15-440 Distributed Systems

11 - Fault Tolerance, Logging and Recovery

Tuesday, Oct 2nd, 2018

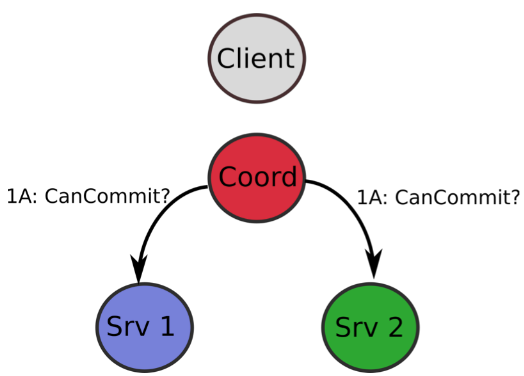
Logistics Updates

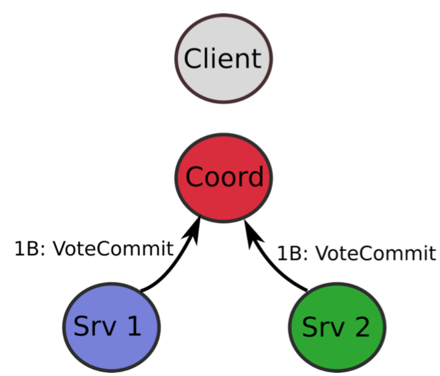
- P1 Part A checkpoint
  - Part A due: Saturday 10/6 (6-week drop deadline 10/8)
  - *Please WORK hard on it!*
- HW2 will be released 10/02
  - HW 2 due: Friday 10/12
- Midterm-I – 10/18, 10:30 - Noon (details to follow)
  - Midterm-I – Review on 10/16 in class.

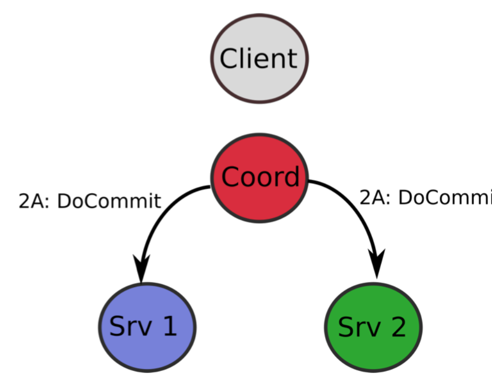
Recap: Last Lecture

- ACID Properties
  - Atomicity, Consistency, Isolation, Durability

- 2-Phase Commit for distributed transactions
- 2PC assumptions:
  - Coordinator
  - Ability to **recover** state, **persistence** after “DoCommit”







Today's Lecture Outline

- Motivation – Fault Tolerance
- Fault Tolerance using Checkpoints
- Fault Tolerance using Logging and Recovery
- Logging and Recovery in Practice: ARIES

What is Fault Tolerance?

- Dealing successfully with partial failure within a distributed system
- Fault tolerant ~> dependable systems
- Dependability implies the following:

1. Availability
2. Reliability
3. Safety
4. Maintainability

Dependability Concepts

- *Availability* – the system is ready to be used immediately.
  - "High availability": system is ready at any given time, with high probability.

- *Reliability* – the system runs continuously without failure.
  - "High reliability": system works without interruption during a long period of time.

Subtle difference. Consider:

- Random but rare failures (one millisecond every hour)
- Predictable maintenance (two weeks every year)

Dependability Concepts

- *Safety* – if a system fails, nothing catastrophic will happen. (e.g. process control systems)

- *Maintainability* – when a system fails, it can be repaired easily and quickly (sometimes, without its users noticing the failure). Also called Recovery.
  - What's a failure? : System that cannot meet its goals => faults
  - Recover from all kinds of faults:
    - Transient: appears once, then disappears
    - Intermittent: occurs, vanishes, reappears
    - Permanent: requires replacement / repair

Failure Models

Type of Failure	Description
Crash failure	Server halts, working correctly before.
Omission failure Receive omission Send omission	Server fails to respond to request Server fails to receive incoming msg Server fails to send msg
Timing failure	Server's response outside specified time interval
Response failure Value failure State transition failure	Incorrect server response Wrong value of response Deviation from flow of control
Arbitrary (Byzantine) failure	Server may produce arbitrary responses at arbitrary times

Masking Failures by Redundancy

1. *Information Redundancy* – add extra bits to allow for error detection/recovery

   (Hamming codes: detect 2-bit errors, correct 1-bit errors)

