Towards a Unified Theory of Replication

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Why a Unified Theory of Replication?

(1) Better way to build replication systems

(2) Way to build better replication systems

Better Way to Build Replication Systems

Separate mechanism from policy
- Continuum of policies v. point solutions

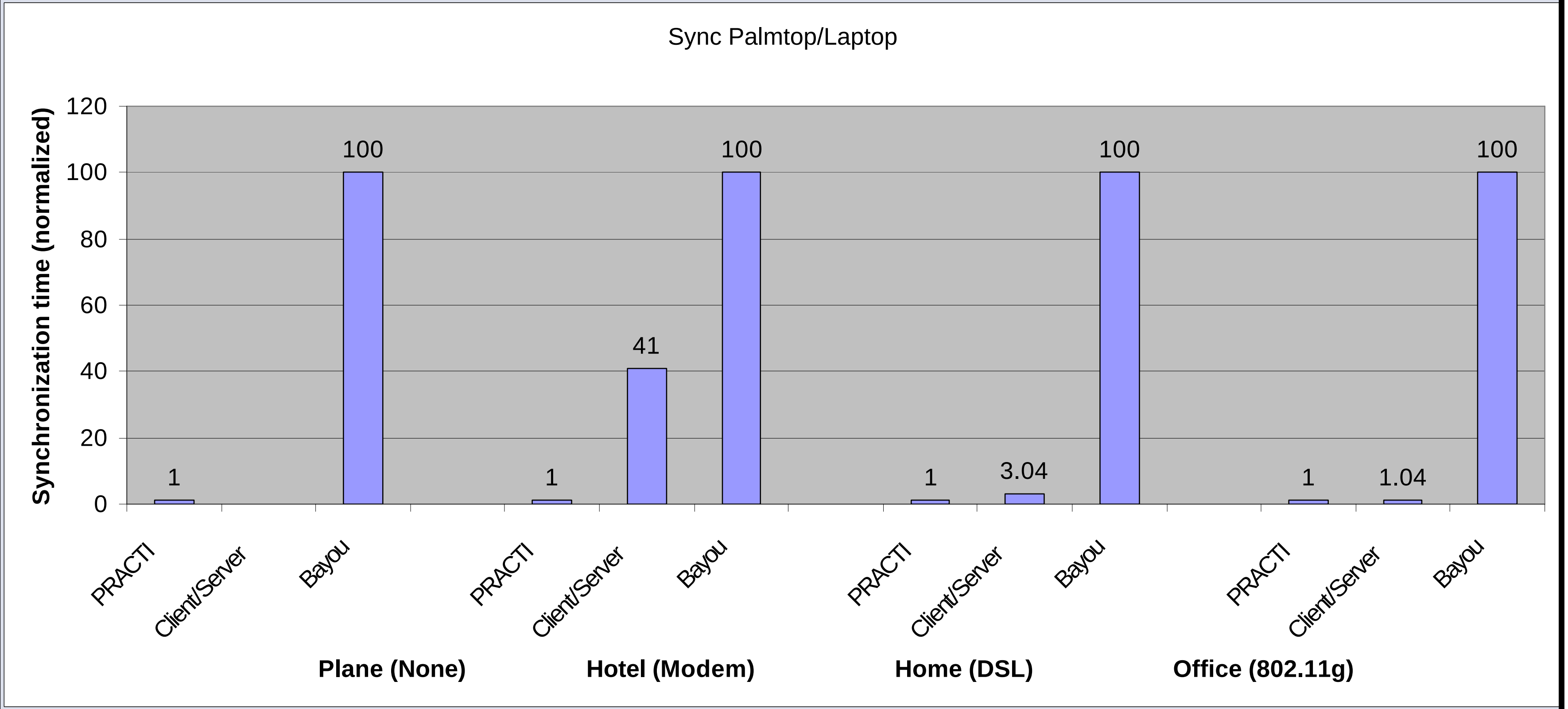
Simpler to design and deploy
- Replication microkernel or toolkit

Integrate disparate theories/protocols
- Quorums, client-server, leases, server replication, p2p, …

Simplify teaching
- A few principles v. a bunch of case studies

Goal: Reduce the development effort for a new replication system by an order of magnitude

A Way to Build Better Replication Systems



Synchronize palmtop to laptop

- Client-server: Limited by network to server
- Bayou: Limited by fraction of shared data (1%)

Order of magnitude improvements available!

Outline

- Case for a unified theory of replication
- PRACTI: A first step
- Evaluation
- Future directions

Case for a Unified Theory of Replication*

Current systems entangle mechanism with policy

- E.g., Coda v. Bayou
- 14 OSDI/SOSP papers in 10 years
  - New environment → new trade-offs → new mechanisms
  - Not clear new systems dominate old ones (or that 14 is "enough")

Current literature fragmented

- Client-server v. quorums v. server replication v. p2p v. …
- E.g., Coda and Bayou each have separate server-replication and client-server caching protocols

Impact

- Systems narrowly tailored for specific environments
- Significant effort to develop system for new environment

* Scope: "Large scale" replication

- WAN, mobile, enterprise, etc.
- File systems, tuple stores, databases, distributed objects, …

Vision: Replication Microkernel/Toolkit

Universal Policy — Policy

Replication Core — Mechanism

Grand Challenges:

- Each large-scale FS from OSDI/SOSP 1990-2005 as <1000-line "policy layer"
- "Universal policy" – self-tuning replication
  - Control replication to meet high level goals
  - e.g., "Minimize response time and maximize availability while providing causal consistency and less than 1 minute staleness to all replicas while using less than 2x demand-read traffic."

