Speculative Use of Idle Resources

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Topic

- Use idle OS capacity speculatively
- Current ad-hoc mechanisms interfere
  - Caching + prefetching
  - Process + data migration
- **Goal: provide unified + integrated idle-time facility**
  - Replace ad-hoc → simplify + improve
  - Enable new techniques

Outline

- Introduction
  - Plenty of idle capacity → utilize it
- Resource model
  - Prioritization, preemptability, isolation
- Open issues
  - Model extensions
  - Costs of idle-time use and speculation
  - Impact of speculation on caches

Outline (Cont.)

- Proof-of-concept implementation
  - Idle-time networking
- Related work
  - Real-time systems
  - Speculative techniques
  - Non-speculative uses for idle-time
- Proposed research
  - Application: idle-time NFS

Introduction

- Motivation
  - Much idle capacity…
- Key Idea
  - …utilize it
  - Goal: all resources always busy
- Analogy
  - CPU with speculative branch execution

Motivation

- Idle resources = lost opportunity
- Idle capacity available, even when system is “fully loaded”
  - 50-70% memory available
  - 70% of CPUs idle (Condor)
- **Idea: use idle OS resource capacity speculatively**

Key Idea

- **Use idle OS capacity speculatively**
- Can interfere with regular use, causing…
  - …**delay** → minimize
  - …**incorrect processing** → prevent
- Both must be addressed
- Similar: CPU w/speculative execution

Analogy: CPUs

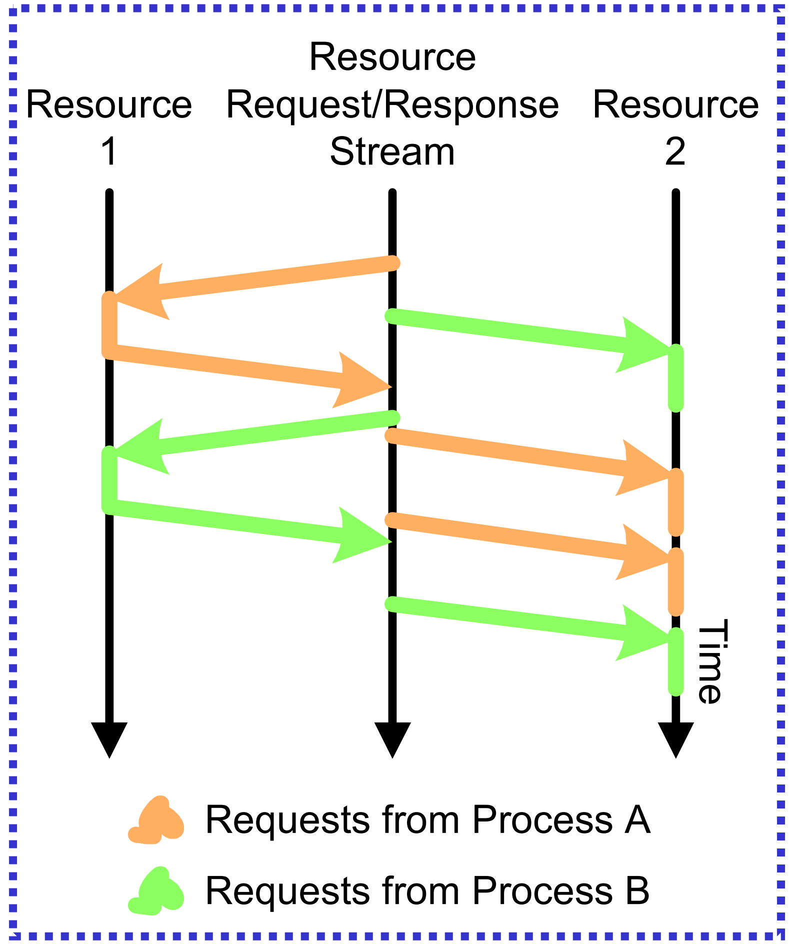
- Predict control flow (**speculate**)
- Execute likely future instructions
- Use **idle resources**
  - Bus bandwidth → pre-fetching
  - Execution units → pre-execution
- Speculation cost < performance gain
- Reduce **speculation cost** with hardware

Model

- Speculative idle-time use requires
  1. **Access to idle-time capacity**
  2. **Mechanism to speculative use it**
- Define simple models
  - Resource use
  - OS processing
- Identify required properties for (1) and (2)
- **Task:** validate model

Simple Resource Model

- **OS sees resource request stream**
  - "Send packet"
  - "Allocate page"
  - "Run me"
- Distinguish requests
  - FG (regular)
  - BG (idle-time)
- Minimize FG delays
  - Examples follow…



Principles

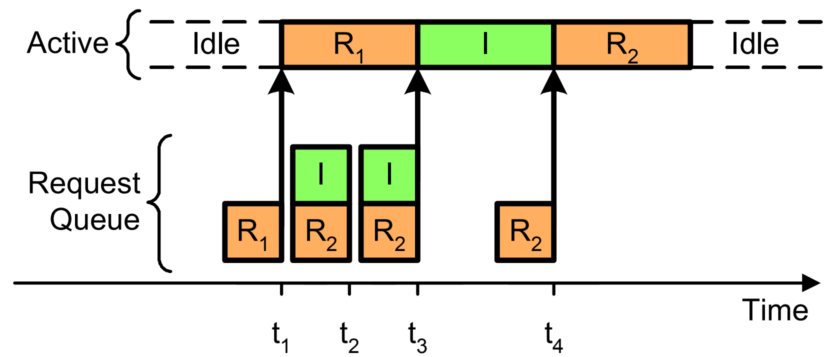
1. Prioritization
2. Preemptability
3. Isolation

