MODIST: Transparent Model Checking of Unmodified Distributed Systems

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Distributed system: hard to get right

- Complicated protocol + code
  - Node has no centralized view of entire system
  - Must correctly handle a large number of failures
    - Link failure, message delay, machine crash
  - Getting worse: larger scale, failures more likely
- Randomized testing
  - Low coverage
  - Non-deterministic

MODIST summary

- MOdel checker for DISTributed systems
  - Comprehensive: check many corner cases
  - "In-situ:" check unmodified, real implementations
  - Deterministic: detected errors can be replayed

- Results
  - Checked Berkeley DB replication, Paxos-MPS (managing Microsoft production data centers) [D3S, NSDI08], and PacificA [MSR-TR]
  - 35 bugs, 31 confirmed
  - 10 protocol bugs, found in every system checked

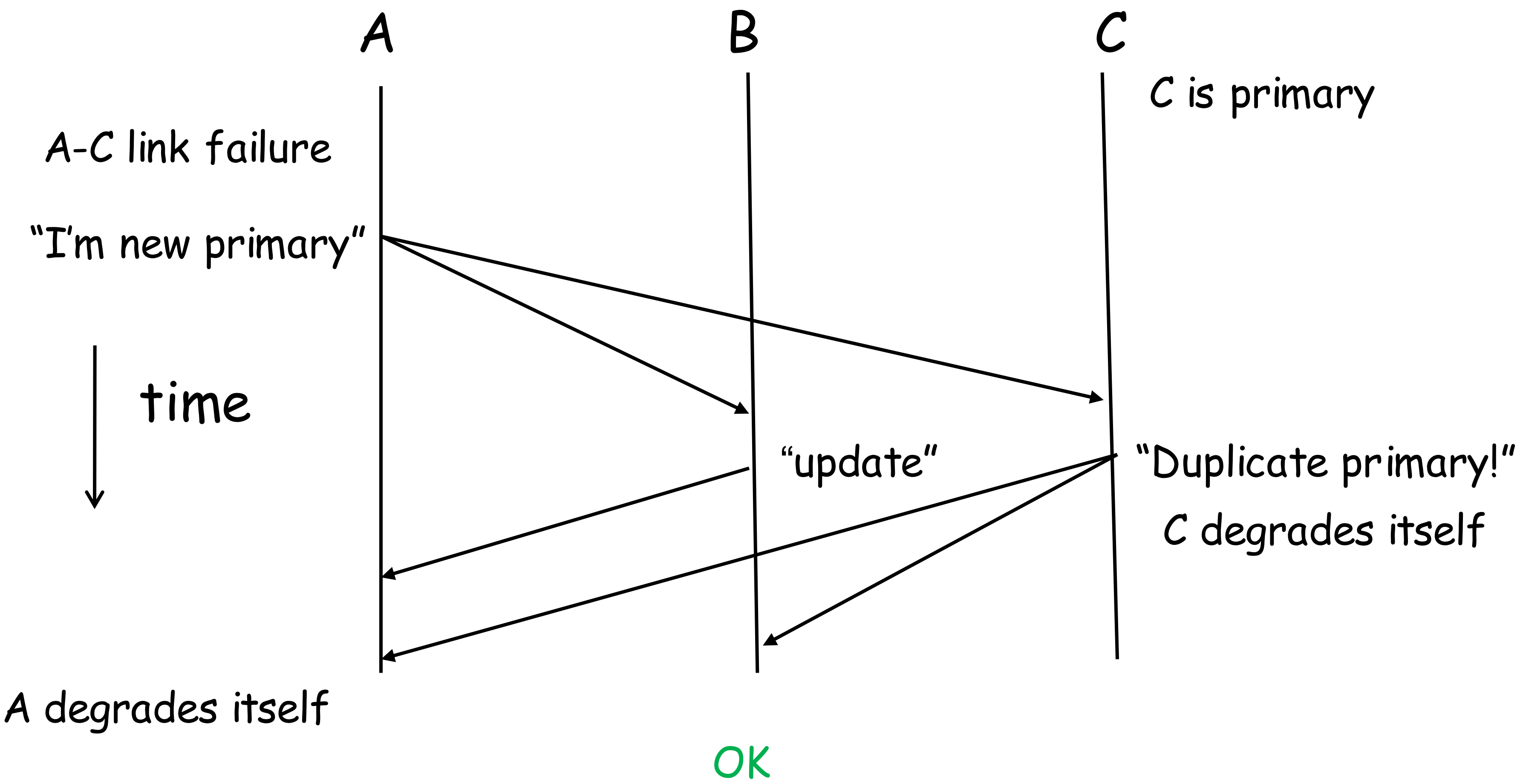
Outline

- Overview
  - Real Berkeley DB bug
  - How MODIST finds the bug
- Implementation challenges
- Errors

