Summary for Advanced Computer Systems at University of Copenhagen 2021/2022. These notes are mostly based on the lecture slides and reading material.

Fundamentals

Common Problems of Systems

- **Emergent Properties**
  properties not showing up in individual components, but when combining those components
- **Propagation of Effects**
  what looks at first to be a small disruption or a local change can have effects that reach from one end of a system to the other
- **Incommensurate Scaling**
  as a system increases in size or speed, not all parts of it follow the same scaling rules, so things stop working
- **Trade-offs**
  waterbed effect: pushing down on a problem at one point causes another problem to pop up somewhere else

System technical definition:

A **system** is a set of interconnected components that has an expected behavior observed at the interface with its environment.

Divide all the things in the world into two groups:

- those under discussion (part of the system)
- those that are not part **(environment)**
- the interactions between system and its environment are the **interface** between the system and environment

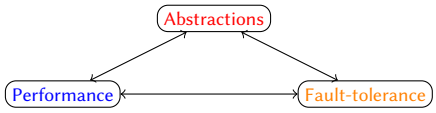
Fundamentals

- Abstractions: interpreters, memory, communication links
- Modularity with clients and services (RPC)
- Techniques for performance

Learning goals

- Identify the fundamental abstractions in computer systems
- Explain how names are used in the fundamental abstractions
- Being able to design a top-level abstraction, based on lower-level abstractions
- Discuss performance and fault-tolerance of a design

Central Trade-off: Abstractions, Performance, Fault-Tolerance



Examples for Trade-off

- To improve performance one might has to ignore the abstraction and take the behavior of the underlying concrete implementation into account
- when introducing another layer of abstraction we might introduce new kinds of errors (for example when introducing RPC, we can have communication errors)
- introducing mechanisms for fault-tolerance can have a negative effect on performance

Names

Names make connections between the different abstractions.

- Examples
  - IP-address
  - IR
- Names require a mapping scheme
- How can we map names?
  - Table lookup (e.g. Files inside directories)
  - Recursive lookup
  - Multiple lookup

Memory

- READ(name) → value
- WRITE(name, value)

Examples of Memory

- Physical memory (RAM)
- Multi-level memory hierarchy
- Address spaces and virtual memory with paging
- Key-value stores
- Database storage engines

Interpreters

Interpreter has:

- Instruction repertoire
- Environment
- Instruction pointer

Interpretation Loop:

```
do forever
  instruction <- READ(instruction_pointer)
  perform instruction in environment context
  if interrupt_signal = True
    instruction_pointer <- entry of INTERRUPT_HANDLER
    environment <- environment of INTERRUPT_HANDLER
```

Examples of Interpreters:

- Processors (CPU)
- Programming language interpreters
- Frameworks (e.g. MapReduce, Spark)
- layered programs (RPCs)

Communication links

- SEND(linkName, outgoingMessageBuffer)
- RECEIVE(linkName, incomingMessageBuffer)

Examples of Communication Links:

- Ethernet interface
- IP datagram service
- TCP sockets
- Message-Oriented Middleware (MOM)
- Multicast (e.g. CATOCS Causal and Totally-Ordered Communication System)

Other Abstractions

- Synchronization
  - Locks
  - Condition variables & monitors
- Data processing
  - Data transformations
  - Operators

Modularity through Clients and Services, RPC

Layers and Modules

- Interpreters often organized in layers
- Modules
  - Components that can be separately designed / implemented / managed / replaced (*Saltzer & Kaashoek glossary*)
  - "Instructions" of higher-level interpreters
  - Recursive: can be whole interpreters themselves!

Isolating Errors: Enforced Modularity

Problem: What happens when modules fail with (unintended) errors?

→ only that particular module should fail rest of system should still work (for this need enforced modularity)

Example: Clients & Services

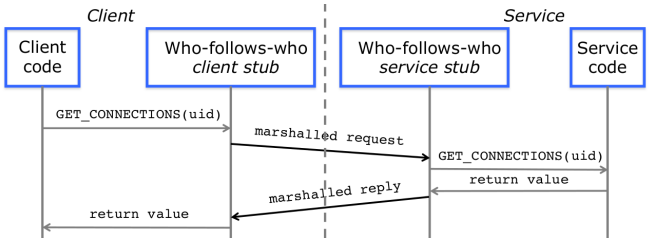
- Restrict communication to *message only*
- Client request / Service response (or reply)
- Conceptually client and service in different computers

Example: OS Virtualization

- Create virtualized version of fundamental abstraction
- Client and services remain isolated even on same computer
- VMs: virtualize the virtualizer

RPC: Remote Procedure Call

- Client-service request / response interactions
- Automate marshalling and communication



RPC Semantics

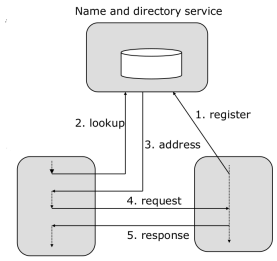
- **At-least-once**
  - Operation is *idempotent* (naturally occurs if side-effect free)
  - Stub just retries operation → failures can still occur!
  - Example: calculate SQRT
- **At-most-once**
  - Operation does have side-effects
  - Stub must ensure duplicate-free transmission
  - Example: transfer $100 from my account to yours
- **Exactly-once**
  - possible for certain classes of failures
  - Stub & service keep track (*durably*) of requests and responses
  - Example: bank cannot develop amnesia!

How to achieve RPCs?

- Special-purpose **request-reply protocol** e.g. DNS
  - Developer must design protocol and marshalling scheme
- **Classic RPC** protocols, DCE, Sun RPC
  - Special APIs and schemes for marshalling
- **RMI: Remote Method Invocation**
  - RPCs for methods in OO languages
  - Compiler-generated proxies
- **Web Services**
  - many modes of communication possible, including RPC-style communication
  - Tools available to compile proxies, e.g., JAX-WS
  - Generic marshalling (e.g., XML, JSON, Protocol Buffers) over HTTP transport
    → **programming-language Independence**

RPC and Naming

- Most basic extension to the synchronous interaction pattern
  - Avoid having to name the destination
  - Ask where destination is
  - then bind to destination
- Advantages:
  - Development is independent of deployment properties (e.g. network address)
  - more flexibility
    - change of address
  - Can be combined with
    - Load balancing
    - Monitoring
    - Routing
    - Advanced service search



Common Issues in Designing Services

- Consistency
  - How to deal with *updates* from multiple clients?
- Coherence
  - How to refresh caches while respecting consistency?
- Scalability
  - What happens to resource usage if we increase the #clients or the #operations?
- Fault Tolerance
  - Under what cirumstances will the service be unavailable?

Other Examples of Services

- File systems: NFS, GFS
- Object stores: Dynamo, PNUTS
- Database: relational DB
- Configuration: Zookeeper
- Even whole computing clouds!
  - Infrastructure-as-a-service (IaaS): e.g. Amazon EC2
  - Platform-as-a-service (PaaS): e.g. Windows Azure
  - Software-as-a-service (SaaS): e.g. Salesforce, Gmail

Techniques for Performance

Motivation: Abstractions, Implementation and Performance

Let I_1 and I_2 be two implementations of an abstraction

- Examples
  - Web service with or without HTTP proxies
  - Virtual memory with or without paging
  - Transactions via concurrency or serialization

⇒ **How can we choose between I_1 and I_2?**

Performance Metrics

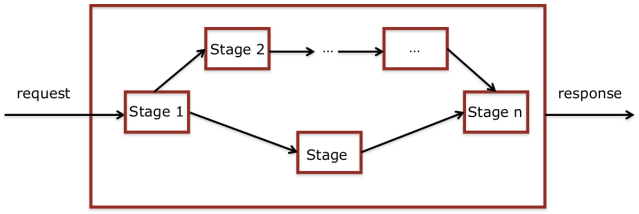
- **latency:** The delay between a change at the input to a system and the corresponding change at its output. From the client/service perspective, the latency of a request is the time from issuing the request until the time the response is received from the service.
- **throughput:** Is a measure of the rate of useful work done by a service for some given workload of requests. If processing is serial, then throughput is inversely proportional to the average time to process a single request

$$throughput = \frac{1}{latency}$$

  If processing is concurrent, then no direct relationship between latency and throughput.
- **scalability:** Scalability is the property of a system to handle a growing amount of work by adding resources to the system
- **overhead:** In a layered system, each layer may have a different view of the capacity and utilization of the underlying resources. Each layer considers what the layer below it do to be *overhead* in time and space, what the layers above it do to be *useful work*.
- **utilization:** The percentage of capacity used for a given workload
- **capacity:** Any consistent measure of the size or amount of a resource.

How can we improve performance?