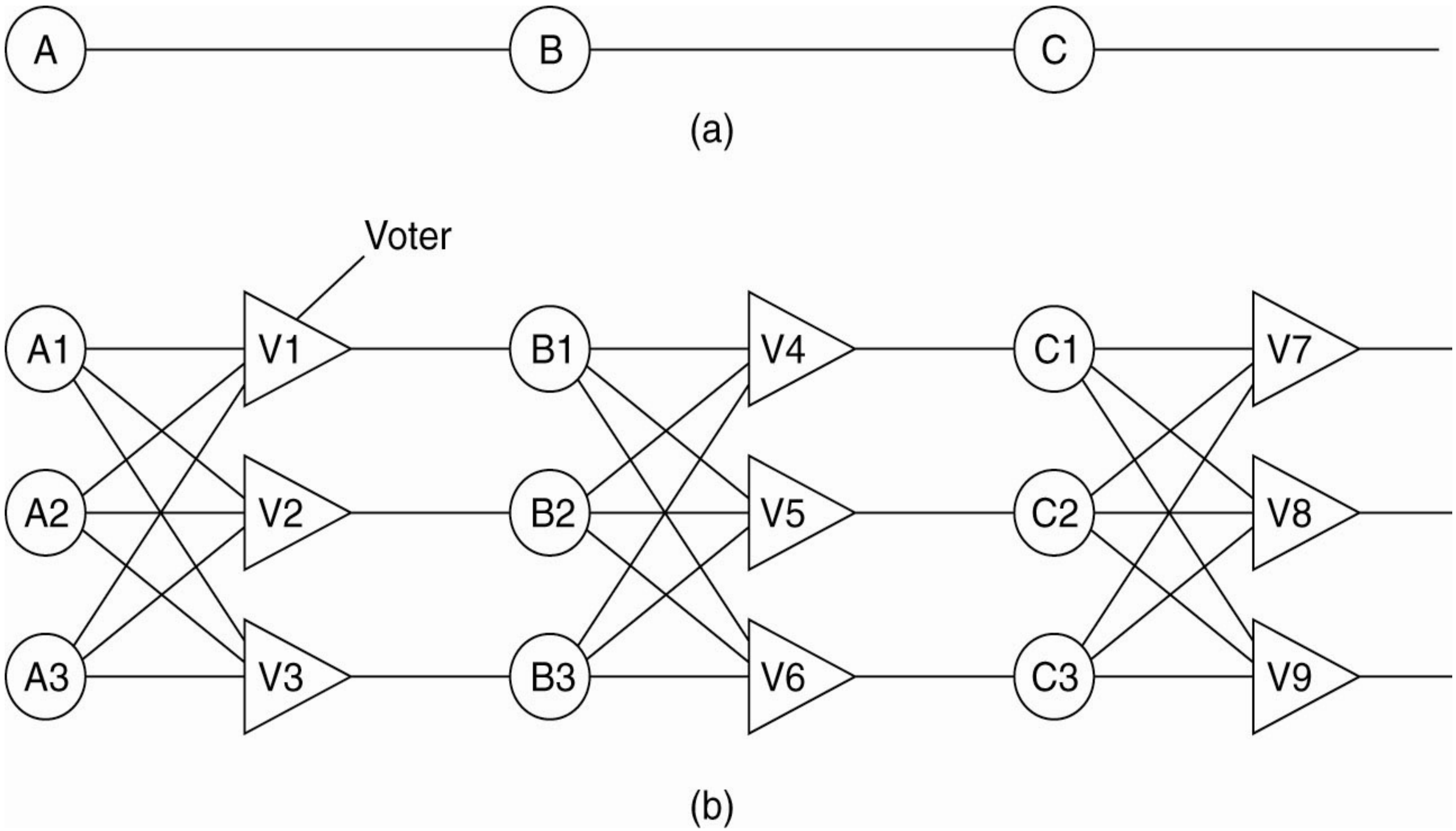
2. *Time Redundancy* – perform operation and, if needs be, perform it again.

   (Purpose of transactions: BEGIN/END/COMMIT/ABORT)

3. *Physical Redundancy* – add extra (duplicate) hardware and/or software to the system.

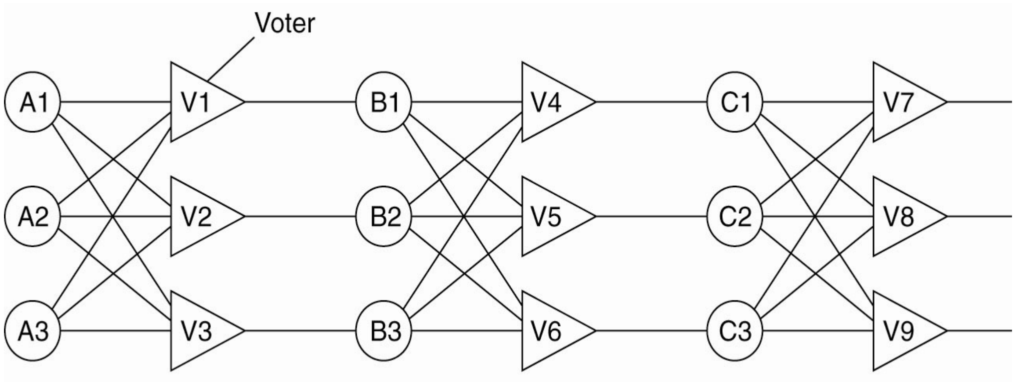
Can you think of Physical redundancy in Nature?