- **All 3 required…**
  - (1) + (2) → min: prevent FG starvation
    opt: minimize FG delay
  - (3) → maintain correctness
- **…for all resources**
  - Bottleneck resource controls behavior

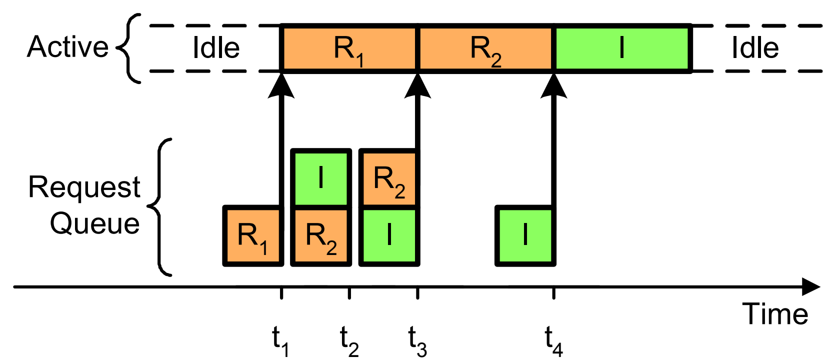
Prioritization

- Never process idle-time requests while regular requests are waiting
- **Priority queue**

- Before



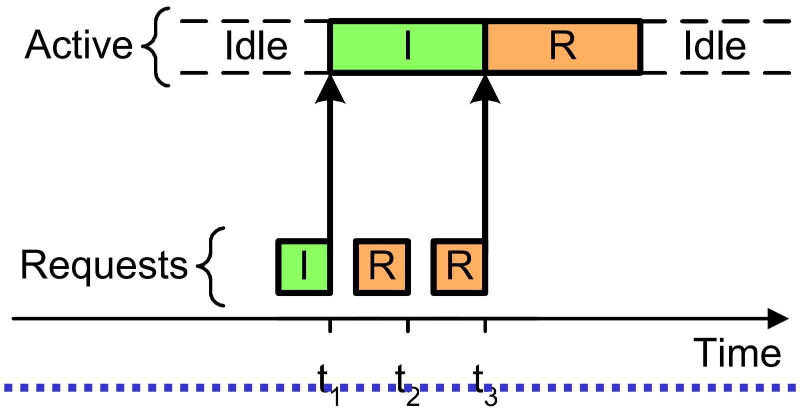
- After



Preemptability

- Preempt active idle-time use for incoming regular requests
- Never preempt regular requests for idle-time use
- **Preemptive servicing**

- Before



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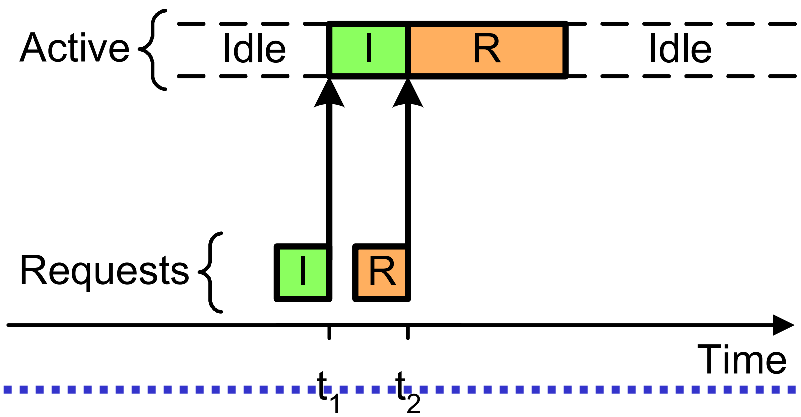
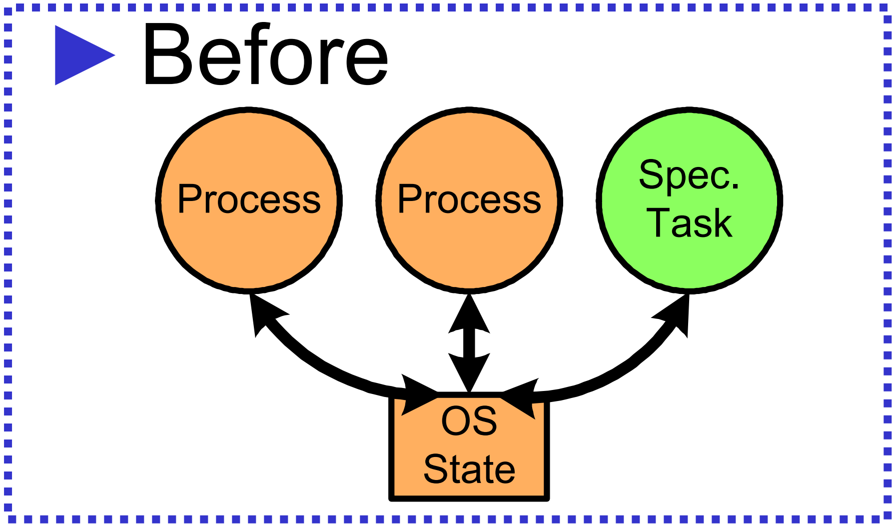
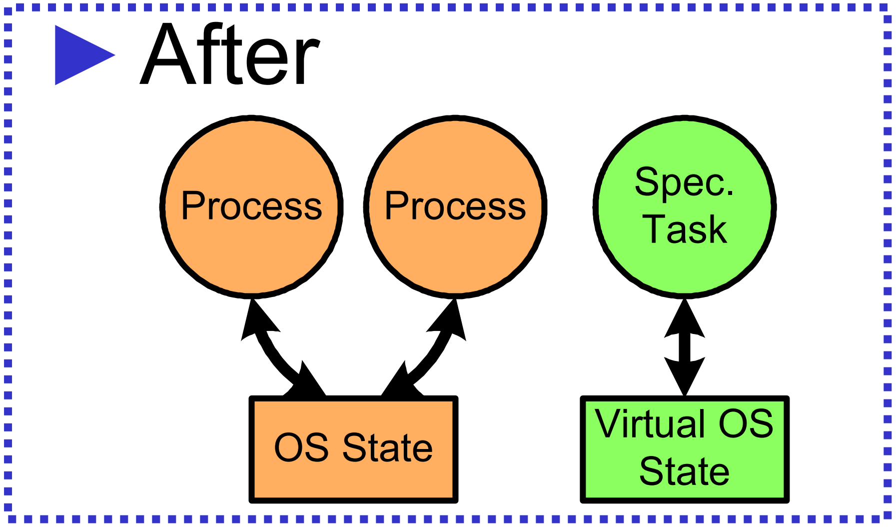