- **Fast-path coding**
  - Split processing into two code paths
  - One optimized for common requests → fast path
  - One slow but comprehensive path for all other requests → slow path
  - Example: Caching



- **Batching**
  - Run multiple requests at once
  - Example: batch I/Os and use elevator algorithm
  - May improve latency and throughput
- **Dallying**
  - Wait until you accumulate some requests and then run them
  - Example: group commit
- **Concurrency**
  - Run multiple requests in different threads
  - May improve both throughput and latency, but must be careful with locking (overhead), correctness
  - Can be hidden under abstractions (e.g. MapReduce, transactions)
  - Example: different web requests run in different threads or even servers
- **Speculation**
  - Guess the next requests and run them in advance

- May overlap expensive operations, instead of waiting for their completion
- Example: prefetching

Concurrency Control

Transaction
- Reliable unit of work against memory abstraction

ACID Properties
- **Atomicity:** transactions are all-or-nothing
- **Consistency:** transaction takes database from one consistent state to another
- **Isolation:** Executes as if it were the only one in the systems (aka before-or-after atomicity)
- **Durability:** once transaction is done ("committed"), results are persistent in the database

The many faces of atomicity
- **Atomicity** is strong modularity mechanism!
  - Hides that one high-level actions is actually made of many sub-actions
- **Before-or-after** atomicity
  - == Isolation
  - Cannot have effects that would only arise by interleaving of parts of transactions
- **All-or-nothing** atomicity
  - == Atomicity (+ Durability)
  - cannot have partially executed transactions
  - Once executed and confirmed, transaction effects are visible and not forgotten

Goal of Concurrency Control
- Transactions should be executed so that it is *as though* they executed in some serial order
  - Also called **Isolation** or **Serializability** or **Before-or-after atomicity**
- Weaker variants also possible
  - Lower "degrees of isolation"

Example
Consider two transactions (Xacts):

```
T1: BEGIN A=A+100, B=B-100 END
T2: BEGIN A=1.06*A, B=1.06*B END
```

- T1 transfers $100 from B's account to A's account
- T2 credits both accounts with 6% interest
- If submitted concurrently, net effect should be equivalent to Xacts running in some serial order
  - No guarantee that T1 "logically" occurs before T2 (or vice-versa) - but one of them is true

Different Solutions (Locking Protocols)
Solution 1
1. Get exclusive lock on entire database
2. Execute transaction
3. Release exclusive lock

- Transactions execute in *critical section*
- Serializability guaranteed because execution is serial!

Problems:

- no concurrency, only serial schedules

Solution 2
1. Get exclusive locks on *accessed* data items
2. execute transaction
3. release exclusive locks

- Greater concurrency

Problems:

- need to know objects a priori, least concurrency

Solution 3
1. Get exclusive locks on data items that are *modified*; get shared locks on data items that are only *read*
2. Execute transaction
3. Release all locks

- Greater concurrency
- Conservative Strict Two Phase Locking (CS2PL)

Problems:

- need to know objects a priori, least concurrency

Solution 4
1. Get exclusive locks on data items that are modified and get shared locks on data items that are read
2. Execute transaction and release locks on objects no longer needed *during execution*

- Greater concurrency
- Conservative Two Phase Locking (C2PL)

Problems:

- Cascading Aborts: assume T1 has locks on $1, 2, 3$ and then starts to release locks $1, 2$, which are immediately acquired by T2, but then T1 does not commit but aborts. now T2 also has to be aborted etc.
- need to know objects a priori, when to release locks

Solution 5
1. Get exclusive locks on data items that are modified and get shared locks on data items that are read, but do this *during execution* of transaction (as needed)
2. Release all locks

- Greater concurrency
- Strict Two Phase Locking (S2PL)

Problems:

- Deadlocks: assume T1 wants $1, 2, 3$ and T2 wants $2, 3, 4$ and that T1 acquires $1, 2$ and T2 $3, 4$ now we have a deadlock.

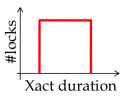
Solution 6
1. Get exclusive locks on data items that are modified and get shared locks on data items that are read, but do this during execution of transaction (as needed)
2. Release locks on objects no longer needed during execution of transaction
3. Cannot acquire locks once any lock has been released (Hence two-phase (acquiring phase and releasing phase)

- Greater concurrency
- Two Phase Locking (2PL)

Problems:

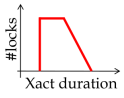
- Cascading aborts and Deadlocks

Summary of Alternatives
- Conservative Strict 2PL
  - no deadlocks, no cascading aborts
  - **But** need to know objects a priori, least concurrency



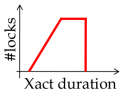
	S	X
S	Yes	No
X	No	No

- Conservative 2PL
  - no deadlocks, more concurrency than Conservative Strict 2PL
  - **But** need to know objects a priori, when to release locks, need to deal with cascading aborts



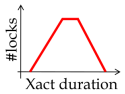
	S	X
S	Yes	No
X	No	No

- Strict 2PL
  - no cascading aborts, no need to know objects a priori or when to release locks, more concurrency than Conservative Strict 2PL
  - **But** deadlocks



	S	X
S	Yes	No
X	No	No

- 2PL
  - most concurrency, no need to know objects a priori
  - **But** need to know when to release locks, cascading aborts, deadlocks



Method of choice

- Strict 2PL
  - no cascading aborts, no need to know objects a priori or when to release locks, more concurrency than Conservative Strict 2PL
  - But deadlocks
- Reason for choice
  - Cannot know objects a priori, so no Conservative options → only if you would know something about application!
  - Thus only 2PL and Strict 2PL left
  - 2PL needs to know when to release locks (main problem), and has cascading aborts
  - Hence Strict 2PL
- Implication: Need to deal with deadlocks!

Lock Management

- Lock/unlock requests handled by lock manager
- Lock table entry:
  - Number of transactions currently holding a lock
  - Type of lock held (shared or exclusive)
  - Pointer to queue of lock requests
- Locking and unlocking have to be atomic operations
- **Lock upgrade:** transaction that holds a shared lock can be upgraded to hold an exclusive lock

Dynamic Databases: Locking the objects that exist now in the database is not enough!

- If we relax the assumption that the DB is a fixed collection of objects, even Strict 2PL will not work correctly:
  - T1 locks all pages containing sailor records with *rating* = 1, and finds **oldest** sailor (say, age = 71)
  - Next, T2 inserts a new sailor; rating = 1, age = 96
  - T2 also deletes oldest sailor with rating = 2 (and, say, age = 80), and commits
  - T1 now locks all pages containing sailor records with rating = 2, and finds **oldest** (say, age = 63)
- No consistent DB state where T1 is "correct"!

The Problem

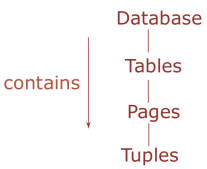
- T1 implicitly assumes that it has locked the set of all sailor records with rating = 1
  - assumption only holds if no sailor records are added while T1 is executing!
  - Need some mechanism to enforce this assumption. **(Index locking and predicate locking)**
- Example shows that correctness is guaranteed for locking on individual objects only if the set of objects is fixed!

Index Locking

- If data is accessed by an **index** on the rating field, T1 should **lock the index page** containing the data entries with rating = 1
  - if there are no records with rating = 1, T1 must lock the index page where such a data entry would be, if it existed!
- if there is **no suitable index**, T1 must **lock all pages**, and lock the file/table to prevent new pages from being added, to ensure that no new records with rating = 1 are added

Multiple-Granularity Locks

- Hard to decide what granularity to lock (tuple vs. pages vs. tables)
- Shouldn't have to decide!
- Data "containers" are nested



Solution: New Lock Modes, Protocol

- Allow Xacts to lock at each level, but with a special protocol using new **"intention" locks**
- before locking and item, Xact must set "intention locks" on all its ancestors
- for unlock, go from specific to general (i.e., bottom-up)
- **SIX mode:** like S & IX at the same time

	--	IS	IX	S	X
--	√	√	√	√	√
IS	√	√	√	√	
IX	√	√	√		
S	√	√		√	
X	√				

Schedules

- Consider a possible interleaving (schedule):

```
T1:    A=A+100,                        B=B-100
T2:                A=1.06*A, B=1.06*B
```

- The systems's view of the schedule

```
T1:    R(A),W(A),                      R(B),W(B)
T2:                R(A),W(A),R(B),W(B)
```

Scheduling Transactions

- **Serial schedule:** Schedule that does not interleave the actions of different transactions
- **Equivalent schedules:** For any database state
  - The effect (on the set of objects in the database) of executing the schedules is the same
  - the values read by transactions is the same in the schedules
    - Assume no knowledge of transaction logic
- **Serializable schedule:** A schedule that is equivalent to some serial execution of the transactions.

