CS 5412/LECTURE 23 FAULT TOLERANCE

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BREAKDOWN OF OUR TOPIC

What does the theory tell us?

How do individual systems like HDFS self-repair after failure?

What happens when systems are built in layers? Do new inter-layer coordination issues arise? How can a "restarted" layer be sure that the storage layers it depends on are already fully repaired and correct?

IS FAILURE HANDLING "IMPOSSIBLE?"

This topic has a mix of a new perspective (based on theory) with practical material that revisits something we heard about earlier.

The theory emerges from work to formalize "tolerating a failure."

The practical example we will consider is the fault recovery feature used in the Apache architecture, where it reruns failed tasks.

FIRST A 1000-FOOT REVIEW: WHERE DOES FAULT-TOLERANCE ARISE?

This is a kind of introduction and also a reminder of previous lectures where we touched on the topic

HOW DO APACHE SERVICES HANDLE FAILURE?

We've heard about some of the main "tools"

- Zookeeper, to manage configuration
- HDFS file system, to hold files and unstructured data
- HBASE to manage "structured" data
- Hadoop to run massively parallel computing tasks
- Hive and Pig to do NoSQL database tasks over HBASE, and then to create a nicely formatted (set of) output files

THREE KINDS OF ISSUES TO THINK ABOUT

How does each element work when things are healthy?

How does each element detect failures, and if needed, repair itself to recover from damage the fault might have caused (such as a file that wasn't fully written, and should be deleted and regenerated)?

How do the layers synchronize? If layer A lives on layer B, when layer A is ready to restart after a crash, can it be sure that B is already repaired?

APACHE: KEY ASPECTS

What do applications in the Apache platform do to "detect" failures?

What if a failure is just some form of transient overload and self-corrects?

- How would the component realize it was dropped by everyone else?

How can Apache self-repair the damaged components, and resume?

AS A TIME-LINE

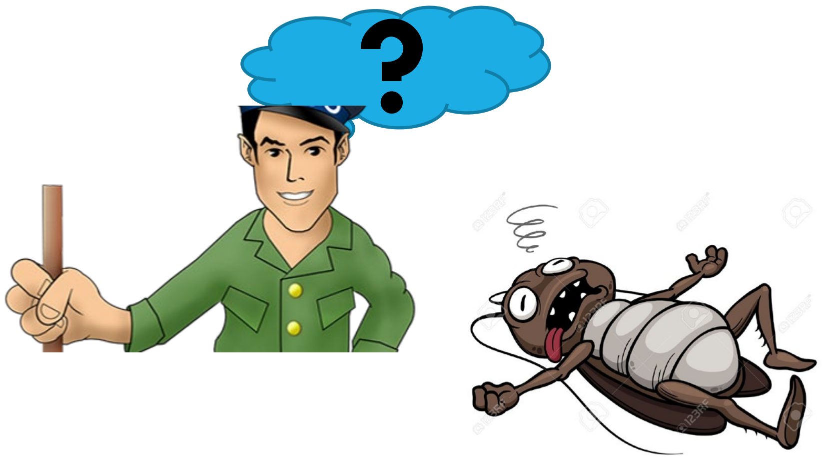
Any system needs to go through a series of stages to deal with failues

If the failure could have damaged data or left an execution in a disrupted state, cleaning up will be important.

HOW TO DETECT A FAILURE

It isn't as easy as you might expect

WAYS TO DETECT FAILURES



Something segment faults or throws an exception, then exits

A process freezes up (like waiting on a lock) and never resumes

A machine crashes and reboots

SOME REALLY WEIRD EXAMPLES

Suppose we just trust TCP timeouts, but have 2 connections to a process.

- What if one connection breaks but the other doesn't?

  … can you think of a way to easily cause this?

- What if A thinks B is down, and B thinks A is down?

When clocks "resynchronize" they can jump ahead or backwards by many seconds or even several minutes.

- What would that do to timeouts?

THE FAMOUS FLP THEOREM

Inconceivable!

SLOW NETWORK LINKS CAN MIMIC CRASHES

MIT Theoreticians Fischer, Lynch and Paterson modelled fault-tolerant agreement protocols (consensus on a single bit, 0/1). This is easy with perfect failure detection, but can we implement perfect detection?.