Isolation

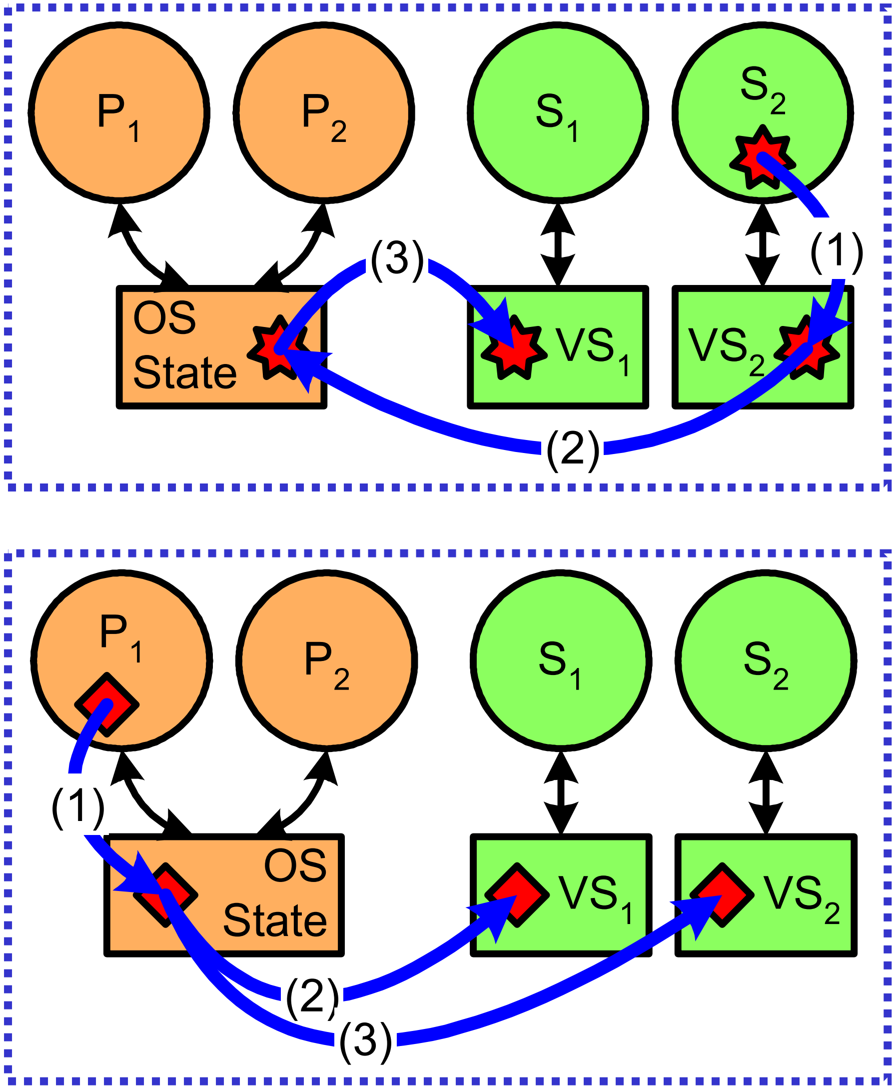
- Side effects of speculations remain hidden until committed or discarded
- **Virtualize OS state**





OS State Virtualization

- Speculations modify **virtual state**
- Successful speculation → **atomic commit**
- Regular state update → **propagate** to virtual states