Anomalies with Interleaved Execution

- Reading Uncommitted Data (WR Conflicts, "dirty reads")

```
T1:   R(A), W(A),                R(B), W(B), Abort
T2:               R(A), W(A), C
```

- Unrepeatable Reads (RW Conflicts)

```
T1:   R(A),                      R(A), W(A), C
T2:          R(A), W(A), C
```

- Overwriting Uncommitted Data (WW Conflicts)

```
T1:   W(A),                W(B), C
T2:         W(A), W(B), C
```

Conflict Serializable Schedules

- Two schedules are **conflict equivalent** if:
  - involve the same actions of the same transactions
  - every pair of conflicting actions is ordered the same way
  - two actions are called **conflicting** if they access the same object and one of them is a write
- Schedule S is **conflict serializable** if S is conflict equivalent to some serial schedule

Example: Schedule not conflict serializable

- the cycle in the graph reveals the problem. The output of T1 depends on T2, and vice-versa.

```
T1:    R(A), W(A),                              R(B), W(B)
T2:                R(A), W(A), R(B), W(B)
```

Precedence Graph

- **Precedence graph:** One node per Xact; edge from T_i to T_j if operation in T_j conflicts with earlier operation in T_i
- **Theorem:** Schedule is conflict serializable if and only if its precedence graph is acyclic
- Strict 2PL only results in conflict serializable schedules
  - Precedence graph is always acyclic

View serializability

- Schedules S1 and S2 are **view equivalent** if:
  - T_i reads initial value of A in S1, then T_i also reads initial value of A in S2
  - if T_i reads a value of A written by T_j in S1, then T_i also reads value of A written by T_j in S2
  - If T_i writes final value of A in S1, then T_i also writes final value of A in S2

Deadlocks

- Deadlock: Cycle of transactions waiting for locks to be released by each other

- Two ways of dealing with deadlocks:
  - Deadlock prevention
  - Deadlock detection

Deadlock Prevention

- Assign priorities based on timestamps
- Lower timestamps get higher priority, i.e., older transactions get prioritized
- Assume T_i wants a lock that T_j holds. Two policies are possible:
  - Wait-Die: If T_i has higher priority, T_i waits for T_j; otherwise T_i aborts
  - Wound-wait: If T_i has higher priority, T_j aborts; otherwise T_i waits
- If a transaction re-starts, make sure it has its original timestamp

Deadlock Detection

- Create a **waits-for graph**:
  - Nodes are transactions
  - There is an edge from T_i to T_j if T_i is waiting for T_j to release a lock
- Periodically check for cycles in the waits-for graph

The Problems with Locking

- Locking is a pessimistic approach in which conflicts are prevented
- Disadvantages:
  - Lock management overhead
  - Deadlock detection/resolution necessary
  - Lock contention for heavily used objects
- We must devise a way to **enforce serializability**, without destroying concurrency
- Two approaches:
  - prevent violations → locking
  - fix violations → aborts

Optimistic CC: Kung-Robinson Model

- optimistic approach based on aborts
- Xacts have three phases
- **READ:** Xacts read from the database, but make changes to private copies of the objects
- **VALIDATE:** check for conflicts
- **WRITE:** make local copies of changes public

Validation

- Test conditions that are **sufficient** to ensure that no conflict occurred
- Each Xact is assigned a numeric id
  - simply use a **timestamp**
- Xact ids assigned at end of READ phase, just before validation begins
- ReadSet(T_i): Set of objects read by Xact T_i
- WriteSet(T_i): Set of objects modified by T_i

Test 1

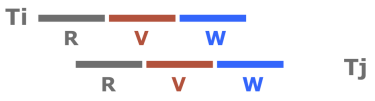
- For all i and j such that $T_i < T_j$, check that T_i completes before T_j begins

Test 2

- For all i and j such that $T_i < T_j$, check that:
  - T_i completes before T_j begins its Write phase
  - WriteSet(T_i) ∩ ReadSet(T_j) is empty

Test 3

- For all i and j such that $T_i < T_j$, check that:
  - T_i completes Read phase before T_j does
  - WriteSet(T_j) ∩ ReadSet(T_J) is empty
  - WriteSet(T_i) ∩ WriteSet(T_j) is empty



Overheads in Optimistic CC

- Must record read/write activity in ReadSet and WriteSet per Xact
  - must create and destroy these sets as needed
- Must check for conflicts during validation, and must make validated writes "global"
  - Critical section can reduce concurrency
  - Scheme for making writes global can reduce clustering of objects
- Optimistic CC restarts Xacts that fail validation
  - work done so far is wasted; requires clean-up
- Still, optimistic techniques widely used in software transactional memory (STM), main-memory databases

Snapshot Isolation

- Often databases implement properties that are **weaker** than serializability
- **Snapshot isolation**
  - **Snapshots:** Transactions see snapshot as of beginning of their execution
  - **First Committer Wins:** Conflicting writes to same item lead to aborts
- May lead to **write skew**
  - Database must have at least one doctor on call
  - Two doctors on call concurrently examine snapshot and see exactly each other on call
  - Doctors update their own records to being on leave
    - No writ-write conflicts: different records!
  - after commits, database has no doctors on call

Experimental Design

Techniques to Evaluate Performance

- Three main techniques
  - Analytical Modeling
  - Simulation
  - Experimentation

Analytical Modeling

- Get intuition about system performance
  - Without actually implementing it!
- Simple model for virtual memory system with paging:

$$\text{AverageLatency} = \text{HitRatio} * \text{Latency}_{\text{Hit}} + (1 - \text{HitRatio}) * \text{Latency}_{\text{Miss}}$$

- With high hit ratio (say, >95%), average time can be pretty close to main memory
  - Some requests still require going to disk, of course, and take full disk latency blow
- How can we know the hit ratio?

Simulation

- Study properties of hard-to-model process, e.g., locality of workloads vs. hit ratio in cache
- Configure model with known parameters
  - In our example, $\text{Latency}_{\text{Hit}}$ and $\text{Latency}_{\text{Miss}}$
- Simulate behavior of system to get HitRatio

Simulation

- Pros
  - Effort may be smaller than full-blown implementation
  - Allows you to simulate "impossible" or hard-to-experiment-with scenarios → 10Ks of machines, next-generation flash disk not on the market yet
- Cons
  - Estimating parameters
  - Validating models and approximations
  - Choosing workloads

Choosing Workloads & Datasets

- Synthetic workloads & datasets
  - Example: use Zipf distribution to generate workload of page accesses (Zipf distribution: most frequent word occurs twice as often as 2. most frequent and 3 times as often as 3. most frequent etc.)
- Real workloads & datasets
  - Example: Take **trace** of page requests from real application
  - replay trace on your simulator
- Combinations also possible
  - Use real dataset but generate accesses using a distribution
- Issue: How can you tell if workload is representative?

Experimentation

- **Implement** real system (or prototype)
- **Measure** how it behaves with experiments
  - most respected method
  - but also requires most effort
- **Profile** system to determine where time goes

Simple Factor Experimentation

- Understanding multiple influences
- Vary one factor at a time, keep others fixed
- Example: Skew of workload and size of cache
  - Skew = 0.5, vary cache size from 1MB to 1GB
  - Cache size = 500MB, vary skew from 0 to 1
- Care required: Parameters may **influence** each other!

Benchmarking

- **Micro-benchmarks**
  - Measure a specific variable or piece of code, e.g., memory and disk latencies in small experiment to calibrate simulation model
- **Application-level benchmark**
  - whole application designed to stress certain types of systems
  - **SPEC** benchmarks for compute-intensive apps, web servers, file systems, and many others
  - **TPC** benchmarks for databases

Necessary Care with Executing Experiments

- Select **event counts**
  - Number of pages/chunks read
  - Number of clock cycles elapsed → wall-clock time
- But control for **overhead** of event counting itself!
- **Sampling / monitoring**
  - e.g., I/O via iostat/vmstat
- "**Statistics** can prove anything?!"
  - Number of measurements
  - Mean and variance
  - confidence intervals
  - dealing with outliers
  - Setup matters!

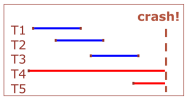
Comparing Alternatives

- Two systems, with throughput-oriented measurements R_2 and R_1
  - Both systems travel same distance D, i.e., do same work but take different time
  - $R_2 = D/T_2$; $R_1 = D/T_1$
- Speedup
  - $S_{2,1} = R_2/R_1 = T_1/T_2$
- Relative change
  - $\Delta_{2,1} = (R_2 - R_1)/R_1 = S_{2,1} - 1$
- Example statements
  - System 2 is 1.4 times faster than System 1
  - System 2 is 40% faster than System 1

Implementing All-or-Nothing Atomicity

- Atomicity
  - Transactions may abort ("Rollback")
- Durability
  - What if system stops running? (Causes?)

- Desired behavior after system restart
  - T1, T2, T3 should be durable
  - T4, T5 should be aborted (effects not seen)



Assumptions

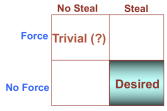
- Concurrency control is in effect
  - Strict 2PL, in particular
- Updates are happening "in place"
  - i.e. data is overwritten on (deleted from) memory using READ / WRITE interface
  - we will use two-level memory with buffer and disk
- Types of failures
  - Crash
  - Media failure
- Always fail-stop! (components notify that they have crashed)

Volatile vs. Nonvolatile vs.Stable Storage

- Volatile Storage
  - Lost in the event of a crash
  - Example: main memory
- Nonvolatile Storage
  - Not lost on crash, but lost on media failure
- Stable Storage
  - Never lost
  - How do you implement this one? (Replication only lower chance of failure)

Surviving Crashes: How to handle the Buffer Pool?

- **Force** every write to disk?
  - Poor response time
  - But provides durability
- **Steal** buffer-pool frames from uncommitted Xacts?
  - If not, poor throughput
  - If so, how can we ensure atomicity?