Berkeley DB replication

- Based on Paxos
  - single primary, multiple secondaries
  - Primary can read and write
  - Secondary can only read
- When primary fails, secondaries can elect new primary
- When duplicate primary detected, degrade both and re-elect
- Bug is in leader election protocol

A real Berkeley DB bug



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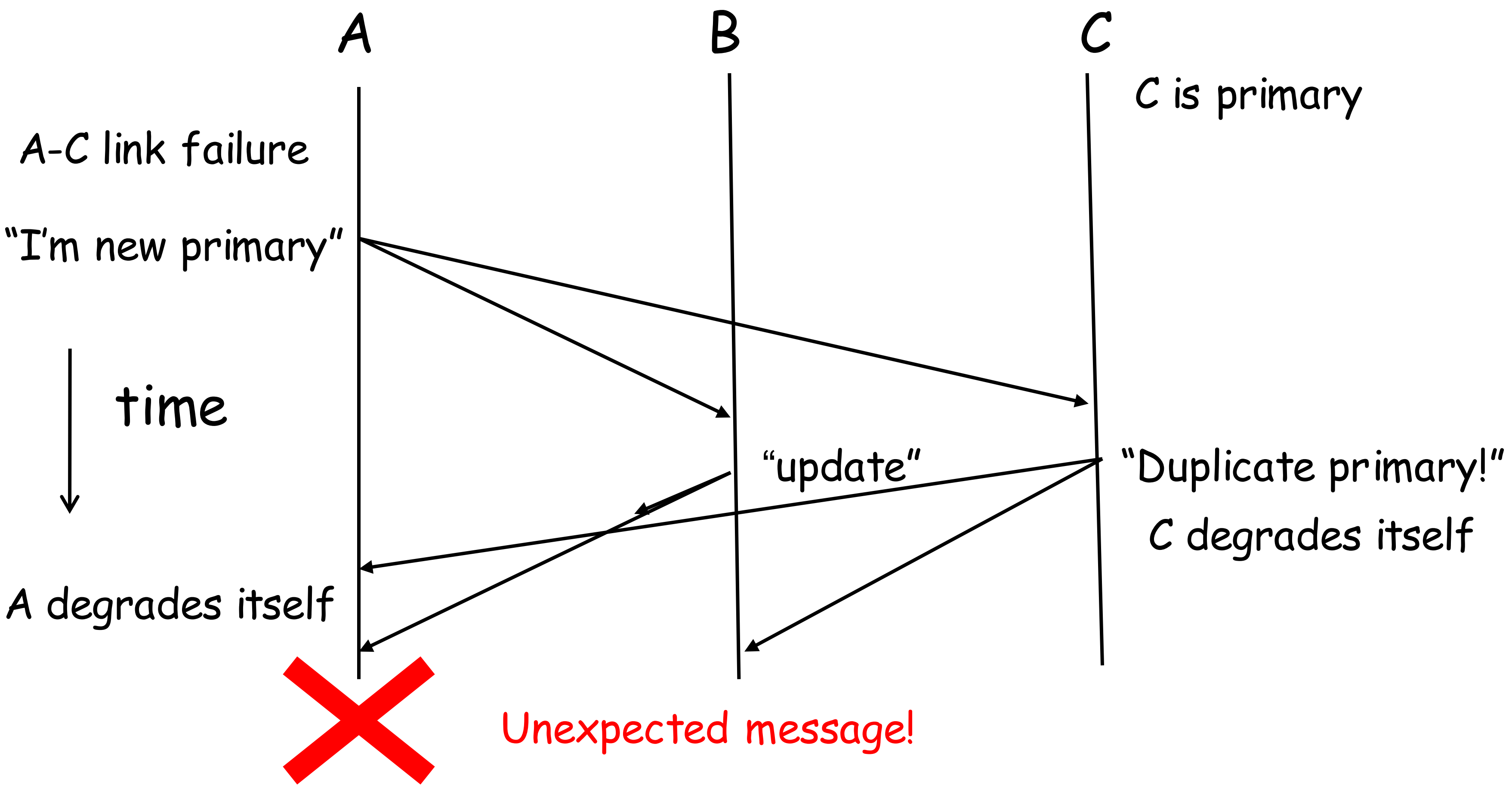