Resource Categories

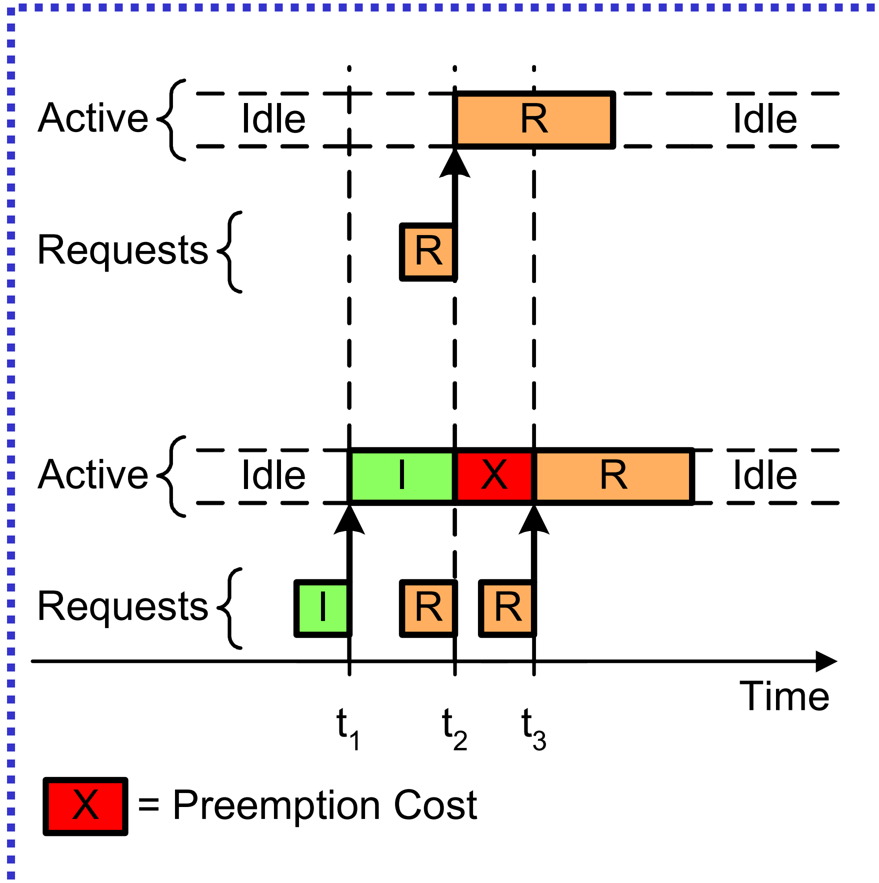
- Spatially-shared
  - Capacity divided → **serve >1 request**
  - **Allocation units** leased indefinitely
- Temporally-shared
  - Not subdivided → **serve 1 request**
  - **Full capacity** leased for 1 request
- Physical devices may combine both
  - Disk: I/O temporal, storage spatial

Open Issues

- Preemption cost
- System-wide support for idle-time
- Inter-resource interference
- Capacity reallocation
- Effects on caches
- Speculative workload generation
- Integrated scheduling of speculations

Preemption Cost

- **Minimize cost**
  - Fixed overhead
  - $\sum$cost < $\sum$gain → win
- Devices often not interruptible
- Some evidence
  - Workload bursty
  - Worst-case rare



Need Model Extension

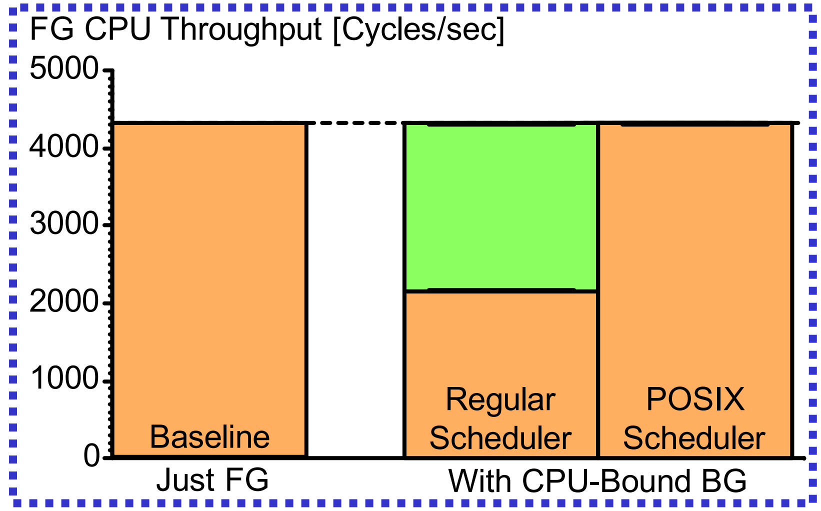
- Current model simplistic
- Does not describe
  - Preemption cost
  - Speculation gain
  - Virtual resources
    - Are themselves users of other resources
  - Dynamic costs (stateful resource)
- **Task:** extend model

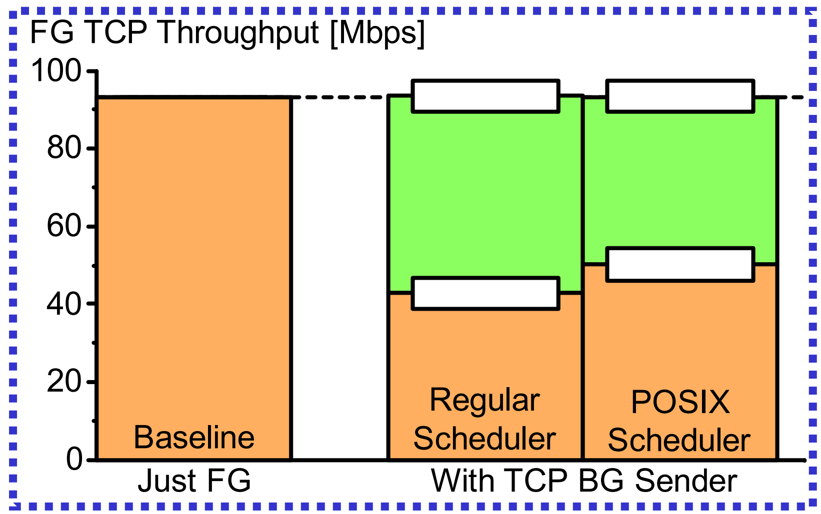
System-Wide Idle-Time

- All resources must support idle-time
  - Bottleneck resource unknown
  - Its scheduler controls overall system
- Unmodified scheduler → interference
  - Example next slide
- **Task:** support other resources
  - For idle-time NFS: disk I/O + storage