More on Steal and Force

- **STEAL** (why enforcing Atomicity is hard)
  - to steal a frame F: current page in F (say P) is written to disk; some Xact holds a lock on P
    - What if the Xact with the lock on P aborts?
    - Must remember the old value of P at steal time (to support UNDOing the write to page P)
- **NO FORCE** (why enforcing Durability is hard)
  - What if system crashes before a modified page is written to disk?
  - Write as little as possible, in a convenient place, at commit time, to support REDOing modifications

	No Steal	Steal
Force	No Redo No Undo	No Redo Undo
No Force	Redo No Undo	Redo Undo

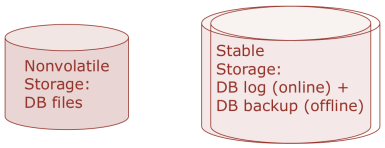
Basic Idea: Logging

- Record REDO and UNDO information, for every update, in a **log**
  - Sequential writes to log (put it on a separate disk)
  - Minimal info (diff) written to log, so multiple updates fit in a single log page
- **Log:** an ordered list of REDO/UNDO actions
  - logical vs. physical logging
  - example physical log record contains:
    <XID, pageID, offset, length, old data, new data>
  - good compromise is physiological logging

Write-Ahead Logging (WAL)

- Golden Rule: Never modify the only copy!
- The Write-Ahead Logging Protocol:
  1. Must force the log record for an update **before** the corresponding data page gets to disk
  2. Must write all log records for a Xact **before commit**
- #1 guarantees Atomicity
- #2 guarantees Durability

Recovery Equations



- Crash Recovery: volatile memory lost
  - Current DB = DB files + DB log (Since last transaction that did not complete
- Media Recovery: nonvolatile storage lost
  - Current DB = DB backup + DB log Since last checkpoint

Recovery: Basic Concepts, ARIES

WAL & the Log

- Each log record has a unique Log Sequence Number (LSN)
  - LSNs always increasing
- Each data page contains a pageLSN
  - The LSN of the most recent log record for an update to that page
- System keeps track of flushedLSN
  - The max LSN flushed so far
- WAL: Before a page is written
  - pageLSN <= flushedLSN

Log Records

- Possible log record types
  - Update
  - Commit
  - Abort
  - End (signifies end of commit or abort)
  - Compensation Log Records (CLRs)
    → for UNDO actions

LogRecord fields:

prevLSN
XID
type
pageID
length
offset
before-image
after-image

(update records only)

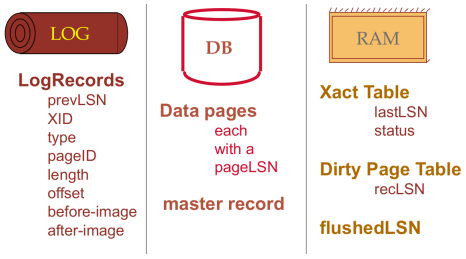
Other Log-Related State

- Transaction Table
  - One entry per active Xact
  - Contains XID, Status (running/commited/aborted) and lastLSN
- Dirty Page Table:
  - One entry per dirty page in buffer pool
  - Contains recLSN – the LSN of the log record which first caused the page to be dirty

Normal Execution of an Xact

- Series of reads &writes, followed by commit or abort
  - We will assume that write is atomic on disk
    (In practice, additional details to deal with non-atomic writes)
- Strict 2PL → concurrency is correctly handled
- STEAL, NO-FORCE buffer management with Write-Ahead Logging

The Big Picture: What's Stored Where



Checkpointing

- Periodically, the DBMS creates a **checkpoint**, to minimize the time taken to recover in the event of a system crash.
- Checkpoint: Write to log
  - begin_checkpoint record: indicates when checkpoint began
  - end_checkpoint record: contains current Xact table and dirty page table. This is a 'fuzzy checkpoint':
    - Other Xacts continue to run; so these tables accurate only as of the time of the begin_checkpoint record
    - **No attempt to force dirty pages to disk**; effectiveness of checkpoint limited by oldest unwritten change to a dirty page, minDirtyPagesLSN
    - use **background process** to flush dirty pages to disk!
  - Store LSN of checkpoint record in a safe place (**master** record)

Transaction Commit

- Write commit record to log
- All log records up to Xact's lastLSN are flushed
  - Guarantees that flushedLSN >= lastLSN
  - Note that log flushes are sequential, synchronous writes to disk
  - Many log records per log page
- Commit() returns
- Write end record to log

Simple Transaction Abort

- For now, consider an explicit abort of a Xact
  - No crash involved
- We want to "play back" the log in reverse order, UNDOing updates
  - Get lastLSN of Xact from Xact table
  - Can follow chain of log records backward via the prevLSN field
- Before starting UNDO, write an Abort log record.
  - For recovering from crash during UNDO!

- To perform UNDO, must have a lock on data!
  - Strict 2PL enforces this
- Before restoring old value of a page, write a CLR:
  - You continue logging while you UNDO!!
  - CLR has one extra field: undonextLSN
    - Points to the next LSN to undo (i.e. the prevLSN of record we are currently undoing)
  - CLRs **never** undone (but they might be Redone when repeating history: guarantees Atomicity!)
- At end of UNDO, write and end log record

Example

- 10 T1 writes P5
- 20 T2 writes P17
- 30 T1 writes P3

P3 written to disk (pageLSN for page 3 at this time is 30)

- 40 T1 aborts
- 50 CLR T1 P3 (undonextLSN: 10)
- 60 CLR T1 P5 (undonextLSN: NULL)
- 70 End T1

Crash Recovery: Big Picture

- Start from a checkpoint (found via master record)
- Three phases
  - Figure out which Xacts committed since checkpoint, which failed (Analysis)
  - REDO all actions (Repeat History)
  - UNDO effects of failed Xacts

Recovery: The Analysis Phase

- Reconstruct state (Xact table and dirty page table) at checkpoint
  - via end_checkpoint record
- Scan log forward from checkpoint
  - End record: Remove Xact from Xact table
  - Other records: Add Xact to Xact table, set lastLSN=LSN, change Xact status on commit
  - Update record: if P not in Dirty Page Table,
    - Add P to Dirty Page Table, set its recLSN=LSN

Recovery: The REDO Phase

- We repeat History to reconstruct state at crash:
  - Reapply all updates (even of aborted Xacts!), redo CLRs
- Scan forward from log record containing the smallest recLSN in Dirty Page Table. For each CLR or update log record with LSN, REDO the action unless:
  - Affected page is not in the Dirty Page Table, or
  - Affected page is in Dirty Page Table, but has recLSN > LSN, or
  - pageLSN (in DB) >= LSN
- To REDO an action:
  - Reapply logged action
  - Set pageLSN to LSN, no additional logging!

Recovery: The UNDO Phase

ToUndo = $\{lsn | lsn$ a lastLSN of a "loser" Xact$\}$

Loser Transactions: all transactions active at the time of the crash. All actions of losers must be undone, and further, these actions must be undone in the reverse of the order in which they appear in the log.

- **Repeat:**
  - Choose largestLSN among ToUndo
  - If this LSN is a CLR and undonextLSN==NULL
    - Write an End record for this Xact
  - If this LSN is a CLR, and undonextLSN != NULL
    - Add undonextLSN to ToUndo
  - Else this LSN is an update. Undo the update write a CLR, add prevLSN to ToUndo
- **Until ToUndo is empty**

Example Recovery: Notes

No optimization in terms of removing pages that we know are clean after a transaction has been aborted, because in the present of other transactions we cannot be sure that page is clean.

When undoing a page at it is not yet in the dirty page table we have to put it there.

Recovery is the same as normal execution (just redoing it to reconstruct state (Transaction Table and Dirty Page Table).

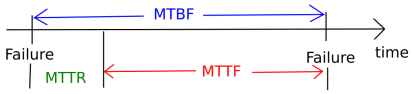
Reliability: Concepts

- Assume a computer has probability of failure p
- If the system needs N computers to work, what is the probability of system working?

- Probability of one component working: 1 - p
- Probability of all components working: $(1 - p)^N$
  - assuming failures are independent!
  - Correlated failures are the reality (and make it even worse)

Reliability Measures

- Mean Time to Failure (MTTF)
- Mean Time to Repair (MTTR)
- Mean Time Between Failures (MTBF)
- MTBF = MTTF + MTTR
- Availability = MTTF / MTBF
- Downtime = (1 - Availability) = MTTR / MTBF



- Consider N = 10,000 and for one computer, MTTF = 30 years then you have $10,000/30 \approx 333$ failures
- In order to estimate the value of MTTF for a system that has long MTTF, run many machines simultaneously. This assumes that failures are evenly distributed during component lifetime.

Reliability & Availability

- Things will crash. Deal with it!
  - Assume you could start with super reliable servers (MTBF of 30 years)
  - Build computing system with 10 thousand of those
  - **Watch one failure per day**
  - Facebook has to mitigate one data center outage every two weeks!