MODIST: simple to use

$ cat bdb.conf

```
# command                                      # working dir    # inject failure?
  ex_rep_mgr.exe –n 3 –m localhost:8000 …        ./node1              1
  ex_rep_mgr.exe –n 3 –m localhost:8001 …        ./node2              1
  ex_rep_mgr.exe –n 3 –m localhost:8002 …        ./node3              1
```

$ modist.exe bdb.conf

```
spawning process 1: ex_rep_mgr.exe …
…
fail link from process 1 to process 3
…
process 3 send to process 1
…
restarting
spawning process 1: ex_rep_mgr.exe
…
```

$ modist.exe bdb.conf –r traces/0/trace

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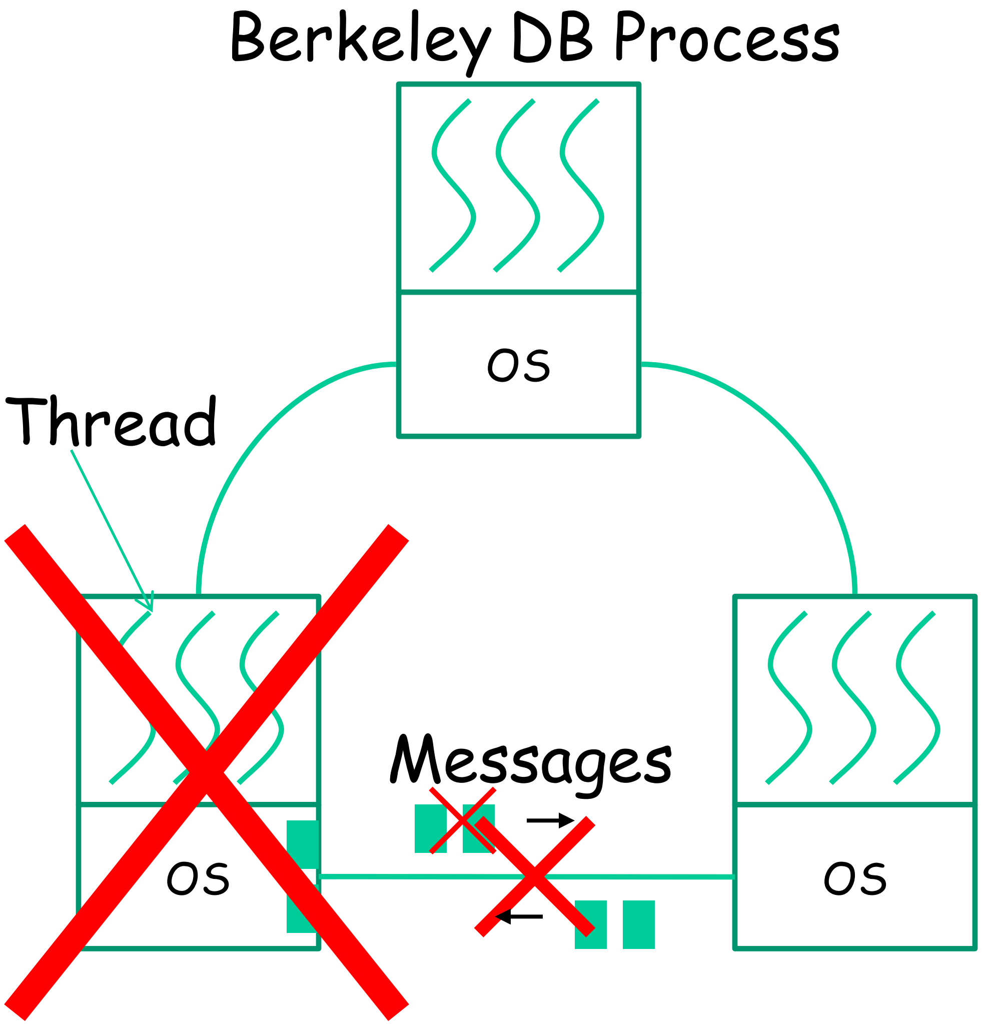
Core model checking idea