Outline

Case for a unified theory of replication

PRACTI: A first step

Evaluation

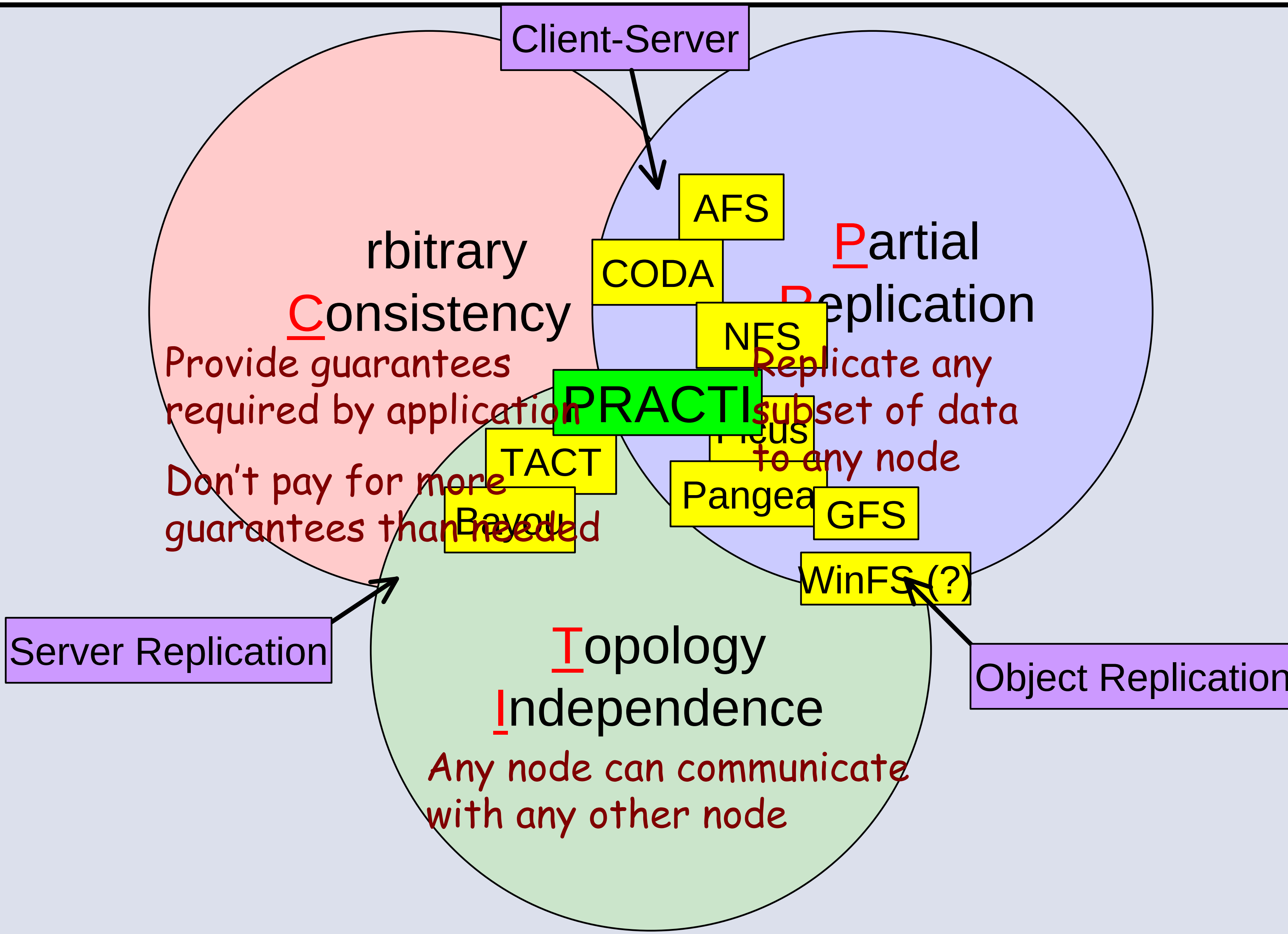
Future directions

“Towards” a Unified Theory

Not there yet

- Today: PRACTI
- Unify large part of design space (almost)
  - Client-server (e.g., NFS, Coda, AFS)
  - Server replication (e.g., Bayou, TACT)
  - Object replication (e.g., Ficus, Pangea)
- Future work to incorporate
  - Quorums, general model of security, DHT-based P2P, content-keyed identifiers, …

Challenge: PRACTI Replication



PRACTI Design Overview

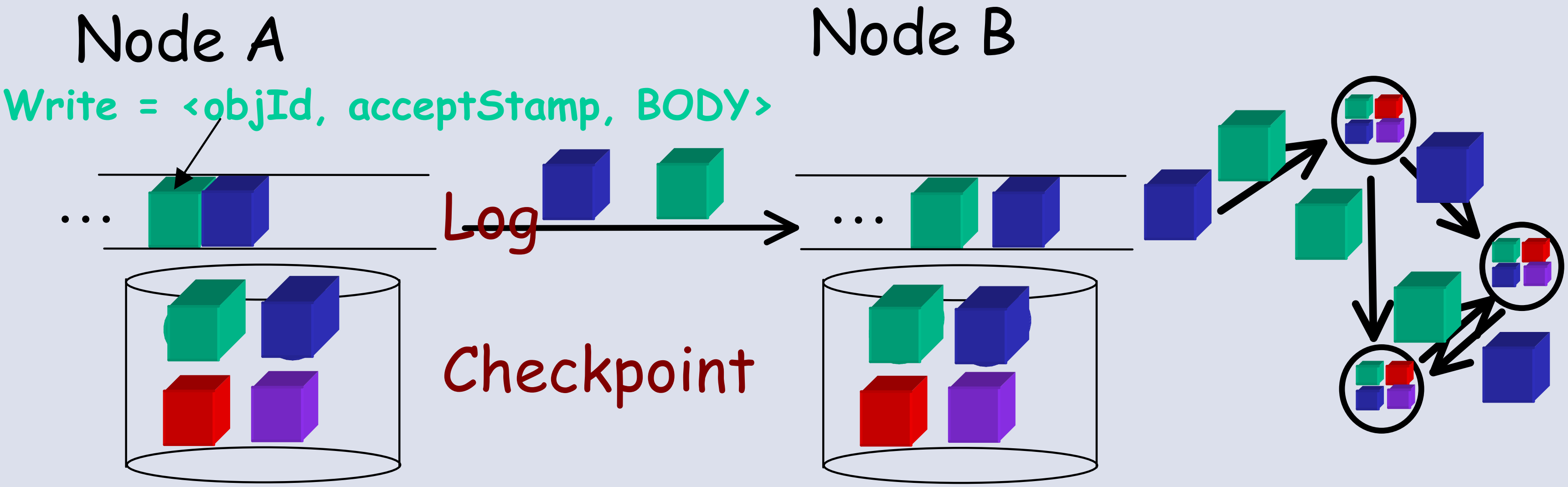
(0) Start with Bayou
- Log-based p2p update exchange
- (Could also go in other direction – generalize client/server…)

(1) Separate data from metadata
- Separate streams for invalidations and bodies
- Challenge: Synchronize these streams

(2) Summarize unneeded metadata
- Imprecise invalidations
- Challenge: Track "precise" and "imprecise" data

(3) Separate mechanism from policy
- Core: PRACTI mechanisms
- Controller: Policy