They proved that in an asynchronous network (like an ethernet), any consensus algorithm that is guaranteed to be correct (consistent) will run some tiny risk of indefinitely stalling and never picking an output value.

One implication: on an ethernet, perfect failure sensing is impossible!

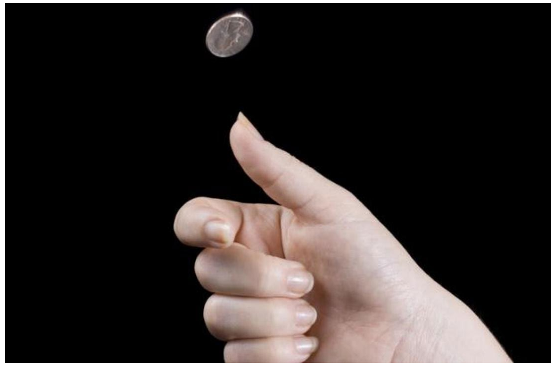
HOW DOES THE "FLP" PROOF WORK?

They look at agreeing on consensus via messages, with no deadlines on message delivery.

Their proof first shows that there must be some input states in which there is a mix of 0 and 1's proposed by the members, and where both are possible outcomes (thinking of an election, with two candidates).

They call this a "bivalent" state, meaning "two possible vote outcomes"

EXAMPLE OF A BIVALENT STATE



Suppose we are running an election and 0 represents voting for John Doe, whereas 1 represents a vote for Sally Smith. Majority wins. But N=50. To cover the risk of ties, we flipped a coin: in a tie, Sally wins.

- Suppose half vote John, half for Sally, but one voter has a "connectivity problem". If that vote isn't submitted on time, it won't be tallied.
- With 25 each, Sally is picked. But if just one Sally vote is delayed, then the exact same election comes out 25 for John, 24 for Sally… John wins
- Can we safely make a decision here?

CORE OF FLP RESULT

Now they will show that from this bivalent state we can force the system to do some work and yet still end up in an equivalent bivalent state. Then they repeat this procedure

Effect is to force the system into an infinite loop!

- And it works no matter what correct consensus protocol you used.
- This makes the result very general

BIVALENT STATE

S_* denotes bivalent state
S_0 denotes a decision 0 state
S_1 denotes a decision 1 state