Example: CPU vs. Network

- POSIX real-time CPU scheduler extensions
  - Prioritization
  - Preemptability
- Experiment: bottleneck...
  - ...**=** CPU → **good**
  - ...**≠** CPU → **bad**
- POSIX only effective when bottleneck = CPU





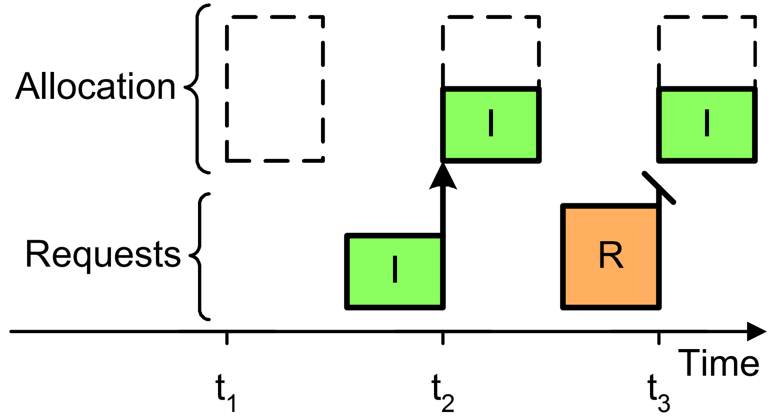
Inter-Resource Interference

- Idle-time use of one resource delays/preempts regular use on another
- Problem: kernel interrupt handling
  - Priority: Lower-layer interrupts
  - Work-conserving interrupt handlers
- Approach: vertically-structured OS
- **Task?** evaluate “vertical” OS

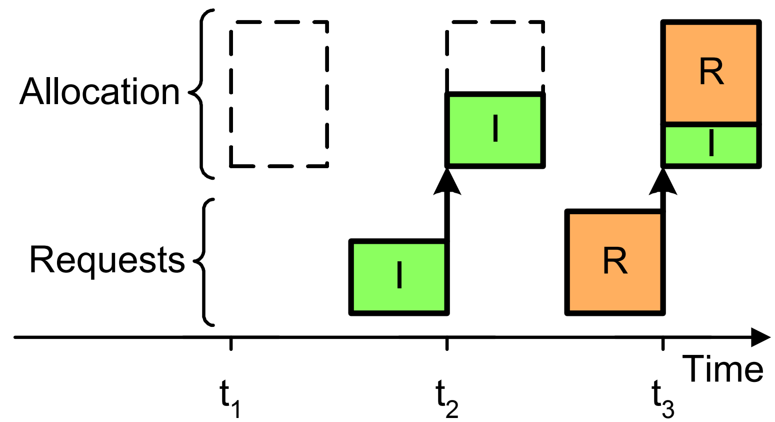
Capacity Reallocation

- Reclaim (enough) idle-time for FG
  - Only for **spatially-shared** resources, e.g. disk space
- Idle-time tasks must cope
- **Task:** investigate transparent reclaim mechanisms

- Before



- After



Effects on Caches

- Speculation → create/flush entries
  - Cache pollution → **loss**
  - Pre-load effect → **gain**
- **Both** observed in studies
- Safe: disable caches for speculations
  - Loose benefit, issue: hardware cache
- **Task?** investigate “cache = resource”
  - Partition + speculate with capacity

Speculative Task Creation

- Who generates speculative tasks?
- Ideal: automatic generation (OS)
  - Hard: cannot look ahead
  - CPUs can, instruction stream static
    - Branch ambiguities are resolvable
  - Resource request stream is dynamic
  - Possible in some cases (Chang)
- **Outside the scope of this proposal**

Integrated Scheduling

- Multi-resource speculation
- Finish unlikely if not all available
- **Availability controls speculation scheduling**
- Need resource requirements
- **Task?** investigate integrated scheduling

- **Task A** uses CPU + net
- **Task B** uses CPU + disk
- Assume net busy
- **Task B** more likely to finish