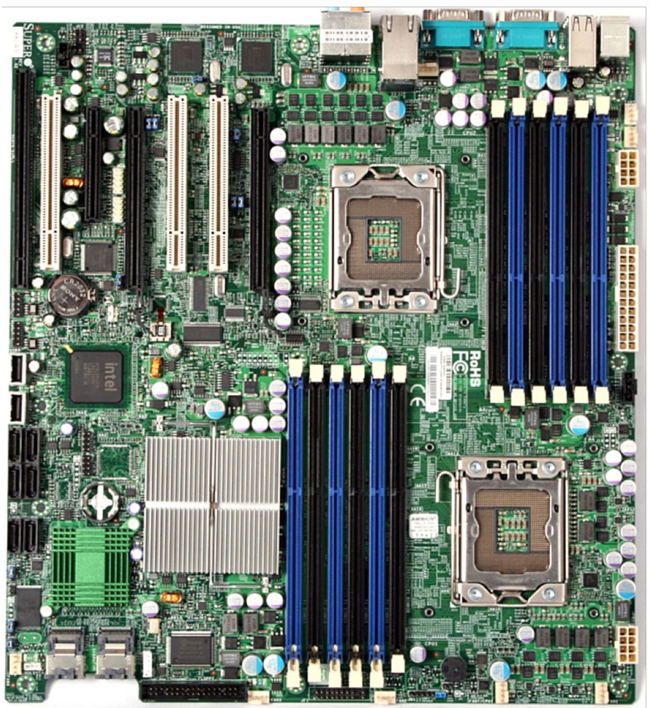
Redundancy in Electronics



Triple modular redundancy in a circuit (b)
A,B,C are circuit elements and V* are voters

Redundancy is Expensive





- But without redundancy, we need to recover after a crash.

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Recovery Strategies

When a failure occurs, we need to bring the system into an error free state (recovery).

1. **Backward Recovery**: return the system to some previous correct state (using *checkpoints*), then continue executing.
   - Packet retransmit in case of lost packet
2. **Forward Recovery**: bring the system into a correct new state, from which it can then continue to execute.
   - Erasure coding → Forward Error Correction

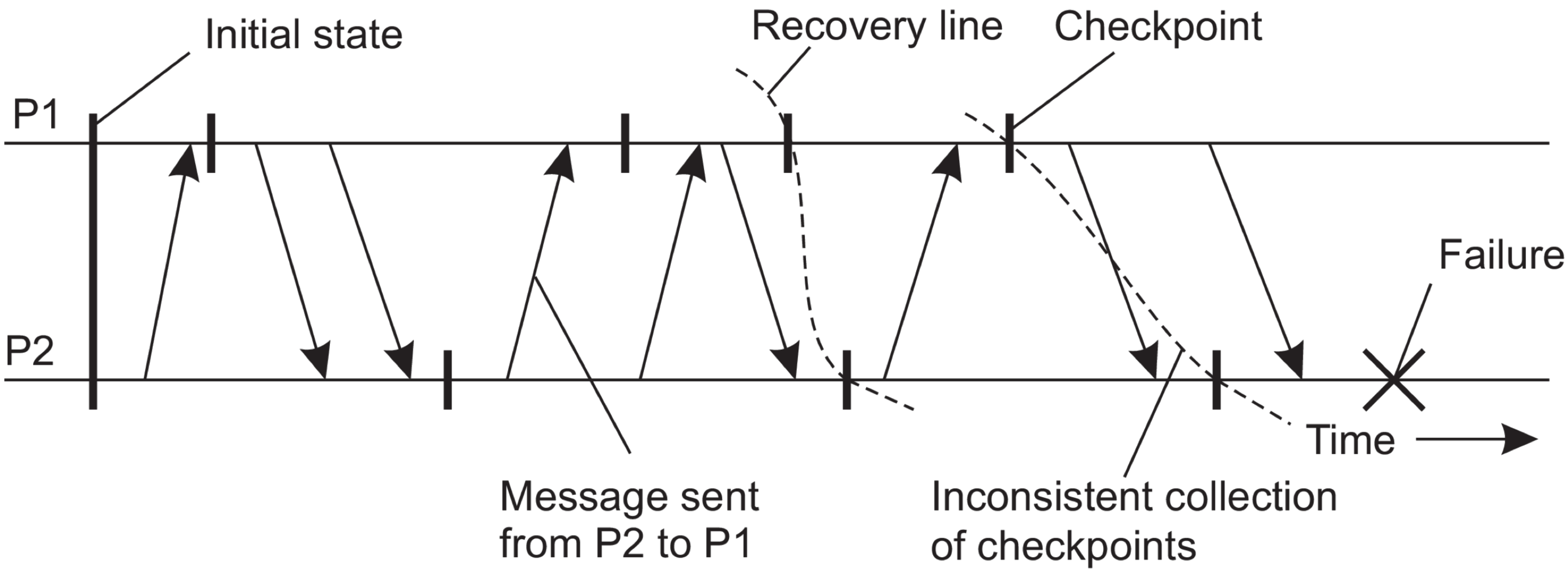
Forward and Backward Recovery

- **Major disadvantage of Backward Recovery**:
  - Checkpointing can be very expensive (especially when errors are very rare).
- **Major disadvantage of Forward Recovery**:
  - In order to work, all potential errors need to be accounted for *up-front*.
  - “Harder” the recovery mechanism need to know how do to bring the system *forward* to a correct state.
- In practice: backward recovery common