System
starts in S_*

Events can
take it to
state S_0

Events can
take it to
state S_1

Sooner or later all executions
decide 0

Sooner or later all executions
decide 1

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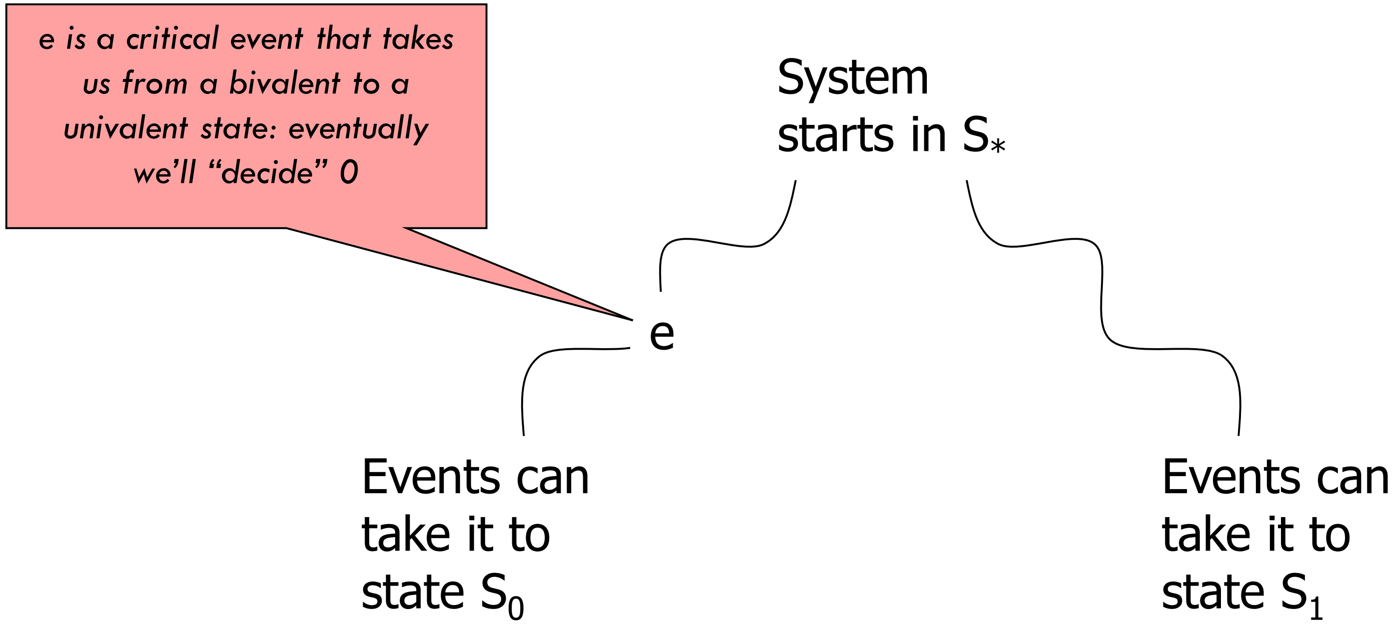
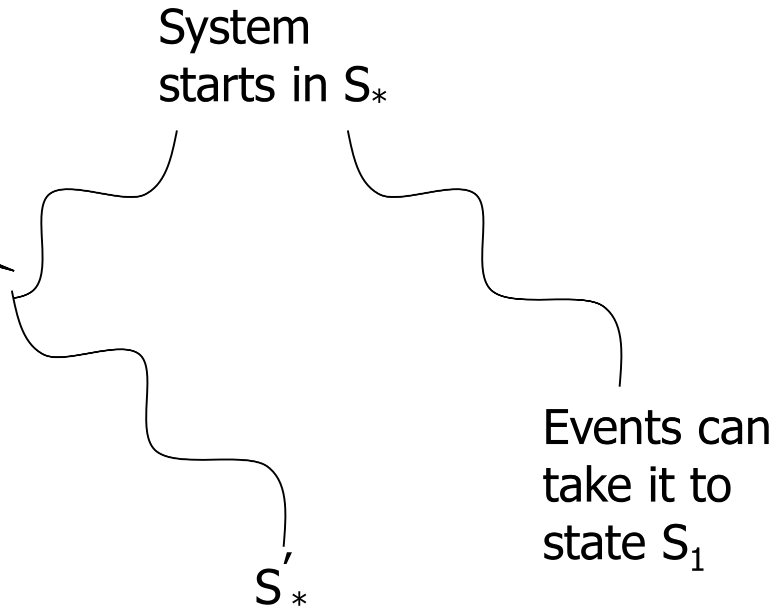
BIVALENT STATE



BIVALENT STATE

They delay e and show that there is a situation in which the system will return to a bivalent state