- Fault-tolerant software is inevitable

- Typical yearly flakiness metrics
  - 1-5% of your disk drives will die
  - Servers will crash at least twice (2-4% failure rate)

Faults, Errors, and Failures

- **Fault**
  - Defect that has potential to cause problems
- **Error**
  - Wrong result caused by an active fault
- **Failure**
  - Unhandled error that causes interface to break its contract

Fault Tolerance

- Error detection
  - Use limited redundancy to verify correctness
  - Example: detect damaged frames in link layer
  - **Fail fast:** report error at interface

- Error containment
  - Limiting propagation of errors
  - Example: enforced modularity
  - **Fail stop:** immediately stop to prevent propagation
  - **Fail safe:** transform wrong values into conservative "acceptable" values, but limiting operation
  - **Fail soft:** continue with only a subset of functionality

Fault Tolerance

- Error masking
  - Ensure correct operation despite errors
  - Example: reliable transmission, process pairs
- We will focus on error masking
  - Main techniques: **Redundancy**

Replication

- State-machine replications (replicated Interpreter)
- Asynchronous replication (replicated memory)
  - Primary-Site
  - Peer-to-Peer
- Synchronous replication (replicated memory)
  - Read-Any, Write-All
  - Quorums

- Techniques only good enough for a specific **failure model**
  - Nuclear holocaust
  - Component maliciously outputs random gibberish (**Byzantine**)
  - Components **crash** without telling you anything
  - Components are **fail-stop**

Asynchronous Replication

- Allows WRITEs to return before all copies have been changed
  - READs nonetheless look at subset of copies
  - Users must be aware of which copy they are reading, and that copies may be out-of-sync for short periods of time

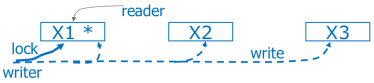
- Two approaches: Primary Site and Peer-to-Peer replication
  - Difference lies in how many copies are "updatable" or "master copies"

Primary Site Replication

- Exactly one copy is designated the primary or master copy. Replicas at other sites cannot be directly updated
  - The primary copy is published
  - other sites subscribe to this copy; these are secondary copies

- Main issue: How are changes to the primary copy propagated to the secondary copies?
  - Done in two steps: First, CAPTURE changes made at primary; then APPLY these changes
  - Many possible implementations for CAPTURE and APPLY

Primary copy



- Writers lock & update primary copy and propagate the update to other copies
- Readers lock and access primary copy
- Widely adopted, e.g. many database systems

Peer-to-Peer Replication

- More than one of the copies of an object can be a master in this approach
  - Changes to a master copy must be propagated to to other copies
  - It two master copies are changed in a conflicting manner, this must be resolved. (e.g., Site 1: Joe's age changed to 35; Site 2: to 36)

- Best used when conflicts do not arise
- **Examples**
  - Each master site owns a disjoint fragment of the data
  - Updating rights owned by one master at a time
  - Operations are associative-commutative

Eventual consistency

- If no new updates are made to an object, after some inconsistency window closes, all accesses will return the same "last" updated value

- **Prefix property:**
  - If Host 1 has seen write $w_{i,2}$: i^{th} write accepted by host 2
  - Then 1 has all writes $w_{j,2}$ (for $j < i$) accepted by 2 prior to $w_{i,2}$

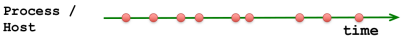
- Assumption: write conflicts will be easy to resolve
  - Even easier if whole-"object" updates only

Events and Histories

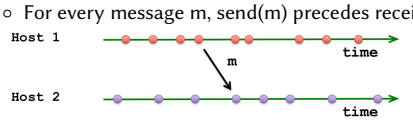
- Processes execute sequences of events
- Events can be of 3 types:
  - local
  - send
  - receive
- The local history h_p of process p is the sequence of events executed by process

Ordering Events

- Observation 1:
  - Events in local history are **totally ordered**



- Observation 2:
  - For every message m, send(m) precedes receive(m)

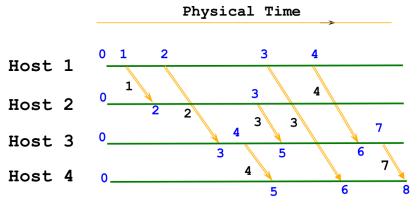


Happens-Before (Lamport [1978])

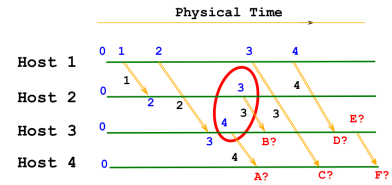
- Relative time? Define Happens-Before (→):
  - On the same process: a → b, if time(a) < time(b)
  - If p1 sends m to p2: send(m) → receive(m)
  - Transitivity: If a → b and b → c then a → c

- Lamport Algorithm establishes partial ordering:
  - All processes use counter (clock) with initial value of 0
  - Counter incremented / assigned to each event as timestamp
  - A send (msg) event carries its timestamp
  - For receive (msg) event, counter is updated by max (receiver-counter, message-timestamp) + 1

Lamport Logical Time



Problem:



Can we say: if timestamp(e) < timestamp (f) then e precedes f ?

Logically concurrent events!

Source: Freedman

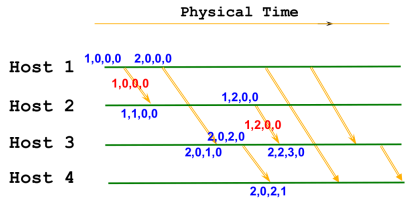
Vector Logical Clocks

- **With Lamport Logical Time**
  - e precedes f $\Rightarrow$ timestamp(e) < timestamp(f), but
  - timestamp(e) < timestamp(f) $\not\Rightarrow$ e precedes f

- **Vector Logical time** guarantees this:
  - All hosts use a vector of counters (logical clocks),
  - i-th element is the clock value for host i, initially 0
  - Each host i, increments the i-th element of its vector upon an event, assigns the vector to the event
  - A send(msg) event carries vector timestamp
  - For receive(msg) event:

$$V_{receiver}[j] = \begin{cases} \max(V_{receiver}[j], V_{msg}[j]), & \text{if } j \text{ is not self} \\ V_{receiver}[j] + 1 & \text{otherwise} \end{cases}$$

Example: Vector Logical Time



Comparing Vector Timestamps

- a = b if they agree at every element
- a < b if a[i] <= b[i], for every i, but !(a=b)
- a > b if a[i] >= b[i], for every i, but !(a=b)
- a || b if a[i] < b[i], a[j] > b[j], for some i,j **(conflict!)**

- If one history is prefix of other, then one vector timestamp < other
- If one history is not a prefix of the other, then (at least by example) VTs will not be comparable

Eventual is not the only choice

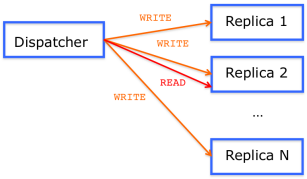
- Host of other properties available (beyond the scope of this course!)
- Examples:
  - Strong consistency
  - Weak consistency
  - Causal consistency
  - Read-your-writes consistency
  - Session consistency
  - Monotonic read consistency
  - Monotonic write consistency

Synchronous Replication

- Hide replication behind READ/WRITE memory abstraction
- Program operates against memory
- Memory makes sure READs and WRITEs are **atomic**
  - **All-or-nothing:** either in all correct replicas or none
  - **Before-or-after:** Equivalent to a total order
- Memory replicates data for fault tolerance

Read Any, Write-All

- For now assume we have a centralized Dispatcher $\rightarrow$ state-machine replication algorithms drop that assumption!
- WRITEs synchronously sent everywhere
- But READs can be answered by any replica



Quorums

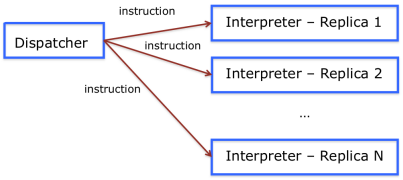
- Read Quorum (Q_r) / Write Quorum (Q_W)
- $Q_r + Q_W > N_{replicas}$
- Reads or writes only succeed if same response is given by respective quorum
  - Read any, Write all case is $Q_W = N_{replicas}$, $Q_r = 1$

State Machines

- A state machine consists of
  - State variables (encoding its state)
- Instructions
  - transforming its state

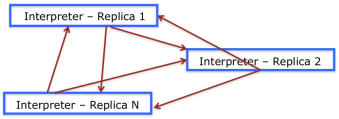
State-Machine Replication (or Active Replication)

- Assumption
  - Instructions of interpreter are deterministic!
  - If replicas of interpreter get same inputs, they will go to the same state and produce the same output



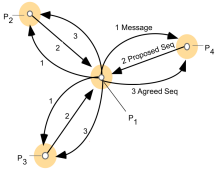
Multicast: Distributing the Dispatcher

- Replicas implement **multicast** operation $\rightarrow$ internalize dispatcher
- Must ensure **atomic** operation execution on all replicas
  - **All-or-nothing:** either in all correct replicas or none
    - also called **Agreement**
  - **Before-or-after:** Equivalent to a total order
    - also called **Order**
  - With at most f failures:
    - **Fail-stop:** requires at least N = f + 1 replicas
    - **Byzantine:** requires at least N = 2f + 1 replicas



Totally Ordered Multicast (ISIS)

- Assume for now no failures
- **Idea**
  - Process 1 sends message with identified i to group
  - Every process p replies with proposed $seq\# = \max(accepted_p, proposed_p) + 1$
  - Process 1 selects maximum number and sends it to group (Note: ties in numbering broken by process numbers)



Reliable and Totally Ordered Multicast?

- if network is **asynchronous** and assuming **crash** failures, **guaranteeing** reliable **and** totally ordered multicast is **IMPOSSIBLE**
- Fischer, Lynch, Patterson (FLP) result $\rightarrow$ Impossibility of Consensus
  - Set of processes with single binary variable
  - Want to decide outcome as 0 or 1 by just exchanging messages
  - **Intuition:** cannot make the difference between crashed process and process running very slowly
  - Adversary **delay** consensus indefinitely
  - Does not mean that consensus cannot be reached in some cases!