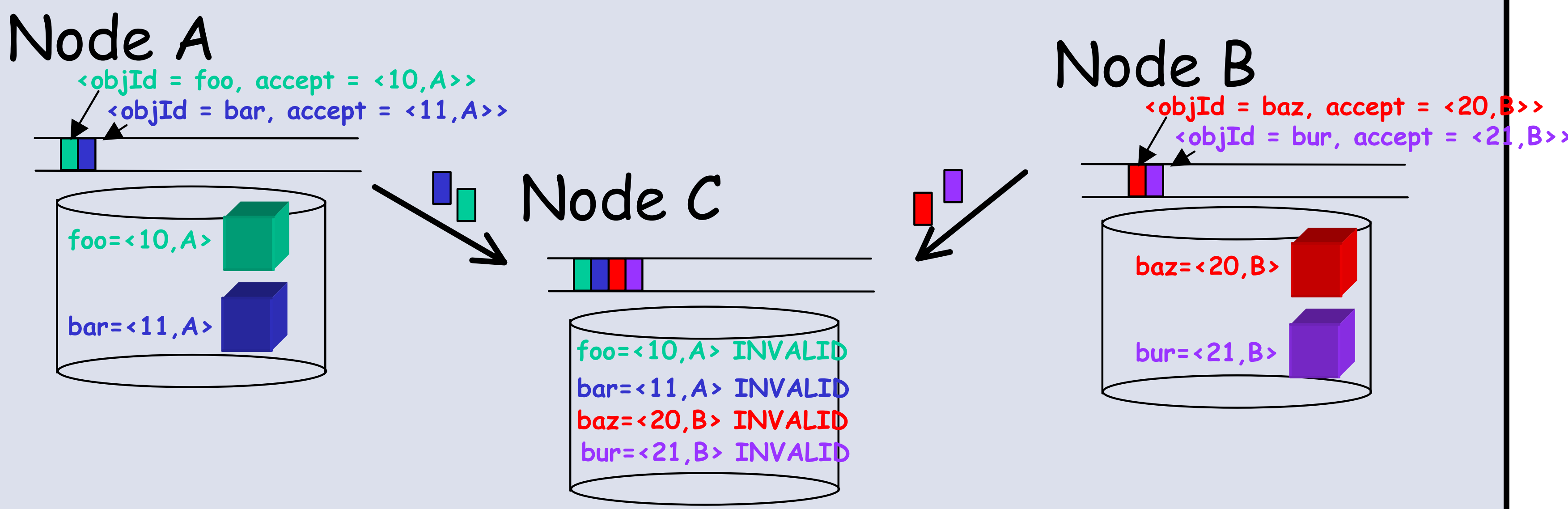
Step 0: Start With Bayou



Updates to log
- Local checkpoint for random access

Log exchange for updates
- ✓TI: Pairwise exchange with any peer
- ✓AC: Prefix property, causal consistency, eventual consistency
- ✘PR: All nodes store all data, see all updates

Step 1: Separate Data and Metadata



Separate data and metadata

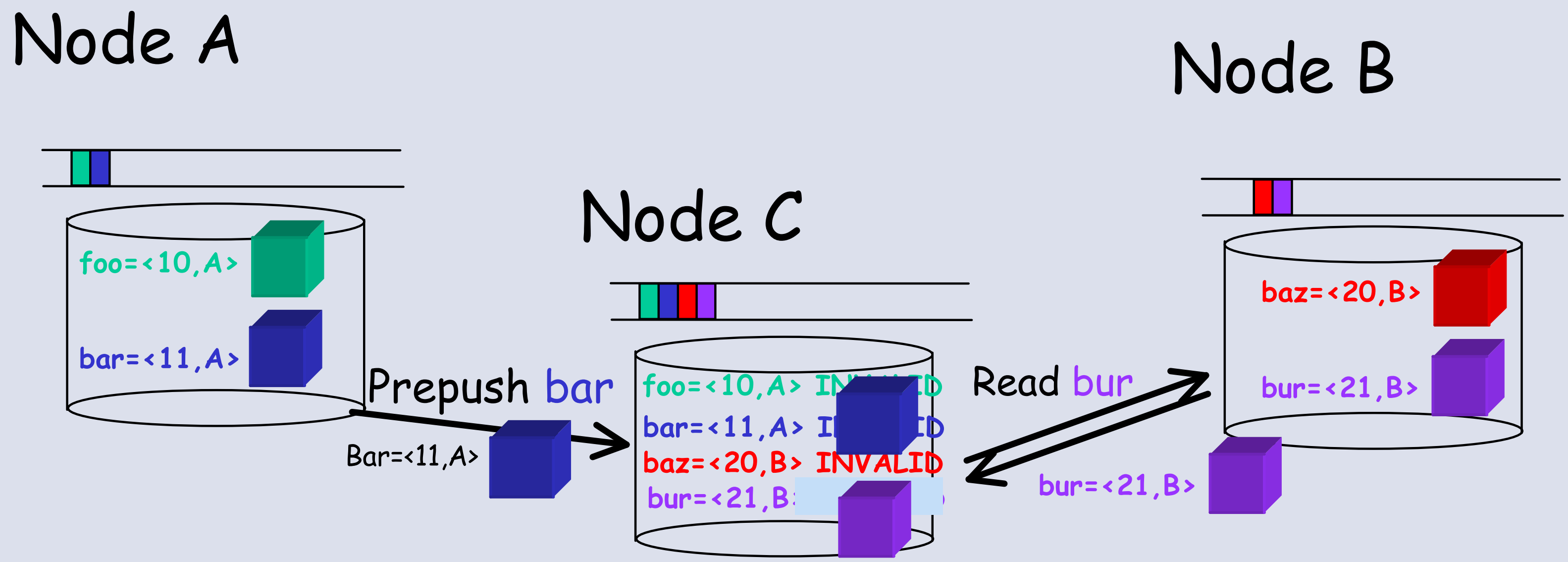
- Metadata: Log invalidations
- Data: Store update bodies in checkpoint

Log exchange:

- Send invalidations separate from bodies

→ Client-server/Server-replication hybrid

Issue: Reading Bodies



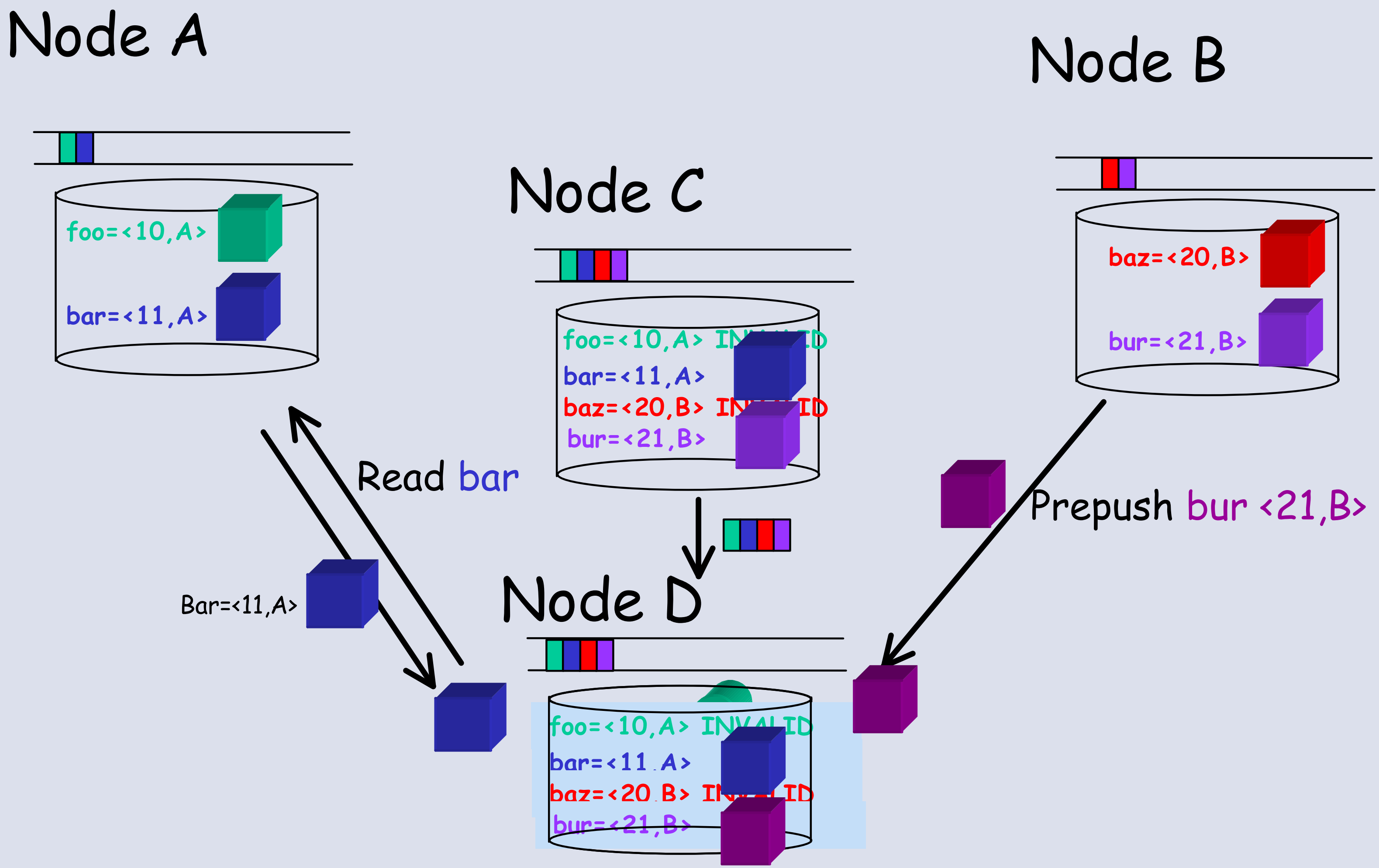
Mechanism: Block until data VALID

- VALID = body matches latest invalidation

Policy: Your choice

- Demand read miss
  - Target is policy choice: client/server, DHT directory, original writer, random, …
- Prefetch
  - TCP-Nice based self-tuning prefetch

Issue: Synchronization of Separate Streams



Retrieved body may be newer than metadata

→ Violate causality

→ Buffer body until apply associated inval

Step 1 Helps…

Keep good Bayou properties

- Topology independence
- Arbitrary consistency
  - Prefix property
  - Causal consistency
  - Eventual consistency

Step towards partial replication

- Nodes only see bodies of interest
  - Order of magnitude improvement!
- Nodes still see all invalidations
  - Limits scalability
    - E.g., Enterprise file system in which every palmtop sees every update by any node

Step 2: Imprecise Invalidations

Nodes subscribe for

- Precise invalidations for interest sets
- Imprecise invalidations for other data

Precise invalidation

- Metadata for one write

  <object ID, accept stamp>

Imprecise invalidation

- Summary of multiple writes

  <objectSet, [start]*, [end]*>

- "One or more objects in objectSet were modified between start and end"

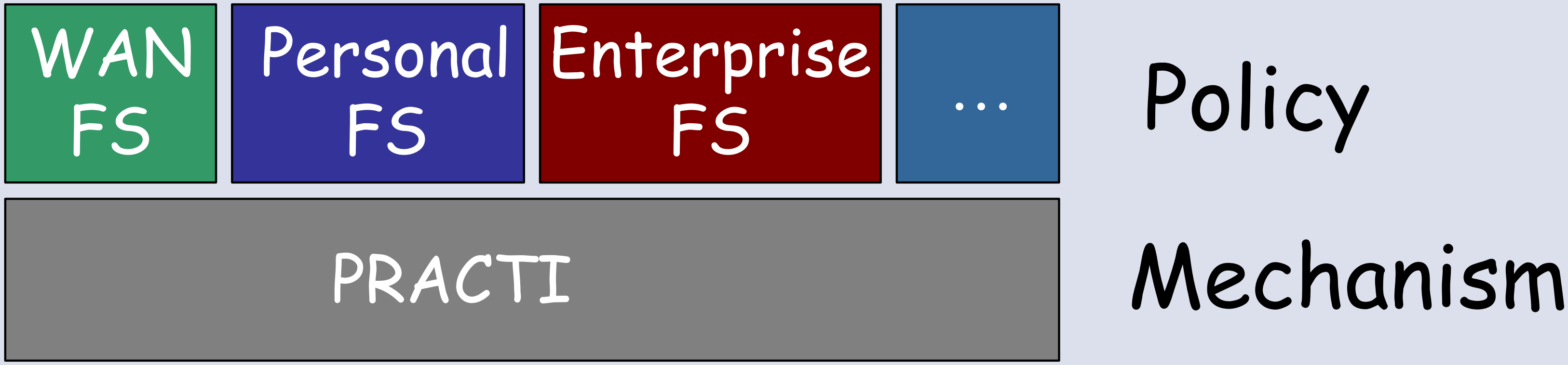
Imprecise Invalidations

<objId, accept>
<objId, accept>
<objId, accept>
<objId, accept>
<objId, accept>
<objId, accept>
<objId, accept>
<objId, accept>

→ <objectSet, [start]*, [end]*>

- Nodes subscribe to invalidation streams
  - Specify which Interest Sets node wants to keep **precise**
  - **Imprecise** Interest Set
    - → Replace collection of invalidations with conservative approximation
    - – Recvr. treats all objects in objSet as if invalidated between start and end
- Bookkeeping details (see paper)
  - Track which Interest Sets are missing invalidations
  - Block reads to **imprecise** Interest Sets
  - Make interest set **precise** when missing invalidations applied

