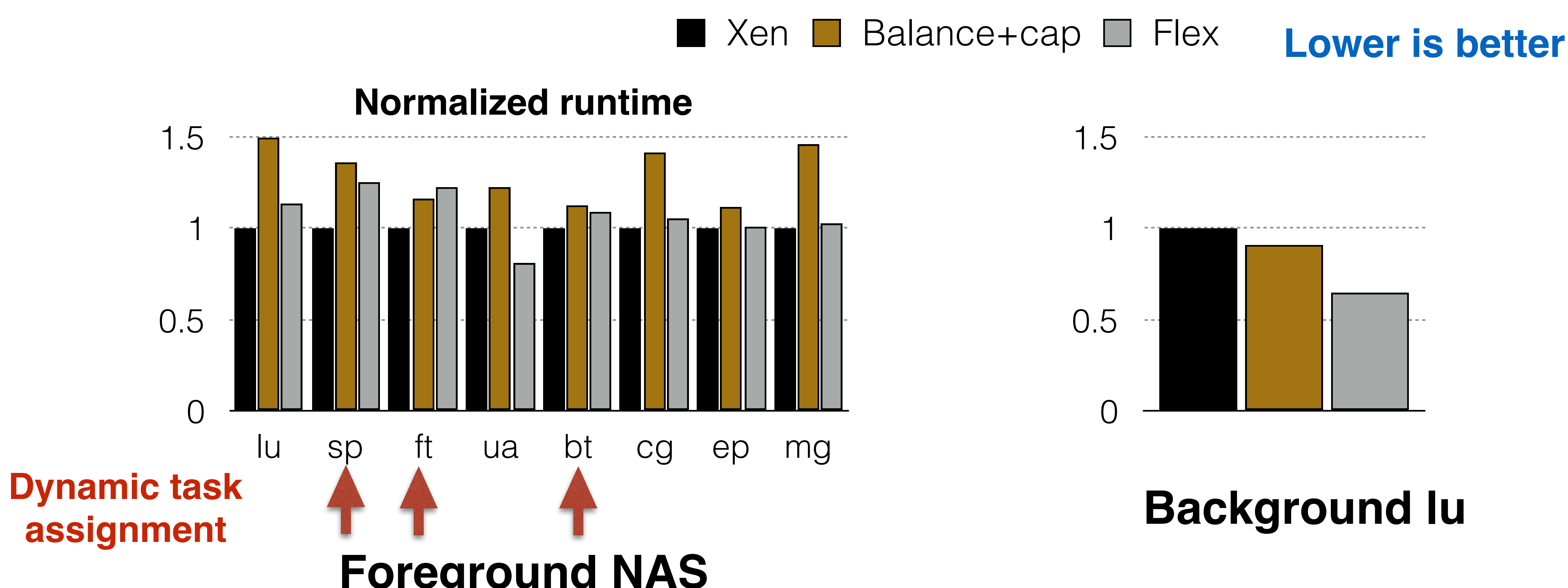


Lower is better

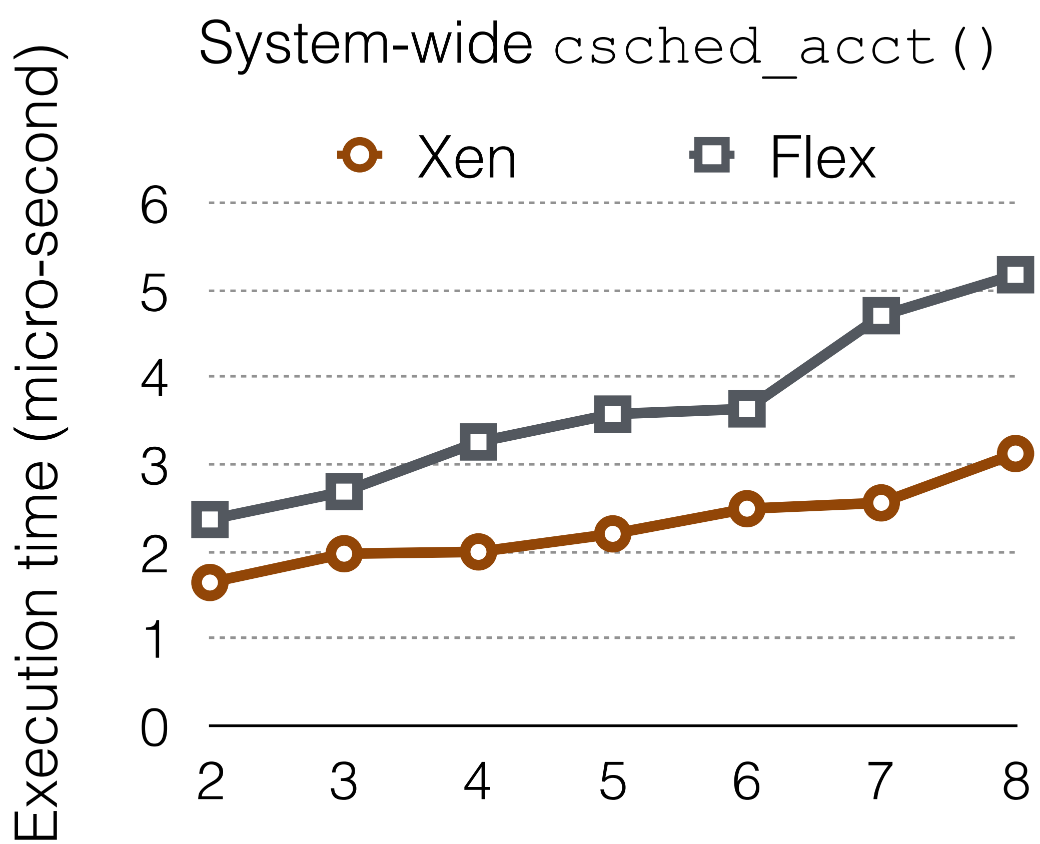
Mix of Parallel Workloads



Results: Flex outperforms balance+cap by **30.4%**

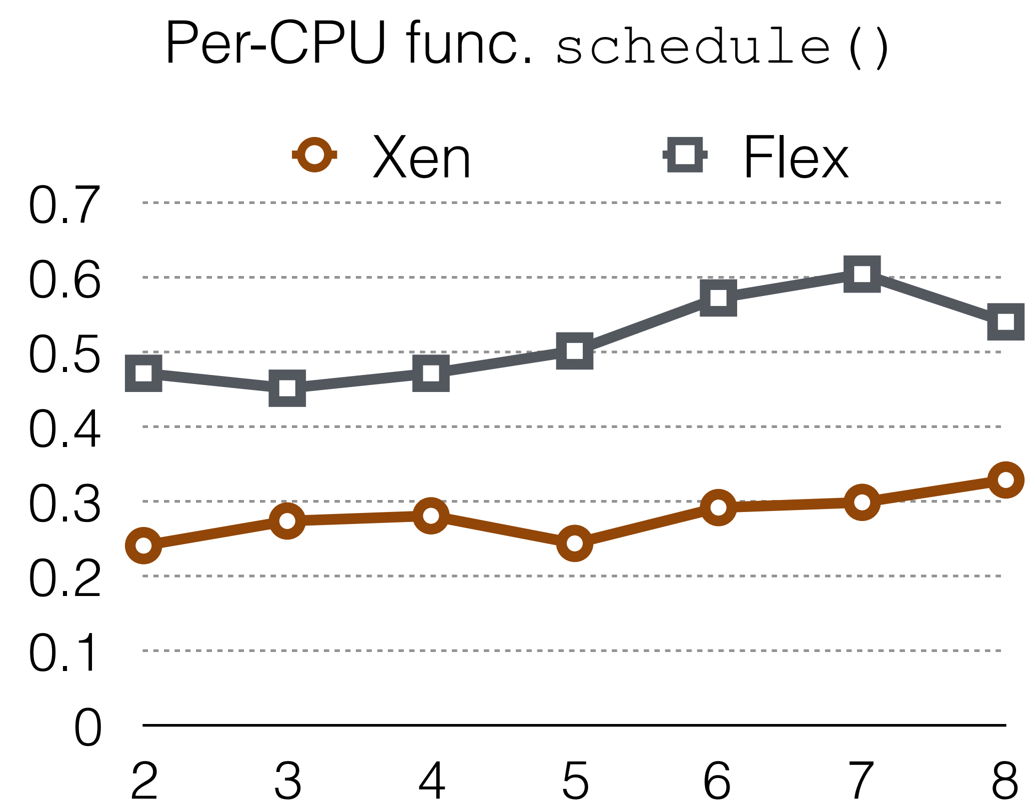


Overhead



FlexW overhead: VM weight adjustment

Overhead increases with # of VMs
performed by the *idle* VM
not affecting parallel performance



FlexS overhead: vCPU stealing

constant overhead, not increases with # of VMs
frequency of schedule() - 30ms
less than1% overhead

Conclusions & Future Work

- Fairness-efficiency tradeoff
  - Straightforward solutions to unfairness lead to poor efficiency
- **Flex**: a holistic solution
  - Adaptively adjusts weight for fairness
  - Flexibly schedule vCPUs to minimize wasted work
  - **Problem**: NOT quite effective for apps with dynamic task assignment
- Future work
  - **Cross-layer** application-cloud coordination

Thank you !

Questions?