- **Solution 1:** Make model **fail-stop**, not crash

- Instead of asynchronous system, make system behave as a (partially) synchronous one with reliable failure detector, e.g., timeout
- Use failure detector to flag failed processes, no doubts
- **Solution 2:** Design **protocol that guarantees safety**, even if it cannot guarantee progress
  - Paxos example of such a protocol

Byzantine Generals

- **Termination:** Eventually each process sets its decision variable
- **Agreement:** The decision value of all the all correct processes is the same: if p_i and p_j are correct and have entered their decided state, then $d_i = d_j$ (for all $i, j = 1, ..., N$)
- **Integrity:** If the commander is correct, then all correct processes decide on the value that the commander proposed

Impossibility with Three Processes

Faulty processes are shown coloured

Solution in Synchronous System

- use two phases
  - in phase 1 commander sends message
  - in second round each process sends received message to others and then do majority vote
- If no majority (e.g. commander is compromised) , play it safe and do nothing

Distributed Transactions

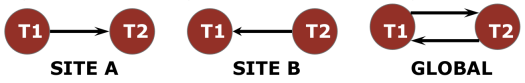
- Users should be able to write Xacts accessing multiple sites just like local Xacts
- enforcing **ACID** class for distributed locking, recovery, and commit protocols
- Hard to scale in number of sites in general
  - Use partitioning / replication techniques for trade-offs

Distributed Locking

- How do we manage locks for objects across many sites?
- **Centralized:** One site does all locking
  - Vulnerable to single site failure
- **Distributed:** Locking for an object done at site where the object is stored

Distributed Deadlock Detection

- Each site maintains a local waits-for graph
- A global deadlock might exist even if the local graphs contain no cycles:

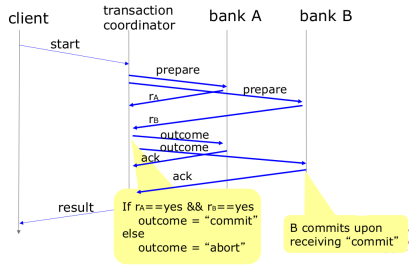


- Three solutions:
  - **Centralized:** send all local graphs to one site
  - **Hierarchical:** organize sites into a hierarchy and send local graphs to parent in the hierarchy
  - **Timeout:** abort Xact if it waits too long

Distributed Recovery

- New issues:
  - New kinds of failure, e.g. links and remote sites
  - If "sub-transactions" of a Xact execute at different sites, all or none must commit → need a **commit protocol** to achieve this
- A log is maintained at each site, as in a centralized DBMS, and **commit protocol actions are additionally logged**

Two-Phase Commit (2PC)



Comments on 2PC

- Two rounds of communication: first **voting**, then **termination**
  - Both initiated by coordinator
- **Any site** can decide to **abort** an Xact
- Every msg reflects a **decision** by the sender
  - To ensure that this decision survives failures, it is first **recorded in the local log**
- All commit protocol log recs for an Xact contain Xactid and Coordinatorid
  - The coordinator's abort/commit record also includes ids of all subordinates/cohorts

Discussion of Failure Scenarios

- Coordinator times out waiting for subordinate's "yes/no" response
  - coordinator can **not** unilaterally decide to commit
  - coordinator **can** unilaterally decide to abort
- If subordinate i responded with "no" ...
  - it **can** unilaterally abort
- If subordinate i responded with "yes" ...
  - it can **not** unilaterally abort (since the coordinator might decide to commit)
  - it can **not** unilaterally commit

Restart After a Failure at a Site

- If we have a commit or abort log rec for Xact T, but not an end rec, must redo/undo T
  - If this site is the coordinator for T, keep sending **commit/abort** msgs to subs until **acks** received
- If we have a prepare log rec for Xact T, but not commit/abort, this site is a subordinate for T
  - Repeatedly contact the coordinator to find status of T, then write **commit/abort** log rec; redo/undo T; and write **end** log rec
- If we don't have even a prepare log rec for T, unilaterally abort and undo T
  - This site may be coordinator! If so, subs may send msgs

Blocking

- If coordinator for Xact T fails, subordinates who have voted yes cannot decide whether to commit or abort T until coordinator recovers
- T is **blocked**
- (one of the major problems of two-phase-commit)

Link and Remote Site Failures

- If a remote site does not respond during the commit protocol for Xact T, either because the site failed or the link failed
- If the current site is a subordinate, and has not yet voted yes, it should abort T
- If the current site is a subordinate and has voted yes, it is blocked until the coordinator responds

2PC with Presumed Abort

- When coordinator aborts T, it undoes T and removes it from the Xact table immediately
  - Doesn't wait for **acks**; "presumes abort" if Xact not in Xact Table. Names of subs not recorded in **abort** log rec
- Subordinates do not send acks on abort
- If subxact does not do updates, it responds to prepare msg with reader instead of yes/no
- Coordinator subsequently ignores readers
- If all subxacts are readers, 2nd phase not needed

Communication

Learning goals

- approaches to design **communication abstractions**
  - transient vs. persistent
  - synchronous vs. asynchronous
- Design and implementation of **message-oriented middleware** (MOM)
- organizing systems using **BASE** methodology
- relationship BASE to eventual consistency and **CAP theorem** (it is impossible to provide **C**onsistency, **A**vailability and **P**artition Tolerance at the same time in distributed systems)
- alternative communication abstractions **data streams** and **multicast** / **gossip**

Partitioning

- use independent services to store different data
- Scalability and Availability improves but now coordination necessary
- employ a communication abstraction

Recall: Protocols and Layering in the Internet

- Layering
  - System broken into vertical hierarchy of protocols
  - Service provided by one layer based solely on service provided by layer below

- Internet model (here four layers)
  - **Application** (e.g. HTTP, DNS, Email..)
  - **Transport** (TCP, UDP)
  - **Network** (IP)
  - **Link** (Ethernet)

Recall: Layers in Hosts and Routers
- Link and network layers implemented everywhere
- End-to-end layer (i.e., transport and application) implemented only at hosts

Different Type of Communication
- Asynchronous: sender can immediately return after sending message without waiting for any acknowledgments from other components
- Synchronous
  - Synchronize at request submission (1)
  - Synchronize at request delivery (2)
  - Synchronize after being fully processed by recipient (3)
- **Transient** vs. **persistent** (temporal decoupling): in persistent communication the sender can send a message and go offline and the receiver can go online at any time and gets the message that was send to him. Sender and receiver can be independent in terms of operation time.

Examples:

- **Persistent** and **Asynchronous**: Email
- **Persistent** and **Synchronous**: Message-queuing systems (1), Online Chat (1) + (2)
- **Transient** and **Asynchronous**: UDP, Erlang
- **Transient** and **Synchronous**: Asynchronous RPC (2), RPC (3)

RPC
- Transparent and hidden communication
- Synchronous
- Transient

Message-Oriented
- Explicit communication SEND/RECEIVE of point-to-point messages
- Synchronous vs. Asynchronous
- Transient vs. Persistent

Message-Oriented Persistent Communication
- Queues make sender and receiver loosely-coupled
- Modes of execution of sender/receiver
  - both running
  - Sender running, Receiver passive
  - Sender passive, Receiver running
  - both passive

Queue Interface
- Put: Put message in queue
- Get: Remove first message from queue (blocking)
- Poll: Check for message and remove first (non-blocking)
- Notify: Handler that is called when message is added

Source / destination are decoupled by **queue names**

Multiple nodes (distributed system) inside message queuing system for high throughput communication

- **Relays:** store and forward messages
- **Brokers:** gateway to transform message formats

How to Employ Queues to Decouple System
Example Bank Transfer

- for scalability partition accounts onto different computers
- use message queue between two accounts
- for ensuring **atomicity** we need to use commit protocol (two-phase commit)

The CAP theorem
CAP Theorem: A scalable service cannot achieve all three properties simultaneously

- Consistency: (i.e. atomicity) client perceives set of operations occurred all at once
- Availability: every request must result in an intended response
- Partition tolerance: operations terminate, even if the network is partitioned

ACID
- Using 2PC (two phase commit) guarantees atomicity (C in CAP)
- If 2PC is used, a transaction is not guaranteed to complete in the case of network partition (either Abort or Blocked) → we choose Consistency over Availability
- If an application can benefit from choosing A over C we need different method (BASE). For example in a social network its more important to have availability.