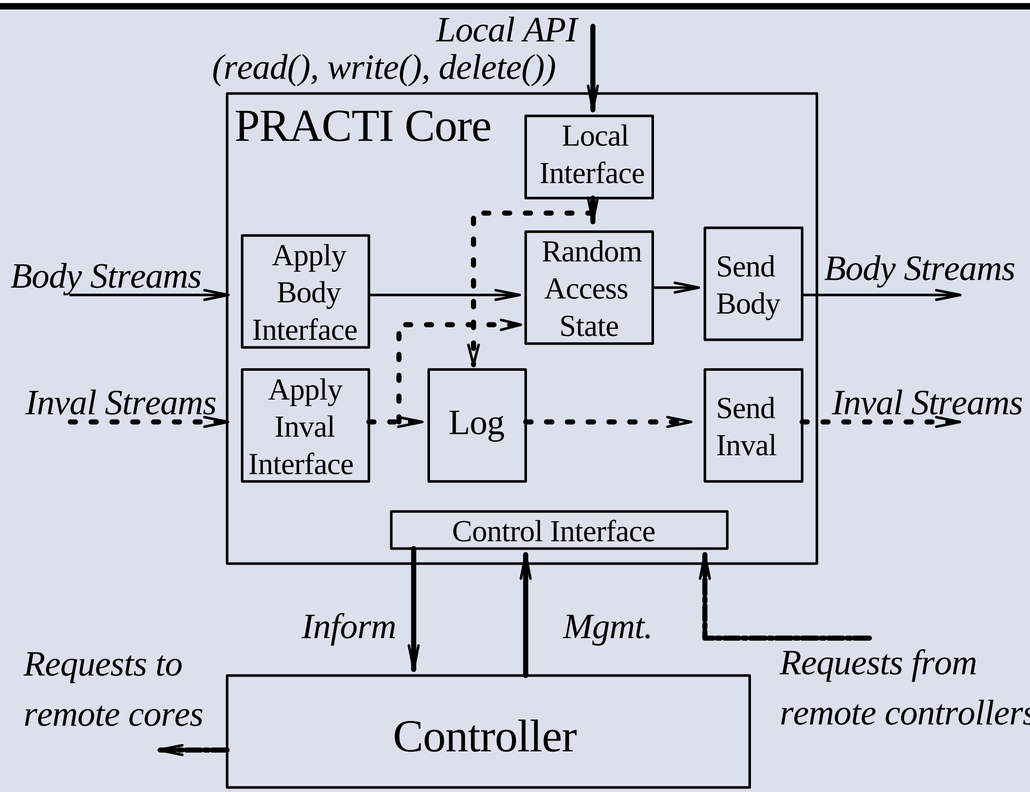
Step 3: Separate Mechanism v. Policy



Goal: Common core mechanism

- "Replication microkernel"
- Vision:
  - Implement replication system for new environment in <1000 lines of policy code

Core v. Controller



Core: Mechanism

- Safety: Any message can be processed at any time
  - Asynchronous message passing style

Controller: Policy

- Liveness: Trigger messages between nodes

Controller Interface

Notified of key events

- Stream begin/end
- Invalidation arrival
- Body arrival
- Local read miss
- …

Directs communication among cores

- Subscribe to inval or body stream
- Request demand read body

Local housekeeping

- Log garbage collection
- Cache replacement

Example: Client-Server Controller

Subscriptions

- Precise invalidations
  - Forall f in <cached files> subscribe to f from server
- Bodies
  - Forall h in <hoard list> subscribe to h from server

Local read miss on file f

```
if(f is imprecise)
   request metadata + body from server
else /* f is precise but invalid */
   request body from server
(read blocks until f is precise and valid)
```

Point of interest perhaps only to me

- Client/server crash recovery really natural/elegant

Example: EnterpriseFS Controller

Support thousands of devices

- Handful of big, geographically distributed servers
- Many desktops, laptops, palmtops, etc.

Read miss

- Use DHT to find nearest copy of data

Replication policy

- DHT tracks file popularity
  - Self-tuning prefetch important updates to where they are/will be needed
- Enforce minimum replication degree for reliability and availability

Details TBD…

PRACTI Design Summary

Result: Subsume many existing mechanisms

- Client/server*: Coda, NFS, AFS, …
- Server replication: Bayou, TACT
- Object replication: Ficus, Pangea, …

Key ideas

(1) Separate data from metadata

- Separate streams for invalidations and bodies
- Challenge: Synchronize these streams

(2) Summarize unneeded metadata

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(3) Separate mechanism from policy

- Core: PRACTI mechanisms
- Controller: Policy

Additional Details

Efficient, continuous update exchange

- Incremental log exchange

Garbage collect logs

- Incremental checkpoint exchange using lpVV data structures

Self-tuning replication

- Prefetch/pre-push bodies over low-priority network channel

Continuous consistency (e.g., TACT)

- Causal consistency by default
- Weaken: Imprecise reads (causal coherence)
- Strengthen: Constraints layer
  - Order error, temporal error, numerical error
- Flexible conflict detection and resolution

Enforce minimum replication for availability

- Bound invalidations

See paper for details

Outline

Case for a unified theory of replication

PRACTI: A first step

Evaluation

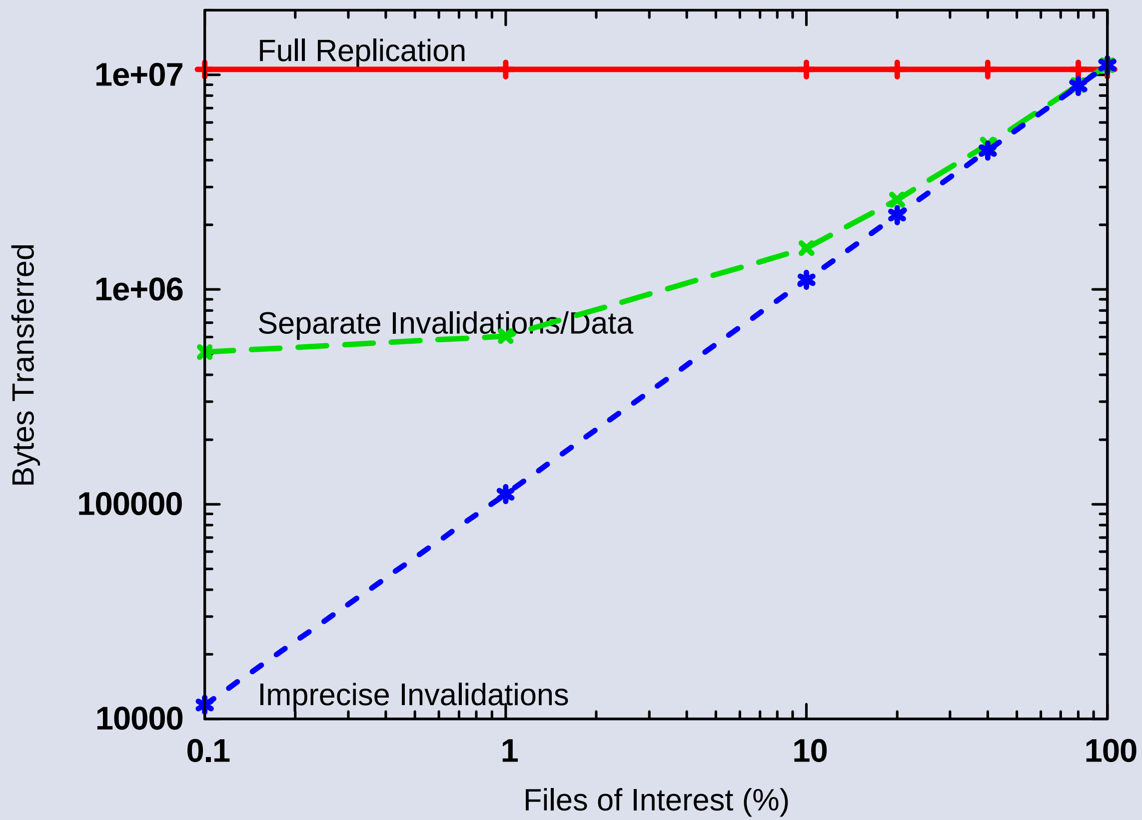
- Methodology
- Benefits of partial replication
- Benefits of topology independence
- Cost of supporting flexible consistency

Future directions

Methodology

How to evaluate "Unified theory"?