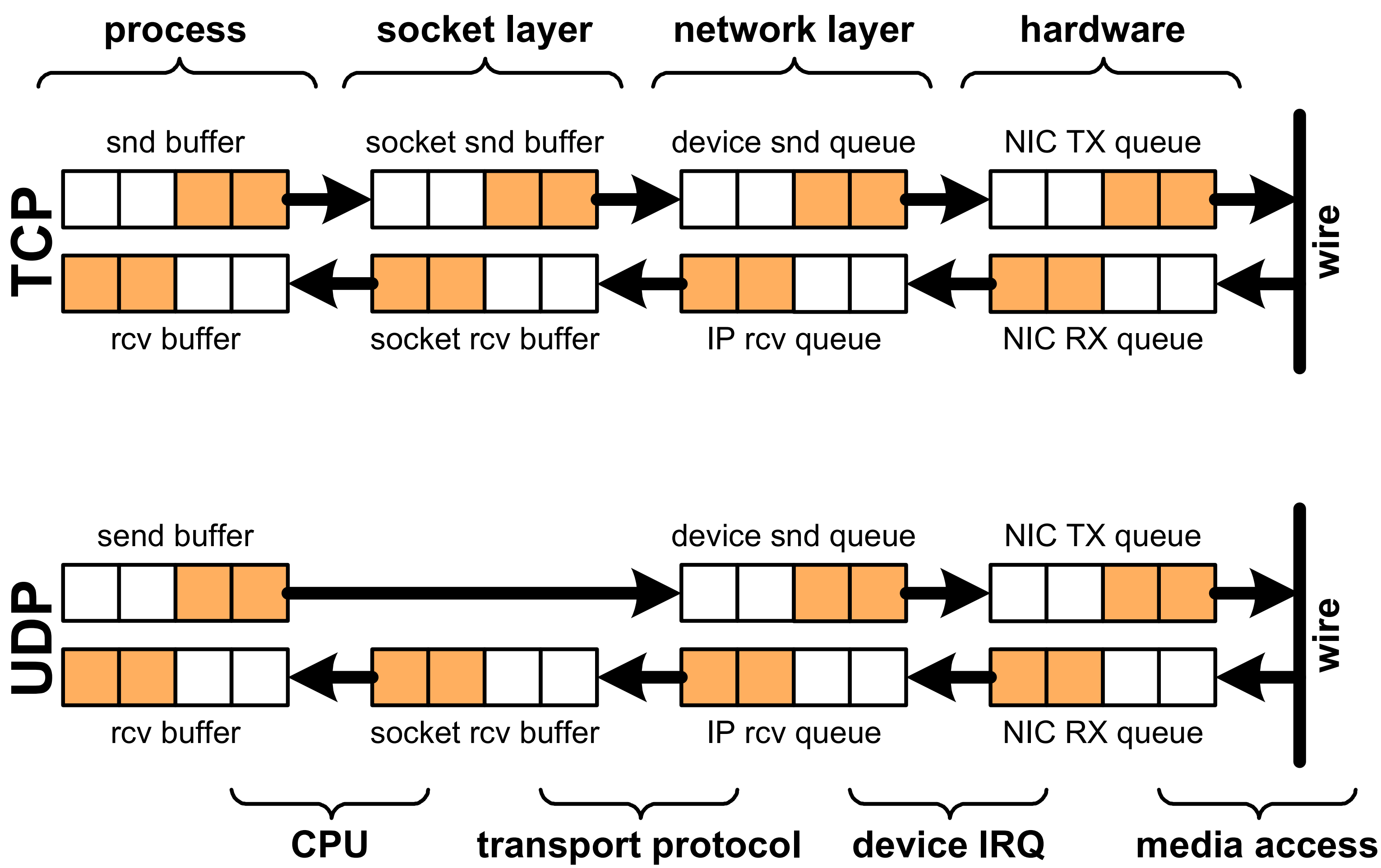
Idle-Time Networking

- Proof-of-concept for model
- **3 principles applied to Internet**
  - Prioritization → two traffic classes
  - Preemptability → abort send/receive
  - Isolation → IP routers are stateless
- **ITN for IP is simple extension**
  - FG = best-effort, BG = “effortless”
  - Similar to diff-serv, etc.
    - But lower-than-default priority

ITN End System Support

- ITN simple for routers (layer 3 only)
  - Use diff-serv “expedited forwarding”
  - Similar to some link layer mechanisms
    - Frame Relay “discard eligible”
    - UNI ATM red/green marking
  - Out of scope (assume present)
- **End systems process layers 3-5**
  - Use router-like layer 3 mechanisms
- Need new mechanisms at layers 4+5

UNIX Network Processing



ITN Mechanism

- **Drop BG when FG active**
  - "Active" = data queued at socket
  - Simplistic + sender-side only
  - TCP drop → congestion control
  - UDP drop → rate reduction (maybe)
- Features

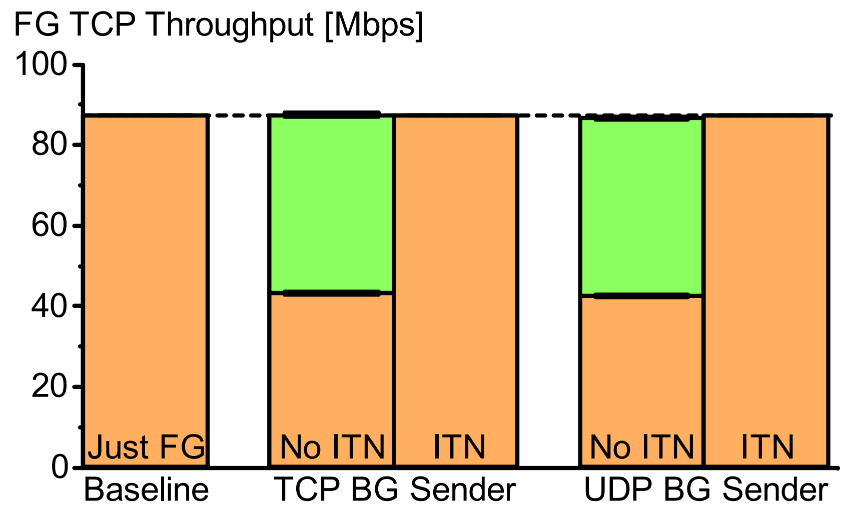
Prioritization	**Yes**	
Preemptability	**Yes**	(packet-level)
Isolation	**No**	