Backward Recovery

- Checkpoint: snapshot the state of the DS
  - Transactions
  - Messages received / sent
  - Roles like coordinator, …
- Frequent checkpoints are expensive
  - Requires writing to stable storage
  - Very slow if checkpoint after every event!
- What can we do to make checkpoints cheaper?
  - Less frequent checkpoints, e.g., "every 10 seconds'

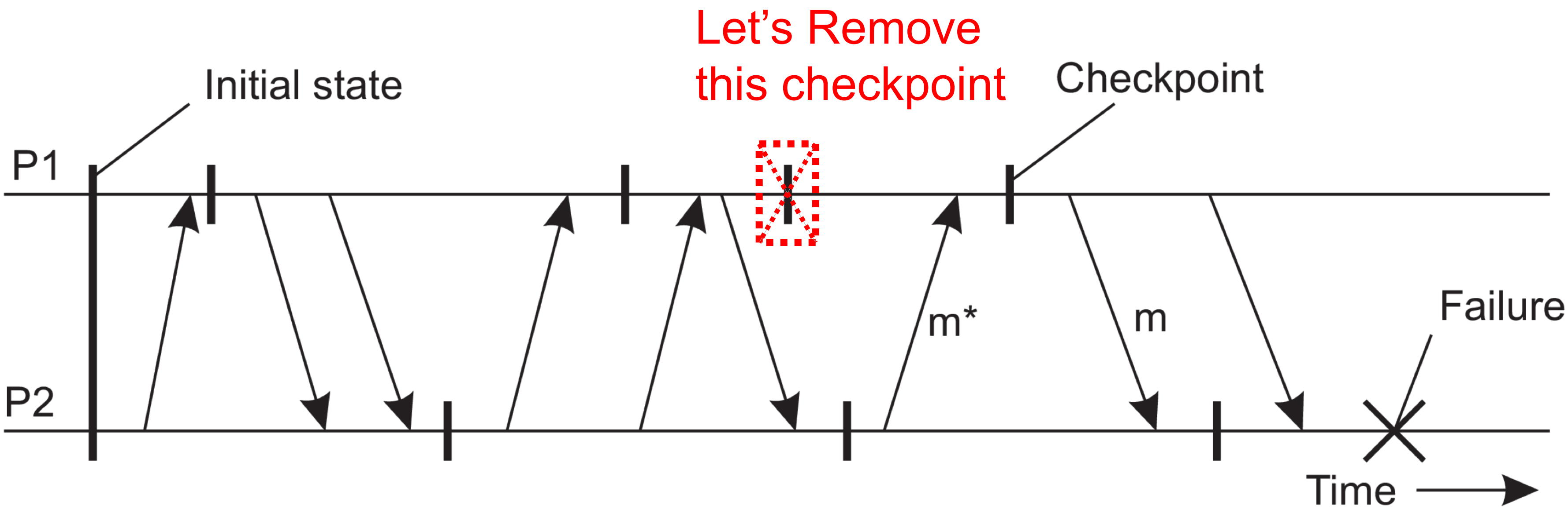
Independent Checkpointing



A recovery line to detect the correct distributed snapshot

This becomes challenging if checkpoints are un-coordinated

The Domino Effect



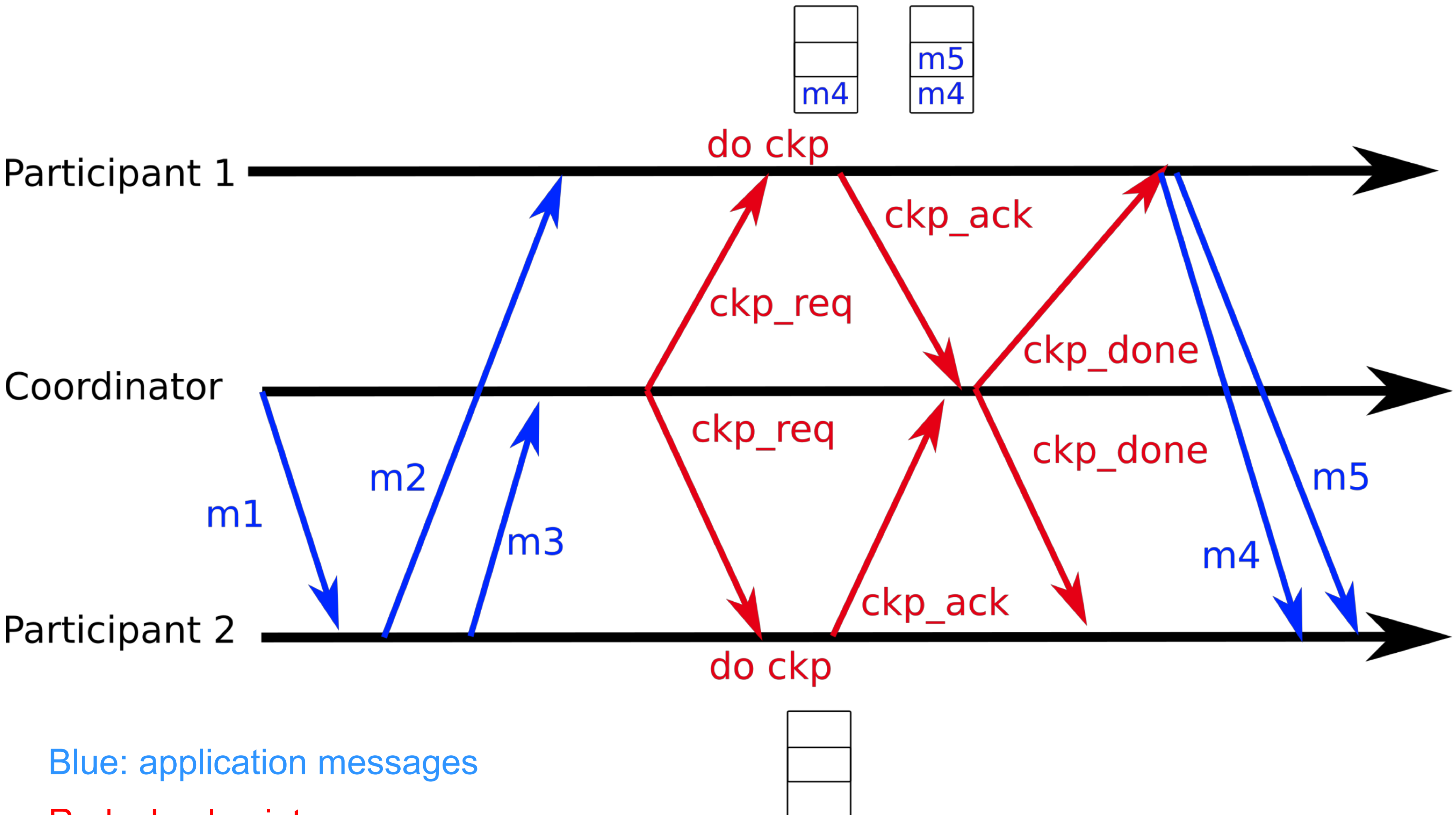
The domino effect – Cascaded rollback

P2 crashes, roll back, but 2 checkpoints inconsistent (P2 shows m received, but P1 does not show m sent)

Coordinated Checkpointing

- Key idea: each process takes a checkpoint after a globally coordinated action. (Why?)
- Simple Solution: 2-phase blocking protocol
  - Coordinator multicast *checkpoint_REQUEST* message
  - Participants receive message, takes a checkpoint, stops sending (application) messages and queues them, and sends back *checkpoint_ACK*
  - Once all participants ACK, coordinator sends *checkpoint_DONE* to allow blocked processes to go on
- Optimization: consider only processes that depend on the recovery of the coordinator (those it sent a message since last checkpoint)