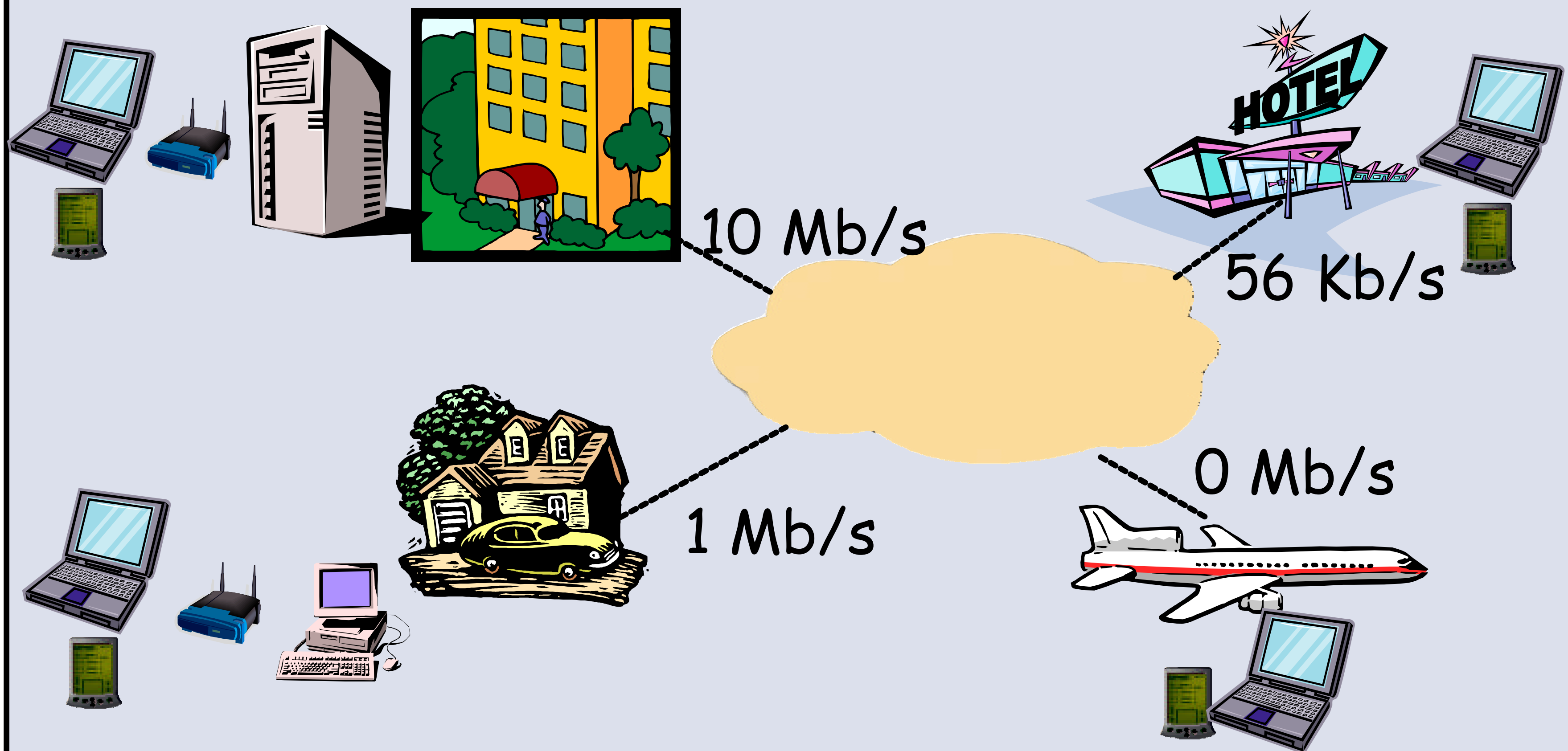
Partial Replication



Order of magnitude improvements

- Both separate inval v. body AND imprecise inval
- Storage requirements see similar improvements