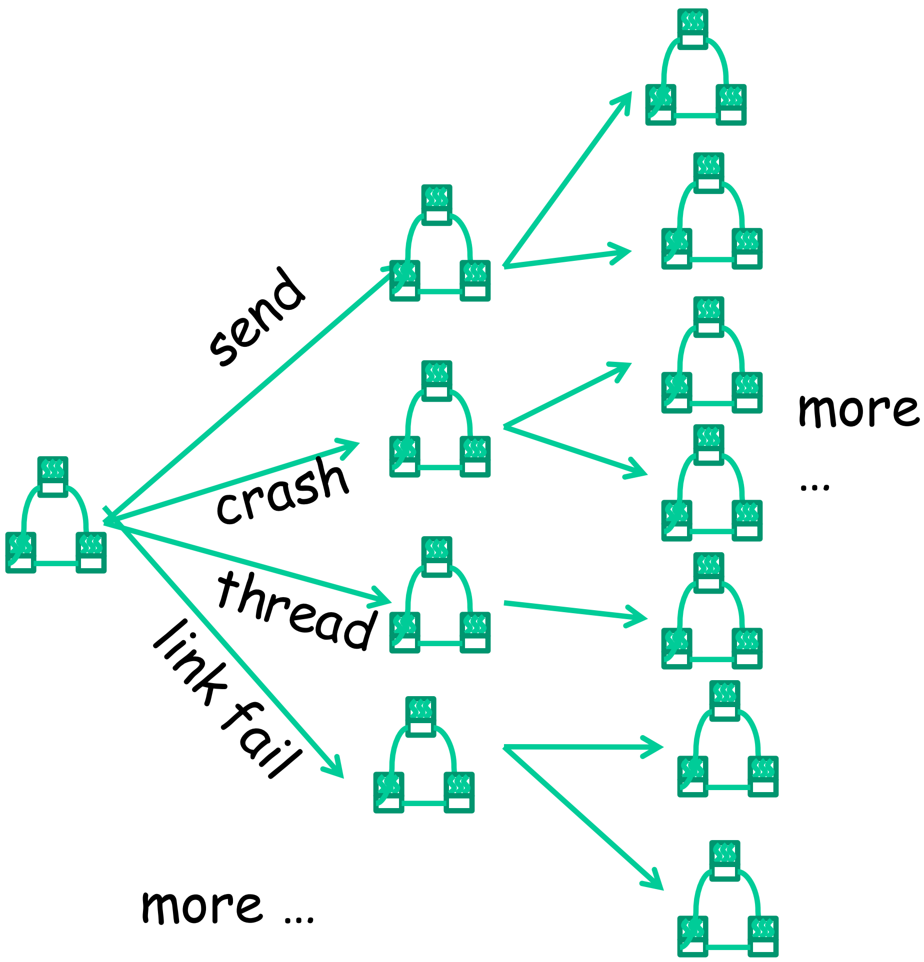
- Goal: explore all states and actions
- Advantage: rare actions appear as often as common ones, thereby quickly driving system into corner case for errors