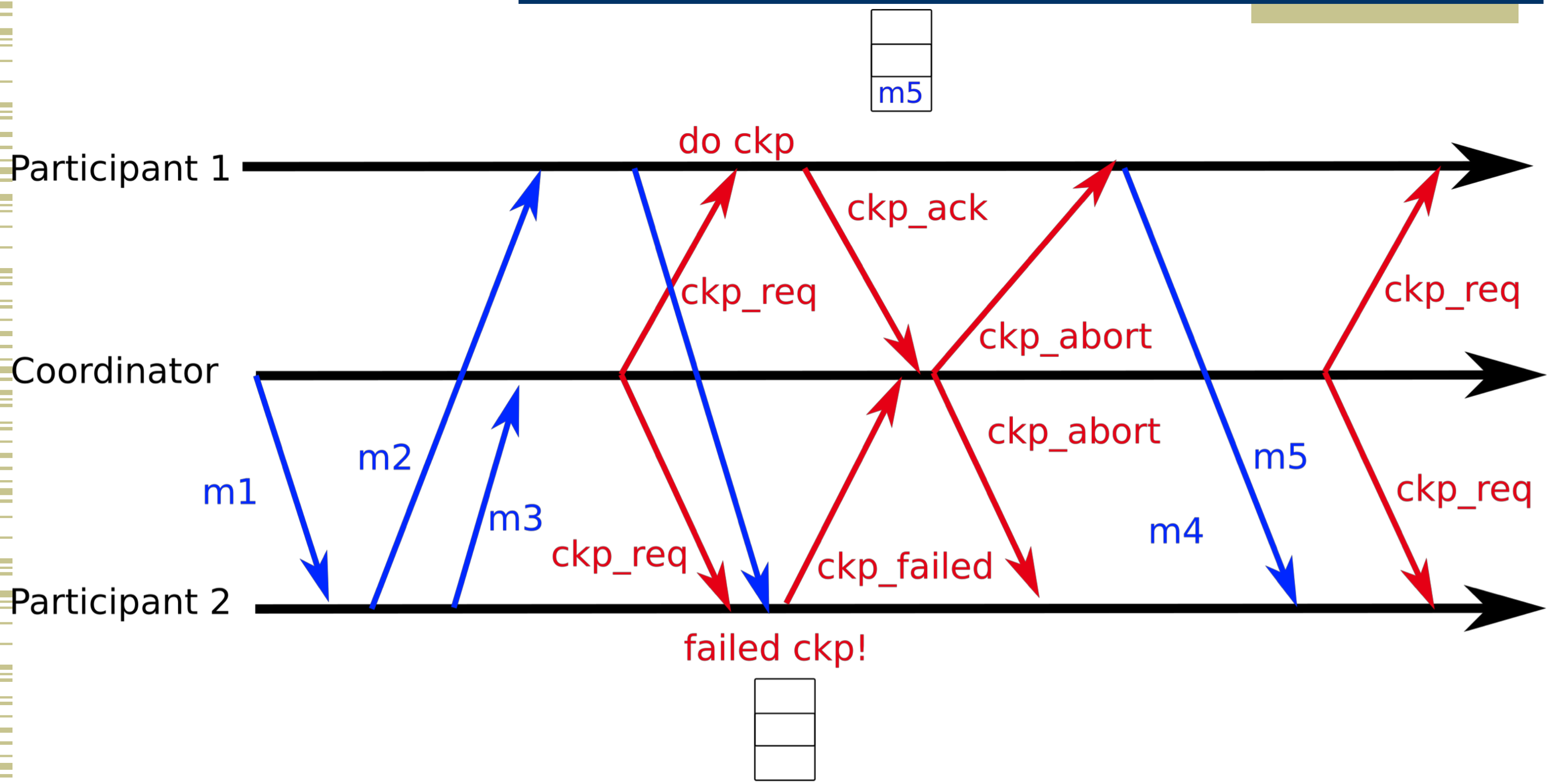
Successful Coord. Checkpoint



Blue: application messages

Red: checkpoint messages

Unsuccessful Coord. Checkpoint



Checkpoints can fail, if participant sent msg before *checkpoint_REQUEST* and receiver gets msg after *checkpoint_REQUEST. Then: abort and do try another coordinated checkpoint soon (compare to 2PC).*

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Goal: Make transactions Reliable

- …in the presence of failures
  - Machines can crash: disk contents (OK), memory (volatile)
  - Assume that machines don't misbehave
  - Networks are flaky, packet loss, handle using timeouts

- If we store database state in memory, a crash will cause loss of "Durability".

- May violate atomicity, i.e. recover such that uncommited transactions COMMIT or ABORT.

- General idea: store enough information to disk to determine global state (in the form of a LOG)

Challenges:

- Disk performance is poor (vs memory)
  - Cannot save all transactions to disk
  - Memory typically several orders of magnitude faster

- Writing to disk to handle arbitrary crash is hard
  - Several reasons, but HDDs and SSDs have buffers

- Same general idea: store enough data on disk so as to recover to a valid state after a crash:
  - Shadow pages and Write-ahead Logging (WAL)
  - Idea is to provide Atomicity and Durability

Shadow Paging Vs WAL

- Shadow Pages
  - Provide Atomicity and Durability, “page” = unit of storage
  - Idea: When writing a page, make a “shadow” copy
    - No references from other pages, edit easily!
  - ABORT: discard shadow page
  - COMMIT: Make shadow page “real”. Update pointers to data on this page from other pages (recursive). Can be done atomically
  - Essentially “copy-on-write” to avoid in-place page update

Shadow Paging vs WAL

- Write-Ahead-Logging
  - Provide Atomicity and Durability
  - Idea: create a log recording every update to database
  - Updates considered reliable when stored on disk
  - Updated versions are kept in memory (page cache)
  - Logs typically store both REDO and UNDO operations