Topology Independence



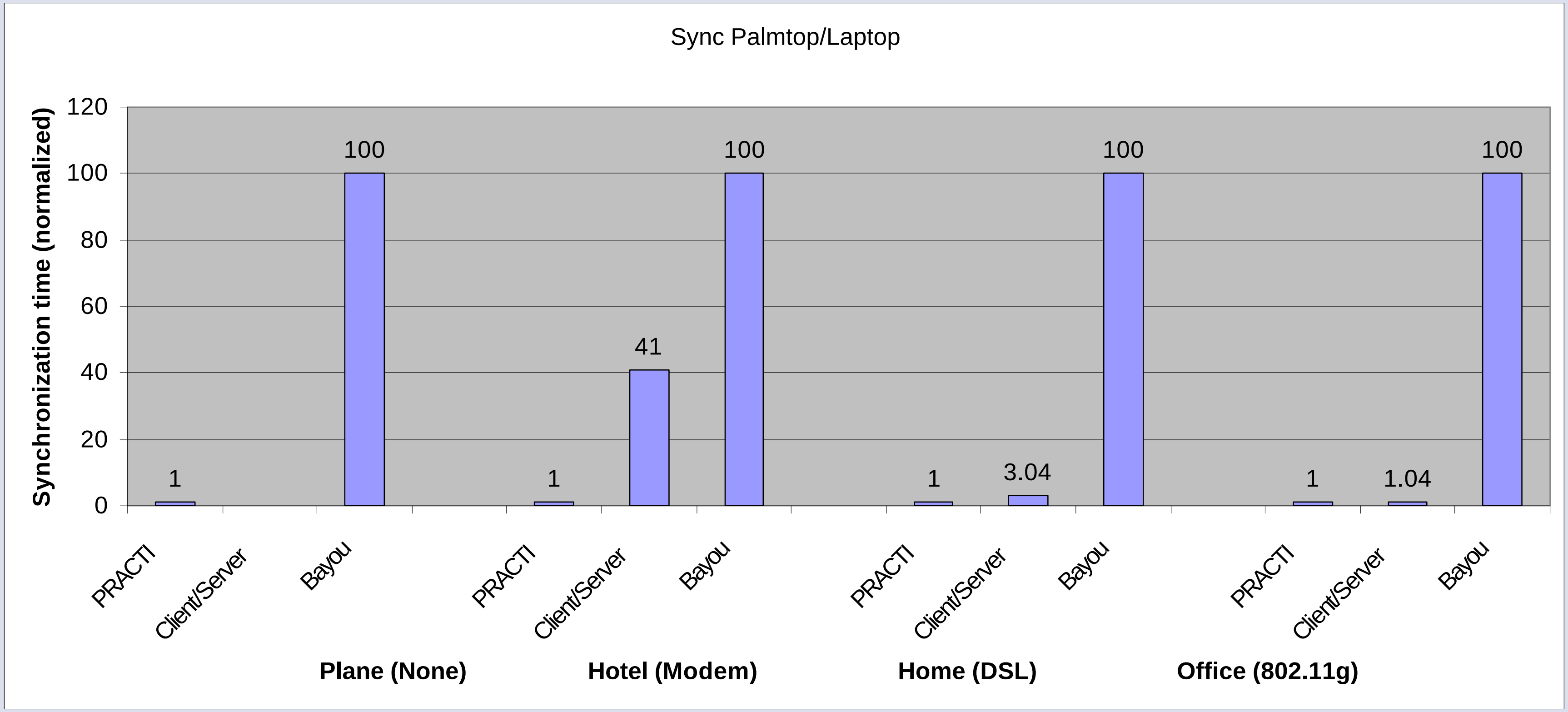
Machines

- Laptop, palmtop, home desktop, office server

Places

- Office, home, hotel, plane

Palmtop/Laptop Sync Time



Synchronize palmtop to laptop

- Client-server: Limited by network to server
- Bayou: Limited by fraction of shared data (1%)

PlanetLabFS

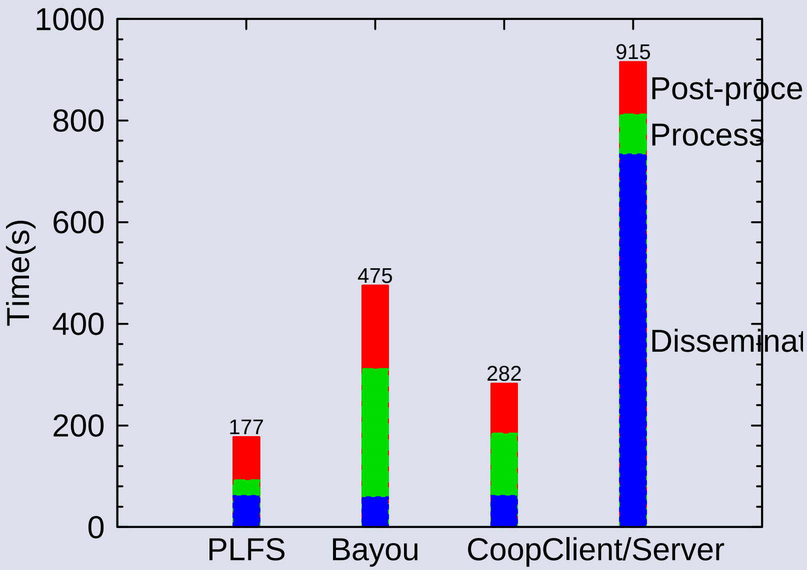
Simplify running experiments

- Track current locations of files via DHT
- Flood initial data, programs from server to clients via cooperative caching
- Direct transfer of data updates among clients via cooperative caching
- Future: Self-tuning prefetching

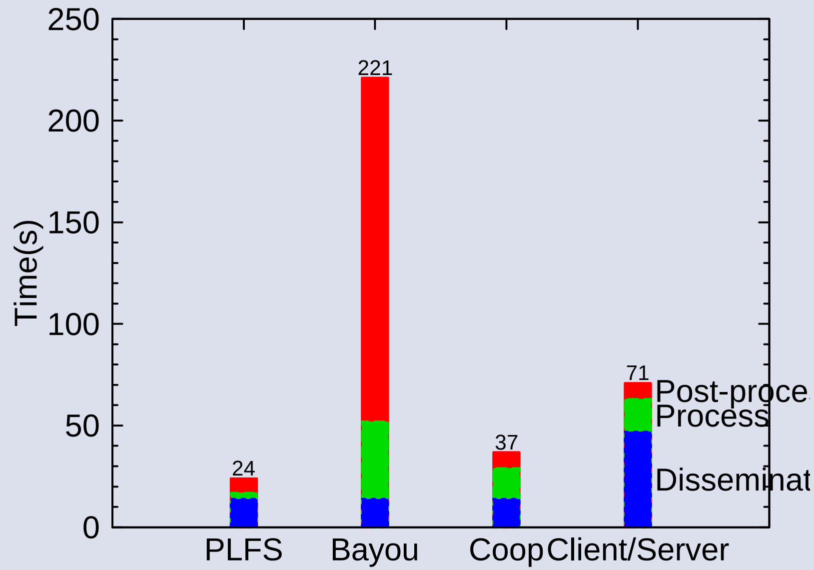
Benchmark

- Phase 1 Disseminate:
  - Disseminate 10MB from server to all clients
- Phase 2 Process:
  - 10x pairwise exchange 1MB between random clients
- Phase 3 Post-Process:
  - Gather 1MB from each client to server

PlanetLabFS



Distributed Nodes



Remote Cluster

- 3x-5x v. client-server (dissemination)
- 2.4x-9x v. server replication (process, post-process)
- 1.5x v. cooperative caching (process)
- TBD: Add self-tuning prefetching

Cost of Consistency

Tunable consistency

- Causal, causal + TACT, sequential, linearizable
- Consistent or coherent
  - Consistency: Order writes across all objects
  - Coherence: Order writes to individual objects