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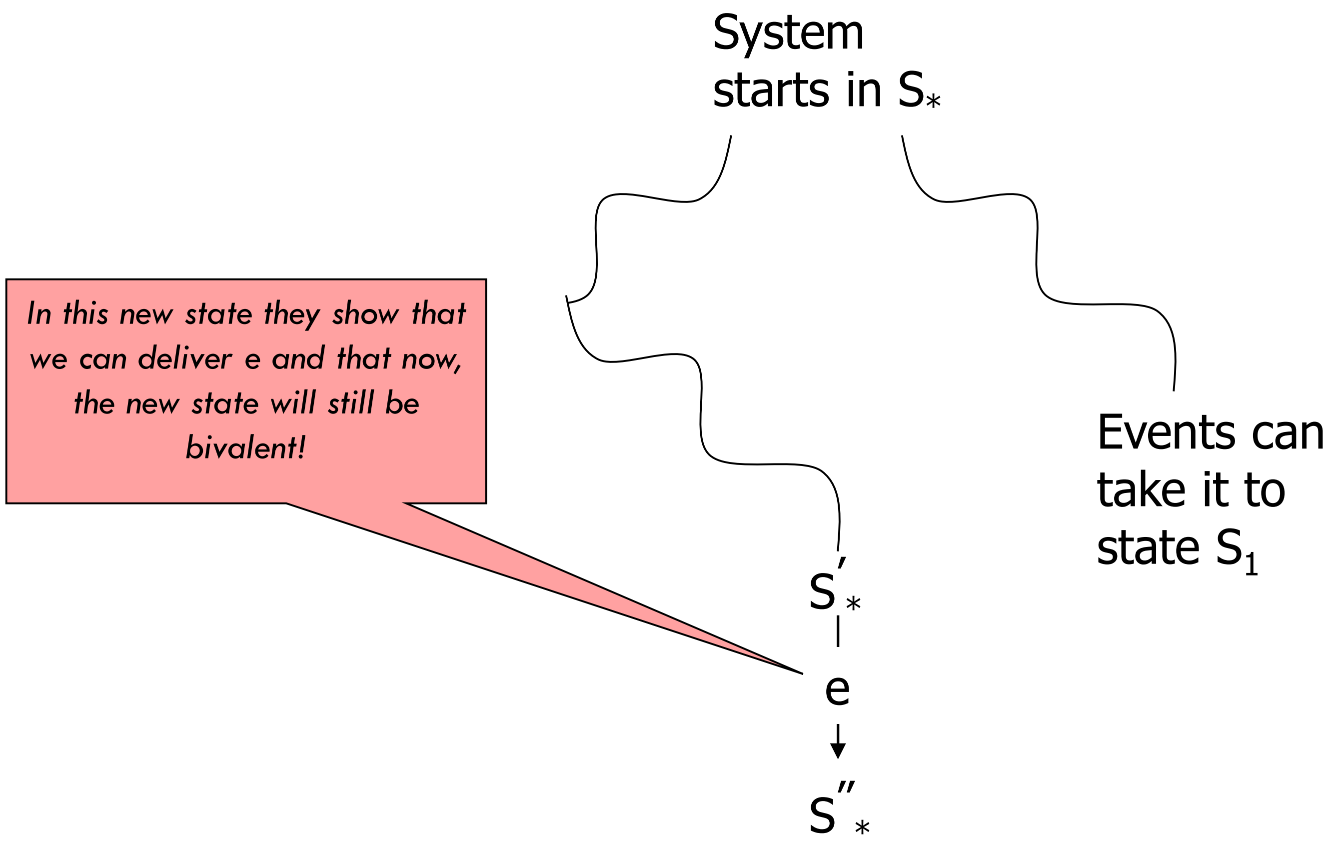
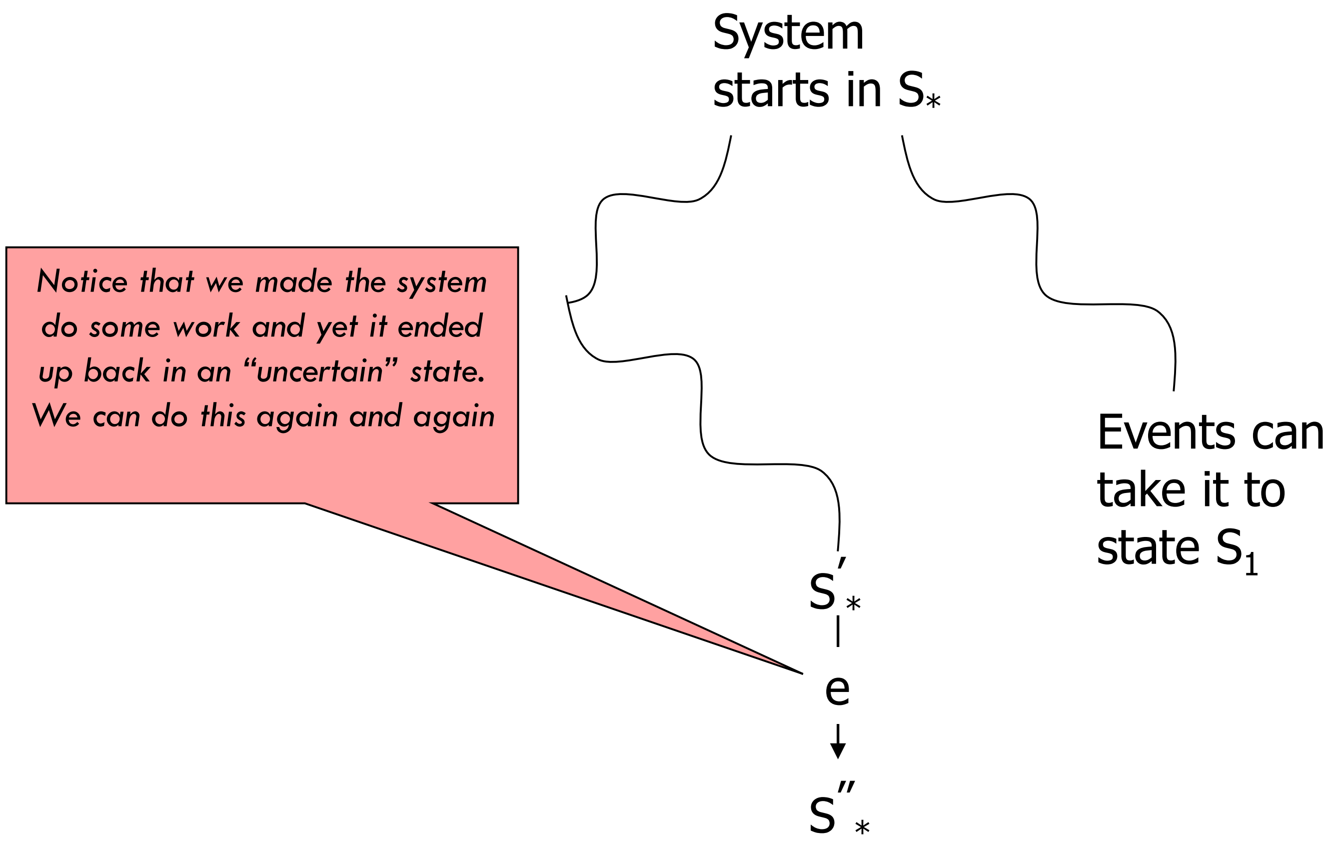