BASE
- **Basically-Available:** only components affected by failure become unavailable, not whole system
- **Soft-State:** a component's state may be out-of-date, and events may be lost without affecting availability
- **Eventually Consistent:** under no further updates and no failures, partitions converge to consistent state

A BASE Scenario
- Users buy and sell items
- simple transaction for item exchange

Now we can **Decouple Item Exchange with Queues**, by having one component taking care of transactions and the other one of users and updates to them. The following issued arise

- Tolerance to loss
- Idempotence
- Order: order can be implemented by a last transaction pointer in the receiver, would be to restrictive on queue implementation to ensure a order

Other Types of Communication Abstractions
- **Stream-Oriented**
  - Continuous vs. discrete
  - Asynchronous vs. Synchronous vs. Isochronous
  - Simple vs. complex
- **Multicast**
  - SEND/RECEIVE over groups
  - Application-level multicast vs. gossip

Gossip
- Epidemic protocols
  - No central coordinator
  - nodes with new information are infected, and try to spread information
- Anti-entropy approach
  - Each node communicates with random node
  - Round: every node does the above
  - Pull vs. push vs. both
  - Spreading update form single to all nodes takes O(log(N))
- **Gossiping**
  - more similar to real world analogy
  - If P is updated it tells random Q
  - if Q already knows, P can lose interest with some percentage
  - at some threshold P stops telling random nodes
  - Not guaranteed that all nodes get infected by update

Data Processing: Basic Concepts and External Sorting

Different Cost Models for Algorithms
- **RAM model**
  - Every basic operation takes constant time
  - Memory access, simple additions, does not matter
- **I/O model**
  - Transfer data from disk in large blocks / pages
  - Count number of I/Os performed
  - **Assumption:** I/Os dominate total cost, any I/O as good as another one → not always true
- **More sophisticated cost models**
  - Create cost function which mixes CPU, memory access, I/O costs
  - Differentiate types of access patterns (sequential, random, semi-random, etc)
  - Complexity can grow very high, very quickly

Example for first external memory algorithm: Sorting
Why sorting?

- Important in data processing (relational queries)
- Used for eliminating duplicates (SELECT DISTINCT)
- Bulk loading B+ trees (need to first sort leaf level pages)
- Data requested in sorted order

- Some join algorithms use sorting
- Some MapReduce implementations use sorting to group keys for reducers

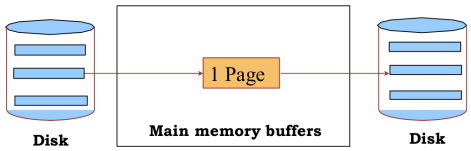
Example: Sorting

If we want to sort 1 TB of data with 1 GB of RAM we cannot rely on normal in-memory sorting implementation using for example QuickSort.

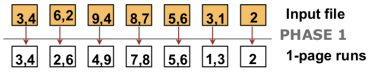
Idea: 2-Way External Merge Sort

2-Way External Merge Sort: Phase 1

- Based on merge sort (now with two phases)
- Read one page at a time from disk
- Sort it in memory (e.g. QuickSort)
- Write it to disk as one temporary file (called "run")
  - Given an input with N pages, Phase 1 produces N runs
- Only one buffer page used



Phase 1: Example

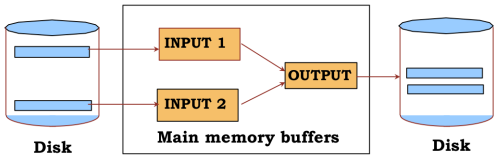


- Assuming the input file has N data pages of size M
- The cost of Phase 1 is:
  - in terms of number or I/Os: 2N
  - in terms of computational steps: $O(NM\log(M))$

2-Way External Merge Sort: Phase 2

Make multiple passes to merge runs

- Pass 1: Merge two runs of length 1 (page)
- Pass 2: Merge two runs of length 2 (pages)
- ... until 1 run of length N
- Three buffer pages used



2-Way External Merge Sort: Example

2-Way External Merge Sort: Analysis

- Total I/O cost for sorting file with N pages
- Cost of Phase 1 = 2 N
- Number of passes in Phase 2 = $\lceil \log_2 N \rceil$
- Cost of each pass in Phase 2 = 2 N
- Cost of Phase 2 = $2N \cdot \lceil \log_2 N \rceil$
- Total cost = $2N(\lceil \log_2 N \rceil + 1)$

Can we do better?

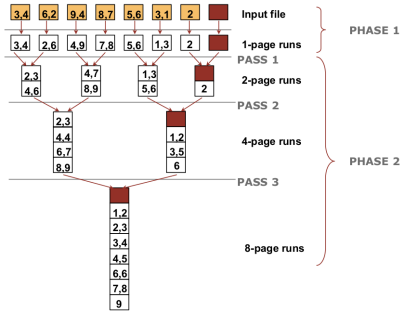
- The cost depends on the #passes
- #passes depends on
  - fan-in during the merge phase
  - the number of runs produced by phase 1

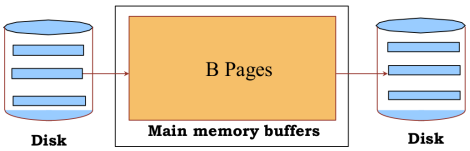
Multi-Way External Merge Sort

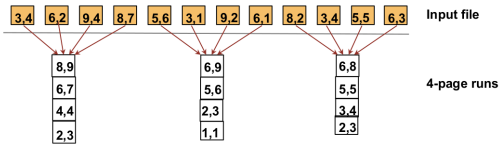
- Phase 1: Read B pages at a time, sort B pages in main memory, and write out B pages
- **Length of each run = B pages**
- Assuming N input pages, number of runs = N/B
- Cost of Phase 1 = 2N

2-Way External Merge Sort: Example

Number of buffer pages B = 4







Multi-Way External Merge Sort Phase 2

- Phase 2: Make multiple passes to merge runs
  - Pass 1: Produce runs of length $B(B-1)$ pages
  - Pass 2: Produce runs of length $B(B-1)^2$ pages
  - ⋮
  - Pass P: Produce runs of Length $B(B-1)^P$ pages

Multi-Way External Merge Sort: Analysis

Total I/O cost for sorting file with N pages

- Cost of Phase 1 = $2N$
- If number of passes in Phase 2 is P then: $B(B-1)^P = N$
- P = $\lceil \log_{B-1} \lceil N/B \rceil \rceil$
- Cost of each pass = $2N$
- Cost of Phase 2 = $2N \cdot \lceil \log_{B-1} \lceil N/B \rceil \rceil$
- Total cost = $2N \cdot (\lceil \log_{B-1} \lceil N/B \rceil \rceil + 1)$
- compared to $2N(\lceil \log_2 N \rceil + 1)$

Can we produce runs larger than the RAM size?

Tournament sort (a.k.a "heapsort", "replacement selection sort")

- use 1 buffer page as the input buffer and 1 buffer page as the output buffer
- Maintain 2 Heap structures in the remaining B-2 pages (H1, H2)
- Read B-2 pages of records and insert them into H1
- While there are still records left
  - get the "min" record m from H1 and send it to the output buffer
  - If H1 is empty then start a new run and put all the records in H2 to H1
  - read another record r from the input buffer
  - if r < m then put it in H2, otherwise put it in H1
- Finish the current run by outputting all the records in H1
- If there is something left in H2, output them as a new run

More on Heapsort

- Fact: average length of a run in heapsort is 2(B-2)
  - B-2 pages are used for the heaps
  - (B-2) + 1/2 (B-2) + 1/4 (B-2) + 1/8 (B-2) + . . . ≈ 2(B-2)
- Worst-Case:
  - min length of a run is
  - this arises if all elements are smaller than elements in H1
- Best-Case:
  - max length of a run is entire size of input
  - this arises if all elements are already sorted (close to sorted)
- QuickSort is faster, but longer and fewer runs often mean fewer passes!

External Merge Sort: Possible Optimizations

- In Phase 2 read/write blocks of pages instead of single page
- Double buffering: to reduce I/O wait time, *prefetch* into "shadow block"

Key Points (External Sorting)

- When data is much too big to fit in memory our "normal" best algorithms might not be the best

- External sorting
  - sorting with two (or more) disks
  - use merge sort (2-phase)
- Optimizations
  - Utilize memory to the fullest
  - use heap/replacement sort to reduce #runs
  - Read sequences of pages from disk
  - keep disks "busy"

External Sorting using Index

Basic concepts: B+ Trees

- Each node in the tree occupies a page
- Entries in non-leave nodes → called index entries: <key value, page_id>
- Entries in leaf nodes → called data entries
  - either containing actual data (direct index)
  - or pointer to them (indirect index)

Using B+ Trees for Sorting

Scenario:

- Table to be sorted has B+ tree index on sorting column(s)

Idea:

- Can retrieve records in order by traversing leaf pages

- **Cost:** root to the left-most leaf, then retrieve all leaf pages (direct index)
- if indirect index is used? Additional cost of retrieving data records: each page fetched just once

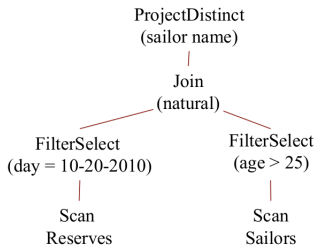
⇒ Always better than external sorting!