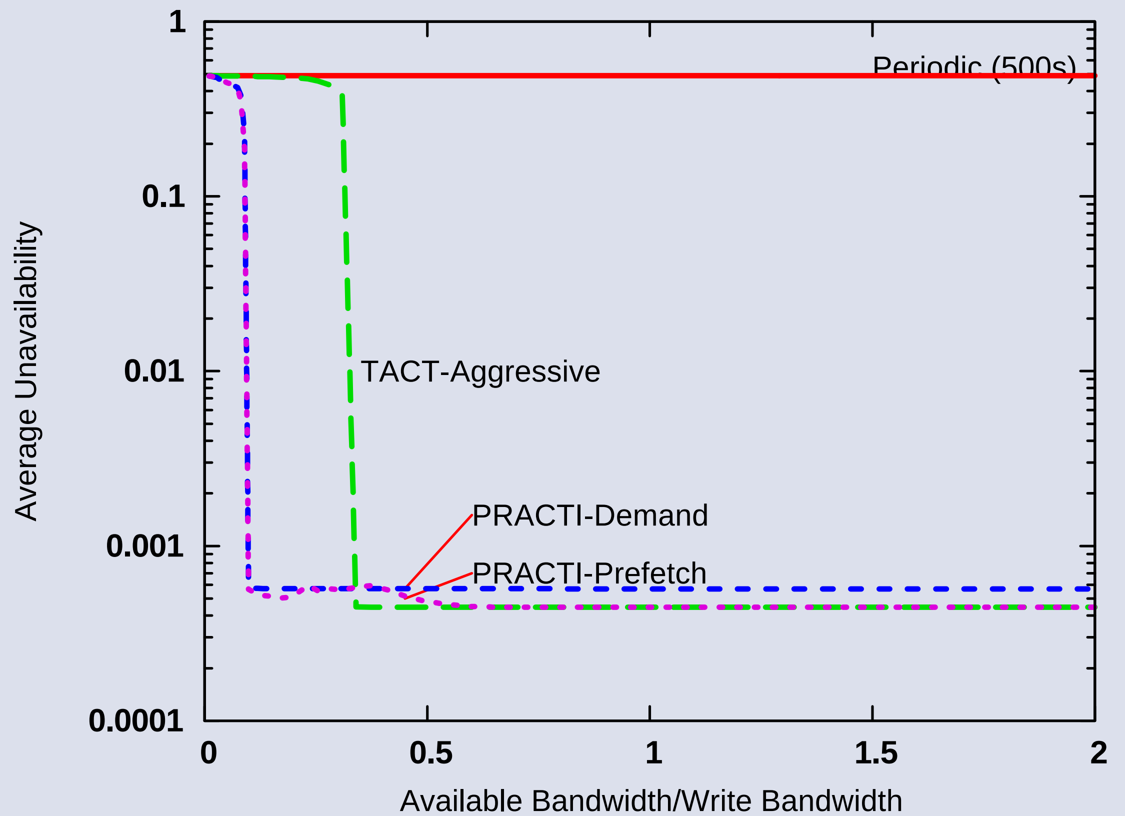
PRACTI benefits

- Semantics specified on per-read, per-write basis
  - What information must a read or write wait for to complete?

  → No unnecessary read delay or write delay
- Separation of invalidations from bodies

  → Minimize delay (hence inconsistency)

Improved Consistency Trade-Offs



	Bayou	TACT-Aggressive	PRACTI
How	Batch	Batch	Incremental
When	Periodic	Frequent	Continuous
Invals	All	All	All*
Bodies	All	All	Self-tuning

Cost of Consistency v. Coherence

Suppose I care about subset of data

- /A/* but not /B/*, /C/*, or /D/*

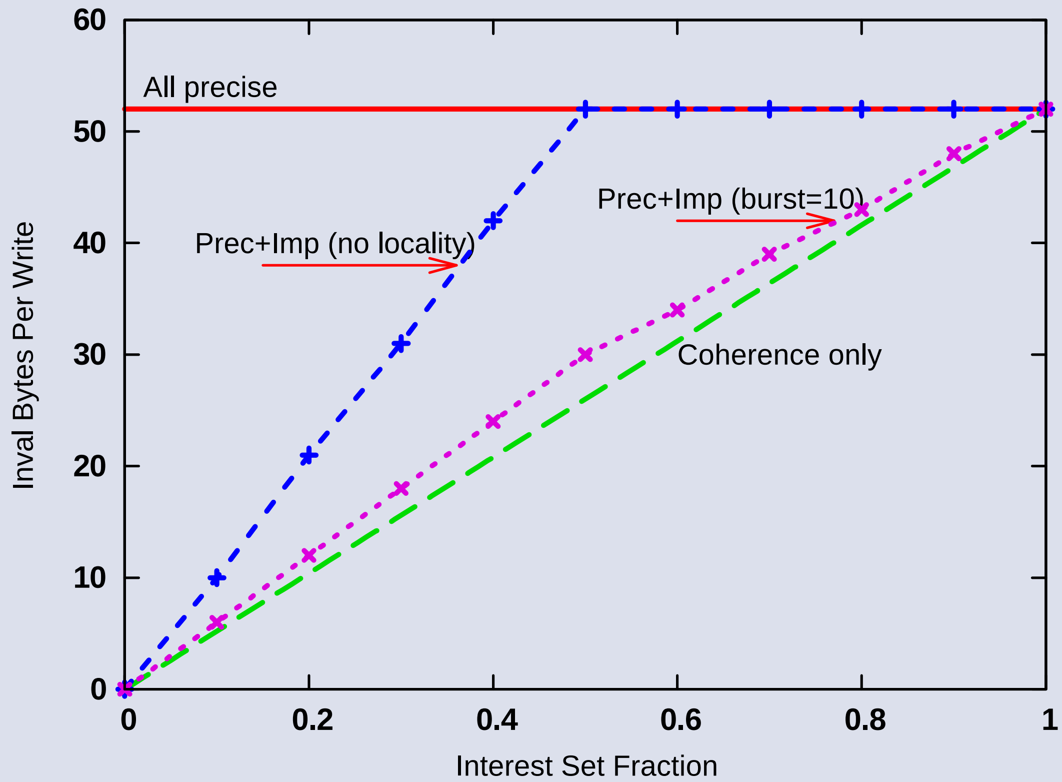
PRACTI

- Precise invalidations for /A/*
- Imprecise invalidations for the rest

Imprecise invalidations: "Placeholders"

- Allow future reads/writes to be consistently ordered with writes to /B/*, /C/*, /D/* if desired
  - Locally or at other nodes
- System that **only** guarantees coherence and **never** provides option of consistency could omit imprecise invalidations
- Worst case: Each precise invalidation paired with imprecise invalidation summarizing writes on which it depends
- How much overhead do these imprecise invalidations impose on nodes that don't use them?

Cost of Consistency



Imprecise invalidations save v. all-precise

Imprecise invalidations cost v. coherence only

- Worst case 2:1 (messages)
- Locality reduces cost

Performance Summary

Better trade-offs

- Partial replication of data
- Partial replication of metadata
- Topology independence
- Minimal consistency cost

Additional benefits (see paper)

- Self-tuning replication of bodies
- Incremental checkpoint transfer

Outline

Motivation

PRACTI Protocol

Evaluation

Future Work/Conclusions

- Towards a unified theory and practice

Questions PRACTI doesn't answer

- Does PRACTI reduce development costs by 10x?
  - Can we support 14 OSDI/SOSP papers in <1000 LOC each?
- Can we support quorums, client-server, server replication, p2p on the same substrate?
- Can we efficiently support callbacks and leases?
- How do various consistency paradigms relate?
  - FIFO, causal, sequential, linearizable, etc.
    v. Reads follow writes, monotonic reads, etc.
    v. Safe, regular, atomic, etc.
- What are the "core mechanisms" for security?
- Can we support FS, tuple store, and DB on same substrate?
- Can we unify other "large scale" replication systems (e.g., cluster)?

Conclusion

Build your next large-scale replication system using PRACTI

- A better way to build replication systems
- A way to build better replication systems

Details on my web page

"**PRACTI Replication for Large-Scale Systems**," M. Dahlin, L. Gao, A. Nayate, A. Venkataramani, P. Yalagandula J. Zheng

"**Dual-Quorum Replication for Edge Services,**" L. Gao, M. Dahlin, J. Zheng, L. Alvisi, A. Iyengar, Middleware 2005

"**Transparent Information Dissemination,**" A. Nayate, M. Dahlin, A. Iyengar, Middleware 2004.

"**A Non-interfering Deployable Web Prefetching System,**" R. Kokku, P. Yalagandula, A. Venkatramani, M. Dahlin,USITS 2003