ITN Implementation

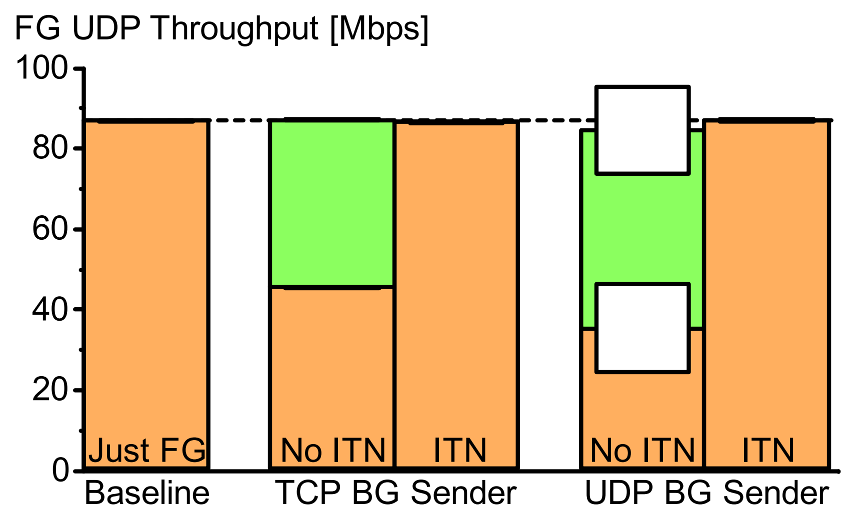
- Proof-of-concept implementation
  - FreeBSD 4.X + modified KAME/ALTQ
  - Linux (CS558 students)
- FreeBSD experiments
  - Private, switched 100Mbps Ethernet
  - Parallel FG + BG sending processes
  - 2 protocols: TCP + UDP
  - 2 FG sender loads: 10% + 100%

ITN Results: FG 100% Load

- FG: TCP
- BG: no, TCP, UDP
- FG: no ITN: ~50%
- **FG ITN: ~99%**

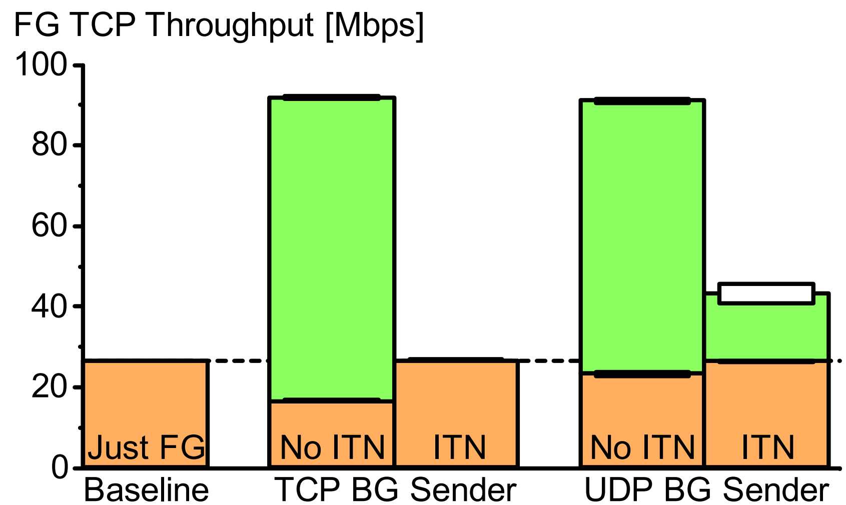


- FG: UDP
- BG: no, TCP, UDP
- FG no ITN: ~47%
- **FG ITN: ~98%**

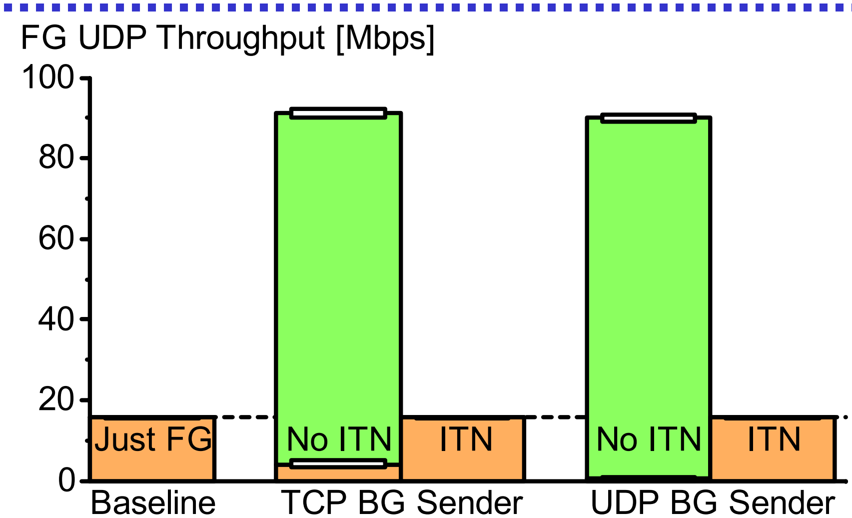


ITN Results: FG 10% Load

- FG: TCP sender
- BG: no, TCP, UDP
- FG no ITN: <80%
- **FG ITN: ~98%**



- FG: UDP sender
- BG: no, TCP, UDP
- FG no ITN: <20%
- **FG ITN: ~97%**



Implementation Summary

- Simplistic proof-of-concept design
  - Prioritization + preemptability
  - No isolation
  - Sender-only
- Still effective
  - Isolate FG from BG to within 1-2%
    - Depends on packet size
- **Task?** design isolation mechanism