- If Unclustered (and indirect) index:
  - Each data entry contains pointer to a data record
  - Data records are not stored in the sorted order of the index
- In general, **one I/O per data record!**

Implementation of Relational Operators

Translating SQL Query to Relational Operators

```
SELECT DISTINCT S.name
FROM R JOIN S
WHERE R.day = 10-20-2010 AND S.age>25
```



Relational Operator Implementation

Implementing relational operators is challenging because:

- Relational queries are declarative
  - There is no efficient predefined strategy
- The data sets are typically very large

Different Relational operators:

- Select
- Project
- Join
- Set operations(union, intersect, except)
- Aggregation

Select Operator

```
SELECT *
FROM Sailor S
WHERE S.Age = 25 AND S.Salary > 100K
```

- How best to perform? Depends on:
  - what indexes are available
  - expected size of result
- Case 1: No index on any selection attribute
- Case 2: Have "matching" index on all selection attributes
- Case 3: Have "matching" index on some (but not all) selection attributes

Case 1: No index on any selection attribute

- Single loop: Just scan and filter!
- If relation has N pages, cost = N
  - Assume |S| = 1000 pages, cost = 1000 pages

Case 2: "Matching" index on all selection attributes

Cost Components:

- Component 1: Traversing index (height of B+-tree)
- Component 2: Traversing sub-set of data entries in index
- Component 3: Fetching actual actual data records (indirect indexes)
  - Depending on how many records fetched (selectivity), random I/O cost **may exceed sequential scan cost!**
- Example: assume selectivity = 10% (100 pages, 10000 tuples):
  - If clustered index, cost is 100 I/Os
  - If unclustered, could be up to 10000 I/Os

Case 3: "Matching" index on some attributes

```
SELECT *
FROM Sailor S
WHERE S.Age = 25 AND S.Salary > 100K
```

Assume index on Age only

- Alternative 1:
  - Use available index (on Age) to get superset of relevant data entries
  - Retrieve the tuples corresponding to the set of data entries
  - Apply remaining predicates on retrieved tuples
  - Return those tuples that satisfy all predicates
- Alternative 2:
  - Sequential scan! (always available)
  - May be again better depending on selectivity

```
SELECT *
FROM Sailor S
WHERE S.Age = 25 AND S.Salary > 100K
```

Assume separate indices on Age and on Salary

- Alternative 1
  - Choose most **selective** access path (index)
    - could be index on Age or Salary, depending on selectivity of the corresponding predicates
  - use this index to get **superset** of relevant data entries
  - retrieve the tuples corresponding to the set
  - apply remaining predicates on retrieved tuples
  - return those tuples that satisfy all predicates
- Alternative 2
  - Get record identifiers (rids) of data records using each index
    - Use index on Age and index on salary
  - Intersect the rids
  - Retrieve the tuples corresponding to the rids
  - Apply remaining predicates on retrieved tuples
  - return those tuples that satisfy all predicates
- Alternative 3
  - Sequential scan

Projection

```
SELECT DISTINCT S.Name, S.Age
FROM Sailor S
```

main issue duplicate elimination

Projection without Indices

- If we have **no** indices
- What strategies can we use?
  - **Sorting:** Duplicates adjacent after sorting
  - **Hashing:** Duplicates hash to same buckets (in disk and memory)

Projection with External Sorting

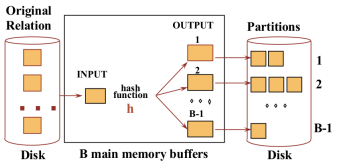
- Phase 1
  - Project out unwanted columns
  - Still produce runs of length B pages
  - But tuples in runs are smaller than input tuples
- Phase 2
  - Eliminate duplicates during merge

Duplicate Elimination with Hashing

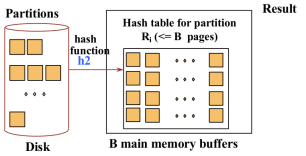
1. Apply hash function
2. Look for duplicates in the corresponding bucket
3. If the input buffer is empty, then read in a page and goto 1

- Two phases:
  - **Partition:** use hash function h to split tuples into partitions on disk
    - key property: all matches live in same partition
  - **ReHash:** for each partition on disk, build a main-memory hash table using a hash function $h2$

- Partition:



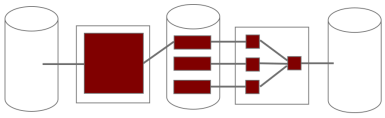
- Rehash:



Duality of Sorting and Hashing

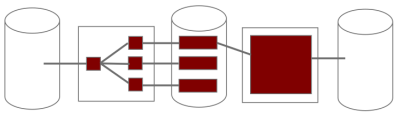
- **Sorting:**
  - physical division, logical combination
    - Split followed by merge
    - Recurse on merging
  - Sequential write (phase 1), random read (phase 2)
  - Fan-in
  - If pipelining and sqrt(N) < B < N, Total Cost = 3N

External Sorting cost = 3*|R| IO's



- **Hashing:**
  - Logical division, physical combination
    - partition followed by concatenate
    - recurse on partitioning
  - random write (phase 1), sequential read (phase 2)
  - Fan-out
  - If pipelining and sqrt(N) < B < N, Total Cost = 3N

External Hashing cost = 3*|R| IO's



So which is better??

- **Sorting pros:**
  - Great if input already sorted (or almost sorted)
  - Great if need output to be sorted anyway
  - Not sensitive to "data skew" or "bad" hash functions
- **Hashing pros:**
  - highly parallelizable
  - Can exploit extra memory to reduce # IOs with hybrid hashing

Relational Operators: Joins

- Joins are very common

```
SELECT *
FROM Reserves R1, Sailors S1
WHERE R1.sid=S1.sid
```

Simple Nested Loops Join

R⋈S:

```
foreach tuple r in R do
    foreach tuple s in S do
        if r.sid == s.sid  then add <r, s>
to result
```

- Suppose R has 1000 pages, S has 500 pages, and each page (of R and S) has 100 tuples
- Cost = |R| + (|{tuples in R}| · |R|) · |S| = 1000 + 100 · 1000 · 500 IOs
  - at 10 ms/IO this takes around 6 days!

Page-Oriented Nested Loops Join

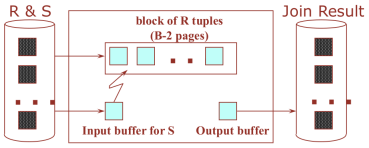
R⋈S:

```
foreach page bR in R do
    foreach page bS in S do
        foreach tuple r in bR do
            foreach tuple s in bSdo
                if ri == sj  then add <r, s> to result
```

- Cost = |R| · |S| + |R| = 1000 · 500 + 1000
- If smaller relation (S) is outer, cost = 500 · 1000 + 500
- Much better than naive per-tuple approach!
  - at 10 ms/IO, total time ≈ 1.4 hour
- the trick is to reduce the # of complete reads of the inner table

Block Nested Loops Join

- Page-oriented NL does not exploit extra buffers
- Idea to use memory efficiently:



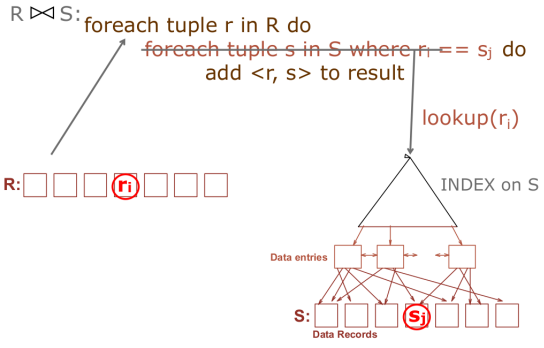
- **Cost:** Scan out + (#outer blocks · scan inner)
  where #outer blocks = ⌈ # of pages of outer / blocksize ⌉

Examples of Block Nested Loops Join

- Say we have B = 100 + 2 memory buffers
- Join cost = |outer| + (#outer blocks · |inner|)
  - #outer blocks = |outer| / 100
- With R as outer (|R| = 1000):
  - Scanning R costs 1000 IO's (done in 10 blocks)
  - Per block of R, we scan S; costs 10 · 500 I/Os
  - Total = 1000 + 10 · 500
  - At 10 ms/IO total time: ≈ 1 minute
- With S as outer (|S| = 500):
  - Scanning S costs 500 IO's (done in 5 blocks)
  - Per block of S, we scan R; costs 5 · 1000 IO's
  - Total = 500 + 5 · 1000
  - At 10 ms/IO, total time: ≈ 55 seconds

Index Nested Loops Join

Instead of scanning in inner loop simply do lookup:



System Design Principles

Design principles applicable to many areas

- **Adopt sweeping simplifications**
  So you can see what you are doing.
- **Avoid excessive generality**
  If it is good for everything it is good for nothing
- **Avoid rarely used components**
  Deterioration and corruption accumulate unnoticed - until next use.
- **Be explicit**
  Get all of the assumptions out on the table
- **Decouple modules with indirection**
  Indirection supports replaceability
- **End-to-end argument**
  The application knows best
- **Escalating complexity principle**
  Adding a feature increases complexity out of proportion
- **Incommensurate scaling rule**
  Changing a parameter by a factor of ten requires a new design
- **Keep digging principle**
  Complex systems fail for complex reasons
- **Law of diminishing returns**
  The more one improves some measure of goodness, the more effort the next improvement will require
- **Open design principle**
  Let anyone comment on the design; you need all the help you can get
- **Principle of least astonishment**
  People are part of the system. Choose interfaces that match the user's experience, expectations, and mental models
- **Robustness principle**
  Be tolerant of inputs, strict on outputs
- **Safety margin principle**
  Keep track of the distance to the edge of the cliff or you may fall over the edge
- **Unyielding foundations rule**
  It is easier to change a module than to change the modularity

Common Faults, Misc

- **safety vs. security:** when a question asks about safety of a system it means it robustness, how well it can tolerate faults etc. and not about security with adversary etc.
- when drawing schedule (no overlapping operations!)
- over engineering in design question / misunderstanding the question