Actions in Berkeley DB replication



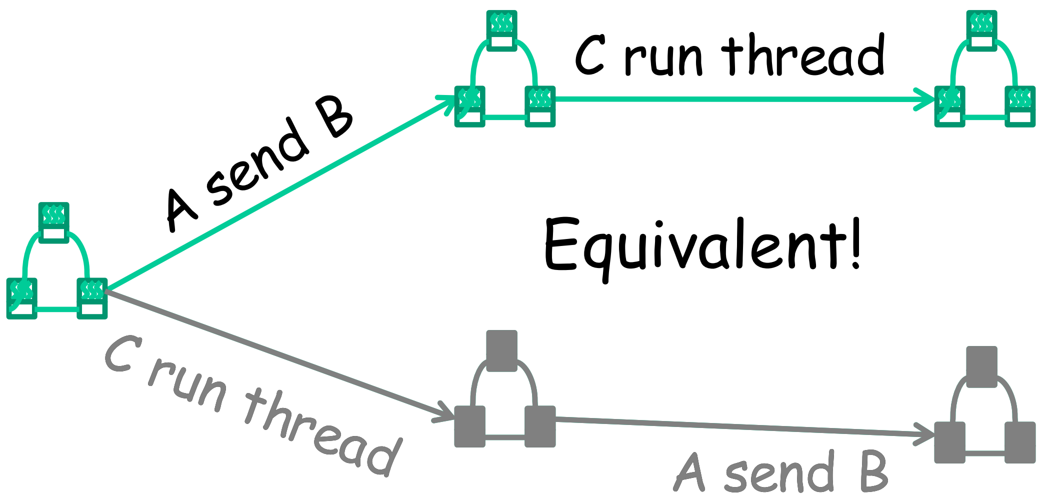
- Normal actions
  - Send message
  - Recv message
  - Run thread
  - …
- Rare actions
  - Delay message
  - Fail link
  - Crash machine
  - …

Ideal: exploring all actions



- Built-in checks
  - Crash
  - Deadlocks
  - Infinite loops
- User-written checks
  - Local assertions
  - Global assertions
    - [D3S, NSDI 08]
- MODIST amplifies

Avoiding redundancy



- Explore only one interleaving of independent actions
  - Partial order reduction [Verisoft, POPL97] [DPOR, PLDI05]
  - Our implementation handles both message passing and thread synchronizations

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Challenges

- How to expose actions?
- How to check often-untested timeout code?
- How to simulate failures?
  - Must be realistic to avoid false positives
- How to schedule actions?
  - Must be deterministic for error replay
    - E.g., asynchronous IO
  - Must avoid deadlocks
  - Must be extensible

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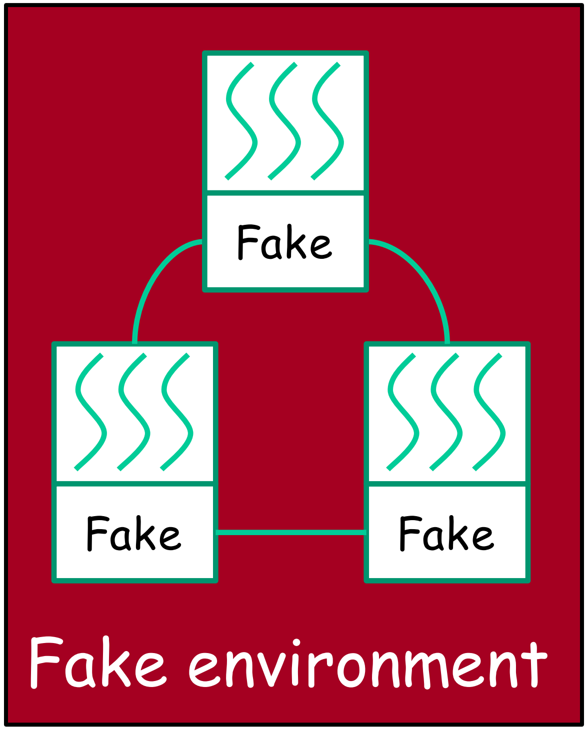
Exposing actions