  - After a crash, recover by replaying log entries to reconstruct correct state

  - WAL is more common, fewer disk operations, transactions considered committed once log written.

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ARIES Recovery Algorithms

- ARIES: **A**lgorithms for **R**ecovery and **I**solation **E**xploiting **S**emantics
- Used in major databases
  - IBM DB2 and Microsoft SQL Server
  - Deals with many practical issues
- Principles
  - Write-ahead logging
  - Repeating history during Redo
  - Logging changes during Undo

Write-Ahead Logging

- View as sequence of entries, sequential number
  - Log-Sequence Number (LSN)
  - Database: fixed size PAGES, storage at page level
- Pages on disk, some also in memory (page cache)
  - "Dirty pages": page in memory differs from one on disk
- Reconstruct global consistent state using
  - Log files + disk contents + (page cache)
- Logs consist of sequence of records
  - What do we need to log?
    - Seq#, which transaction, operation type, what changed…

Write-Ahead Logging

- Logs consist of sequence of records
  - `To record an update to state`
  - `LSN: [prevLSN, TID, “update”, pageID, new value, old value]`
  - PrevLSN forms a backward chain of operations for each TID
  - Storing “old” and “new” values allow REDO operations to bring a page up to date, or UNDO an update reverting to an earlier version
- Transaction Table (TT): All TXNS not written to disk
  - Including Seq Num of the last log entry they caused
- Dirty Page Table (DPT): all dirty pages in memory
  - Modified pages, but not written back to disk.
  - Includes recoveryLSN: first log entry to make page dirty

Recovery using WAL – 3 passes

- Analysis Pass
  - Reconstruct TT and DPT (from start or last checkpoint)
  - Get copies of all pages at the start
- Recovery Pass (redo pass)
  - Replay log forward, make updates to all dirty pages
  - Bring everything to a state at the time of the crash
- Undo Pass
  - Replay log file backward, revert any changes made by transactions that had not committed (use PrevLSN)
  - For each write Compensation Log Record (CLR)
  - Once reach entry without PrevLSN → done