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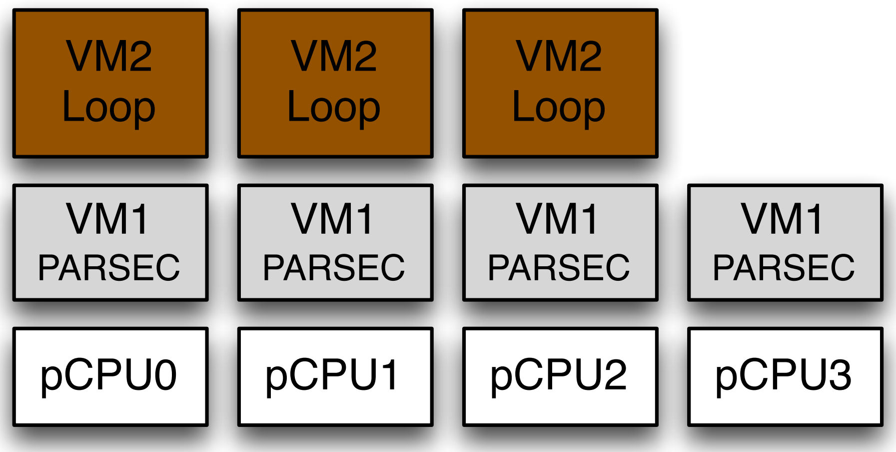
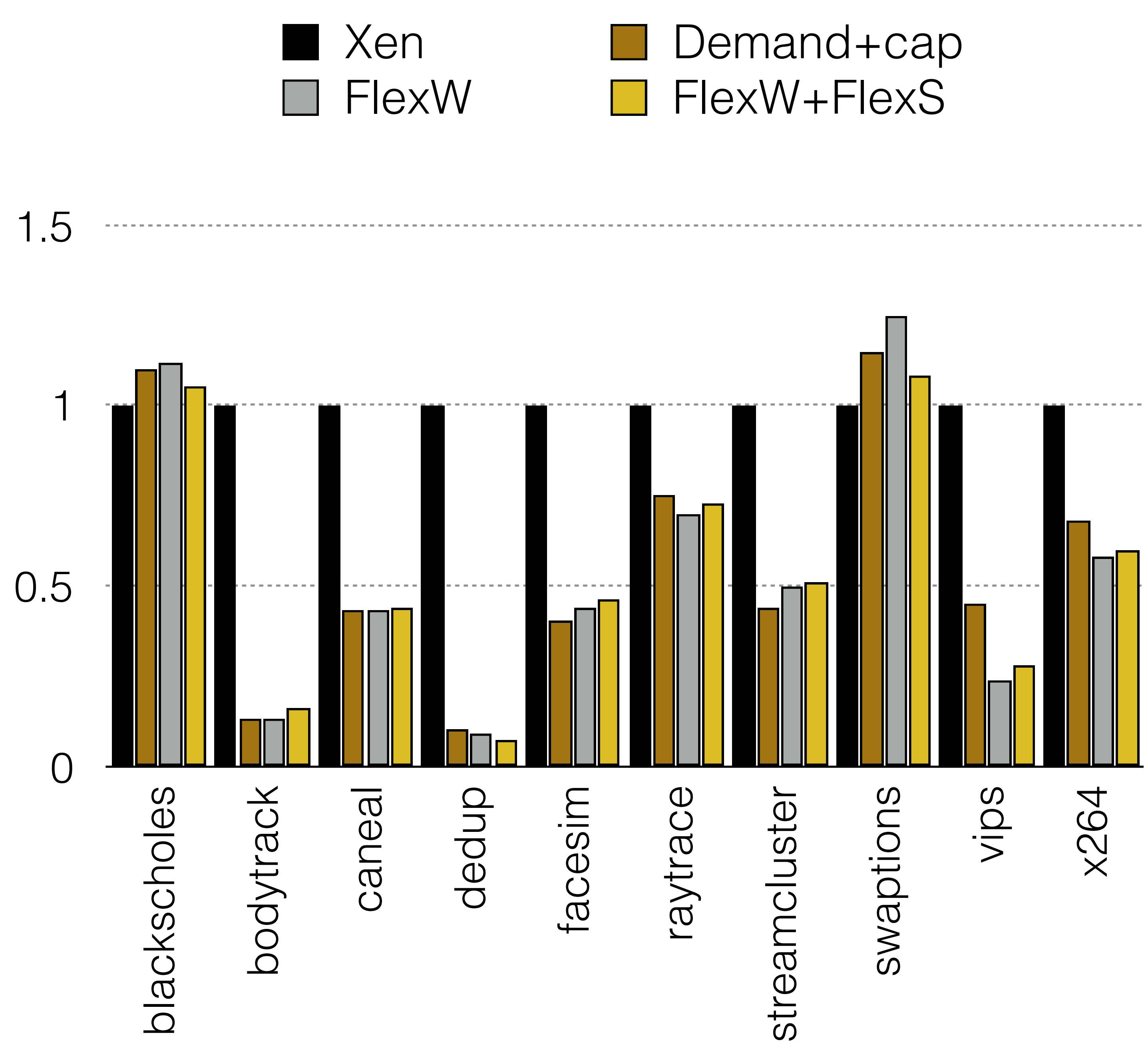
Backup Slides Begin Here …

Parallel Performance (blocking)





Observation: Both Flex and demand+cap improve perf.

Reason: Avoiding vCPU stacking helps a lot

Conclusion: Flex does not incur much penalty to blocking sync.-based apps