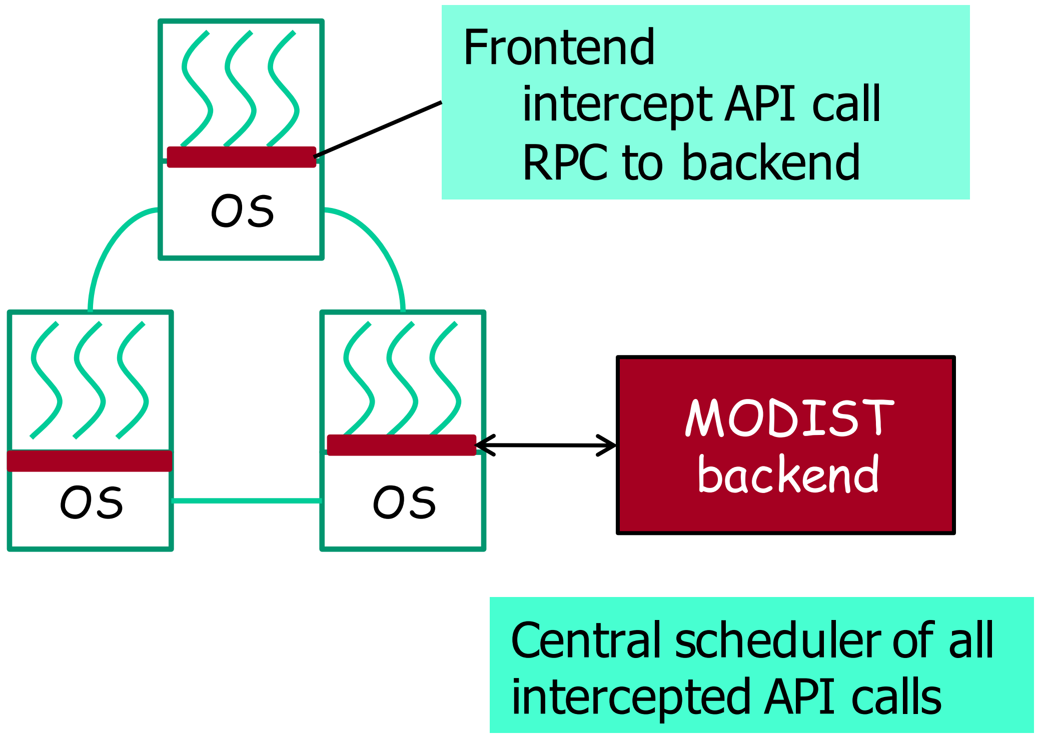
- To check, must know and control actions
- Previous work on distribute system model checking: users must expose actions
  - MaceMC: write app in special language
  - CMC: port app into fake environment
    - We used it to check FS [FiSC, OSDI06]
    - Difficult to check new app, OS
- MODIST uses in-situ checking architecture [EXPLODE, OSDI06]: interlace control needed into checked system

Architecture comparison

Traditional approach



MODIST



- Transparent
- Easy to port to new OS

Frontend: simple

- Intercepted 82 API functions
  - E.g., networking, thread synchronization
- Most wrappers are simple: return failure or call real API function
  - No need to re-implement API functions
  - Average 67 lines per wrapper

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Checking timeouts

- System code heavily uses implicit timers

```
db_timespec now;
now = gettime();  // return current time
if (now >= t + 10 ) // timeout check
        ... // timeout handling code
else
        ... // no timeout
```

- Challenge: can intercept gettime(), but what to return?
  - Want to explore both branches
  - Must know t + 10, but no API call
  - Previous work: manual

Static symbolic analysis

- Key observations
  - Time values are used in simple ways
    - Berkeley DB: db_timespec, mostly +,-, sometimes *,/
    - ➔ Static analysis can pick up time values easily
  - Programmers check timeout soon after current time
    - Intuition: want current time to be "fresh"
    - Berkeley DB: 12 out of 13 are within a few lines
    - ➔ Track only short flows of time values
- Our solution: static intra-procedural symbolic analysis to discover implicit timers
  - Much simpler than state of art symbolic analysis [KLEE, OSDI08]

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Errors

System	KLOC	Protocol bugs	Impl. bugs	Total
Berkeley DB	172.1	2	5	7
Paxos-MPS	53.5	2	11	13
PacificA	12	6	9	15
Total	237.6	10	25	35

- Large, complex systems
- Total 35 bugs, all previously unknown, 31 confirmed
- Protocol bugs in every system, total 10

Conclusion

- MODIST: in-situ model checker for distributed systems
  - Comprehensive, transparent, deterministic
  - Effective
    - Checked Berkeledy DB, Paxos-MPS, PacificA
    - 35 bugs, 10 protocol bugs
- Real distributed protocols are buggy
  - Interestingly, based on proven-correct protocols
  - Bugs stem from concretitzation or customizations