ARIES (WAL): Data Structures

TT: Transaction Table

TID	LastLSN
1	567
2	42
7	67
2	12

DPT: Dirty Page Table

pageID	recoveryLSN
42	567
46	568
77	34
3	42

TID: Transaction ID

LastLSN: LSN of the most recent log record seen for this Transaction. i.e. latest change

pageID: key/ID of a page

recoveryLSN: LSN of first log record that made page dirty i.e. earliest change to page

Example Log File

```
LSN: [prevLSN, TID, type]                                   # All
LSN: [prevLSN, TID, "update", pageID, redo, undo]           # Update
```

DB Buffer

Page 42

LSN=-

a=77
b=55

Page 46

LSN=-

c=22

LOG

TT	
TID	LastLSN

DPT	
pageID	recoveryLSN

Example Log File

```
LSN: [prevLSN, TID, type]                                # All
LSN: [prevLSN, TID, “update”, pageID, redo, undo]        # Update
```

DB Buffer

Page 42

LSN=1

a=78
b=55

Page 46

LSN=-

c=22

LOG

1: [-,1,”update”,42,a+=1, a-=1]

TT	
TID	LastLSN
1	1

DPT	
pageID	recoveryLSN
42	1

Example Log File

```
LSN: [prevLSN, TID, type]                                    # All
LSN: [prevLSN, TID, “update”, pageID, redo, undo]            # Update
```

DB Buffer

Page 42

LSN=2

a=78
b=58

Page 46

LSN=-

c=22

LOG

1: [-,1,”update”,42,a+=1, a-=1
2: [-,2,”update”, 42,b+=3, b-=3]

TT	
TID	LastLSN
1	1
2	2

DPT	
pageID	recoveryLSN
42	1

Example Log File

```
LSN: [prevLSN, TID, type]                                # All
LSN: [prevLSN, TID, “update”, pageID, redo, undo]        # Update
```

DB Buffer

Page 42

LSN=4

a=78
b=59

Page 46

LSN=3

c=24

LOG

1: [-,1,”update”,42,a+=1, a-=1
2: [-,2,”update”, 42,b+=3, b-=3]
3: [2,2,”update”,46,c+=2, c-=2]
4:[1,1,”update”,42, b+=1, b-=1]

TT	
TID	LastLSN
1	4
2	3

DPT	
pageID	recoveryLSN
42	1
46	3

Example Log File

```
LSN: [prevLSN, TID, type]                                # All
LSN: [prevLSN, TID, "update", pageID, redo, undo]        # Update
```

DB Buffer

Page 42

LSN=4

a=78
b=59

Page 46

LSN=3

c=24

LOG

1: [-,1,"update",42,a+=1, a-=1
2: [-,2,"update", 42,b+=3, b-=3]
3: [2,2,"update",46,c+=2, c-=2]
4:[1,1,"update",42, b+=1, b-=1]
5:[3,2,"commit"]

TT	
TID	LastLSN
1	4

DPT	
pageID	recoveryLSN
42	1
46	3

Example Log File

```
LSN: [prevLSN, TID, type]                                    # All
LSN: [prevLSN, TID, “update”, pageID, redo, undo]            # Update
LSN: [prevLSN, TID, “comp”, redoTheUndo, undoNextLSN]        #compensation
```

On **Disk**

Page 42

LSN=-

a=77

b=55

Page 46

LSN=-

c=22

LOG

1: [-,1,”update”,42,a+=1, a-=1

2: [-,2,”update”, 42,b+=3, b-=3]

3: [2,2,”update”,46,c+=2, c-=2]

4:[1,1,”update”,42, b+=1, b-=1]

5:[3,2,”commit”]

Example Log File

```
LSN: [prevLSN, TID, type]                                    # All
LSN: [prevLSN, TID, "update", pageID, redo, undo]            # Update
LSN: [prevLSN, TID, "comp", redoTheUndo, undoNextLSN]  #compensation
```

On **Disk**

Page 42

LSN=-

a=77
b=55

Page 46

LSN=-

c=22

LOG

1. Analysis

1: [-,1,"update",42,a+=1, a-=1
2: [-,2,"update", 42,b+=3, b-=3]
3: [2,2,"update",46,c+=2, c-=2]
4:[1,1,"update",42, b+=1, b-=1]
5:[3,2,"commit"]

TT	
TID	LastLSN
1	4

DPT	
pageID	recoveryLSN
42	1
46	3

1. Analysis to figure out the start of the redo.
=> start from 1

Example Log File

```
LSN: [prevLSN, TID, type]                                      # All
LSN: [prevLSN, TID, “update”, pageID, redo, undo]              # Update
LSN: [prevLSN, TID, “comp”, redoTheUndo, undoNextLSN]          #compensation
```

DB Buffer

Page 42

LSN=4

a=78
b=59

Page 46

LSN=3

c=24

LOG

1. Analysis
2. Redo

1: [-,1,”update”,42,a+=1, a-=1
2: [-,2,”update”, 42,b+=3, b-=3]
3: [2,2,”update”,46,c+=2, c-=2]
4:[1,1,”update”,42, b+=1, b-=1]
5:[3,2,”commit”]