Related Work

- Real-time systems
- Speculative use of idle capacity
  - Prefetching + caching
  - System optimizations
  - Process/data migration
  - Speculative execution in hardware/software
- Non-speculative uses of idle-time
  - Maintenance tasks

Real-Time Systems

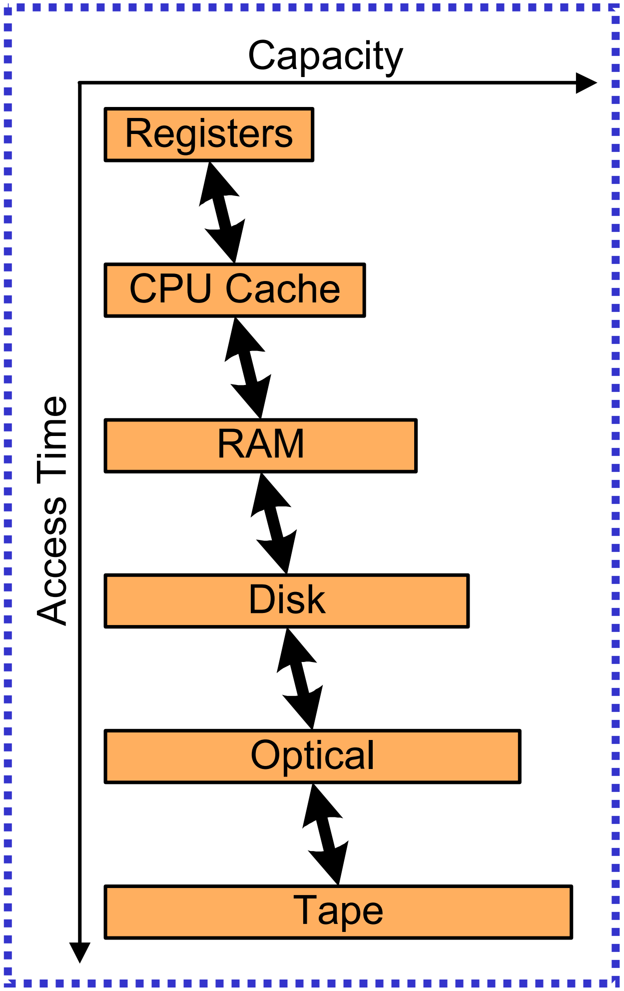
- Correctness of computation depends on **timeliness**
- Key components
  - **(P)** Predictability
  - **(RRS)** Resource requirements specification
  - **(AC)** Admission control
- **All 3 not required for idle-time**

Real-Time Systems (Cont.)

- RT systems prioritize resources
  - (RRS) + (P) → dynamic scheduling for periodic workloads
- **RT prioritized schedulers OK for idle-time prioritization**
- Strict preemptability not required
  - Any order OK that meets deadlines
- RT systems have no isolation

Prefetching + Caching

- Goal: latency hiding
  - Cache: replicas in fast storage
  - Prefetch: interleaved retrieve (then cache)
- Ad-hoc mechanisms for idle-time + speculation
- **Improved through proposed mechanisms**
  - Prefetch in idle capacity
  - Cache in idle storage



Speculative Optimizations

- Disk block replication in idle storage
- Disk arm movement in idle time
- Defragment FS
- “Prefetch the means” (warm caches)
  - Tragedy of the commons
- IKE negotiation + PMTU discovery
- Recompilation, dynamic optimization
- **All predict - none preempt, prioritize or consider costs**

Process + Data Migration

- **Local work → remote idle times**
  - PM: Sprite, Condor, V-System, Butler
  - DM: Mether, SETI, distributed.net
- Detect/predict remote idle times
  - Coarse heuristics focus on 1 resource
  - Idleness system-wide condition
  - Fail to utilize short, transient idle times
- **Only remote hosts benefit from local idle capacity**

Speculative Execution

- Hardware
  - Simultaneous multi-threading
  - Speculative versioning cache
  - Mirage: treat bandwidth for latency
- Software
  - Speculative branch execution in LISP
  - Method-level speculation in Java
  - Information agents

Non-Speculative Uses

- System maintenance
- File system
  - Reorganize LFS
  - Check integrity
  - Scan for viruses
- Cron jobs, net news, email…
  - Try to run with idle resources
  - At deadline, process regularly

Proposed Research

- **Idle-time NFS**
- Extends existing idle-time network
- Requires new mechanisms
  - Disk bandwidth + storage
- File system
  - more interactions + operations
  - FTP, HTTP mostly read-only
- **Addresses several “tasks”**

Tasks

- Proposed research
  1. **Extend model for costs + gains**
  2. **Validate (extended) model**
  3. **Idle-time support for disk I/O + storage**
  4. **Reclaim mechanism for disk storage**
- Tasks outside the thesis scope
  5. Integrated scheduling
  6. Design isolation mechanism
  7. Evaluate vertically-structured OS
  8. Treat caches as resources

Conclusion

- Use idle resources speculatively
- Principles
  - Prioritization, preemptability, isolation
- Issues
- Idle-time networking
  - Implementation + experiments
- Related work
- Proposed research
  - Idle-time NFS