TT	
TID	LastLSN
1	4

DPT	
pageID	recoveryLSN
42	1
46	3

Example Log File

```
LSN: [prevLSN, TID, type]                                 # All
LSN: [prevLSN, TID, “update”, pageID, redo, undo]         # Update
LSN: [prevLSN, TID, “comp”, redoTheUndo, undoNextLSN]     #compensation
```

DB Buffer

Page 42

LSN=6

a=78
b=58

Page 46

LSN=3

c=24

LOG

1. Analysis
2. Redo
3. Undo

1: [-,1,”update”,42,a+=1, a-=1
2: [-,2,”update”, 42,b+=3, b-=3]
3: [2,2,”update”,46,c+=2, c-=2]
4:[1,1,”update”,42, b+=1, b-=1]
5:[3,2,”commit”]

6: [4,1,”comp”,42,b-=1, b+=1]

TT	
TID	LastLSN
1	6

DPT	
pageID	recoveryLSN
42	1
46	3

Example Log File

```
LSN: [prevLSN, TID, type]                                      # All
LSN: [prevLSN, TID, "update", pageID, redo, undo]              # Update
LSN: [prevLSN, TID, "comp", redoTheUndo, undoNextLSN]          #compensation
```

1. Analysis
2. Redo
3. Undo

DB Buffer

Page 42

LSN=7

a=77
b=58

Page 46

LSN=3

c=24

LOG

1: [-,1,"update",42,a+=1, a-=1
2: [-,2,"update", 42,b+=3, b-=3]
3: [2,2,"update",46,c+=2, c-=2]
4:[1,1,"update",42, b+=1, b-=1]
5:[3,2,"commit"]

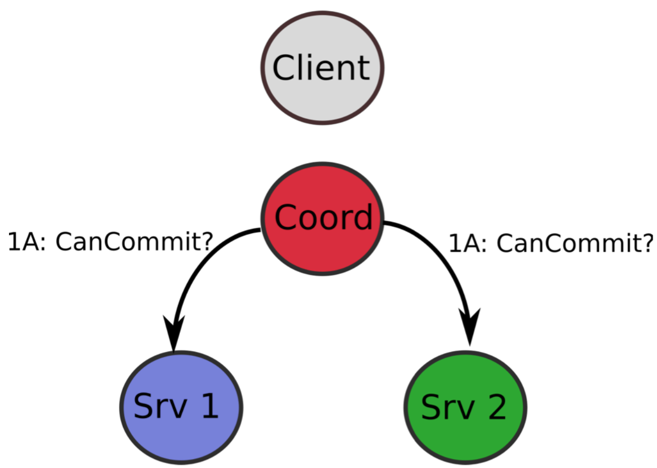
6: [4,1,"comp",42,b-=1, b+=1]
7: [6,1,"comp", 42, a-=1, a+=1]

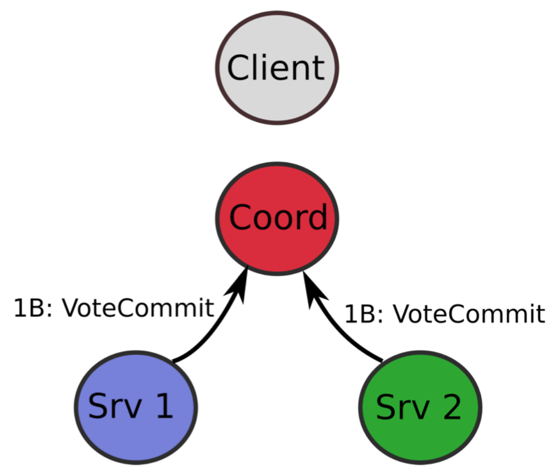
TT	
TID	LastLSN
1	7

DPT	
pageID	recoveryLSN
42	1
46	3

2PC works great with WAL/ARIES

- WAL can integrate with 2PC
  - Have additional log entries that capture 2PC operation
  - **Coordinator:** Include list of participants
  - **Participant:** Indicates coordinator
  - Votes to commit or abort
  - Indication from coordinator to Commit/Abort





Optimizing WAL

- As described earlier:
  - Replay operations back to the beginning of time
  - Log file would be kept forever (→ entire Database)
- In practice, we can do better with CHECKPOINT
  - Periodically save DPT, TT
  - Store any dirty pages to disk, indicate in LOG file
  - Prune initial portion of log file: All transactions upto checkpoint have been committed or aborted.

Summary

- Basic concepts for Fault Tolerant Systems
  - Properties of dependable systems
  - Redundancy, process resilience (see T8.2)
  - Reliable RPCs (see T8.3)
- Fault Tolerance – Backward recovery using checkpoints.
  - Tradeoff: independent vs coordinated checkpointing
- Fault Tolerance –Recovery using Write-Ahead-Logging
  - Balances the overhead of checkpointing and ability to recover to a consistent state

Additional Material in the Book

- Process Resilience (when processes fail) T8.2
  - Have multiple processes (redundancy)
  - Group them (flat, hierarchically), voting
- Reliable RPCs (communication failures) T8.3
  - Several cases to consider (lost reply, client crash, …)
  - Several potential solutions for each case
- Distributed Commit Protocols T8.5
  - Perform operations by all group members, or not at all
  - 2 phase commit, … (last lecture)
- Logging and recovery T8.6