BIVALENT STATE



CORE OF FLP RESULT IN WORDS

In an initially bivalent state, they look at some execution that would lead to a decision state, say "0"

- At some step this run switches from bivalent to univalent, when some process receives some message **m**
- They now explore executions in which **m** is delayed

It turns out that if **m** is delayed, the system always reaches some other bivalent state before any decision can be reached.

CORE OF FLP RESULT

Now they show that there is actually a bivalent state in which they can deliver **m**, the delayed message, *and no decision will occur*.

This form of delayed delivery

- Forced the system to do some work
- Left it in a bivalent state, just like it started.

They just loop and do this again and again. **No decision is ever reached!**

IMPLICATION?

If you have a fault-tolerant protocol able to solve consensus, like Derecho or Paxos or Chain Replication…

… and you have an all-powerful adversary who attacks the system

… it can be prevented from ever reaching a decision!

BUT WHAT DID "IMPOSSIBILITY" MEAN?

In effect, "*fault tolerant consensus is impossible.*"

But do you believe this statement?

Or do you feel as if it is using a tortured concept of "possible" and "impossible" to come up with a cute claim?

AT THE CENTER OF IT: THE ADVERSARY

A very clever adversarial attack.

This is like one of those horror movies where the evil spirit can do the worst possible thing at the worst possible moment.

In practice, no adversary ever has this much control

WE LIVE IN THE REAL WORLD, NOT A MOVIE!

This is a problem!

FLP is clearly a "real" risk.

And yet the kind of attack it imagines cannot really arise! In fact it is easy to show that a system like Derecho or any Paxos protocol will make progress even with really simple added assumptions about message delays being "random" and not "controlled"

SO...

In fact the fault is in the theoretical model! It gives too much power to the attacker.

Yet at the same time, because partitioning failures can cause Paxos or Derecho to freeze up (they can lose quorum), in some sense a result similar to FLP applies in any case!

With real systems, freeze-up is a real risk… even if not due to FLP attacks!

WHAT DOES THIS SAY ABOUT ELECTIONS?

Think back to the John and Sally election scenario

In a real election, sooner or later we call a halt and count the votes that are in hand.

At that point the "votes" are immutable and the set of votes is known. It just becomes an exercise in counting – nothing more. Even the tie-breaking rule, and the outcome of the coin flip, become immutable.

DOES FLP MATTER?

FLP is often cited as a proof that "consistency is impossible" but in fact it only tells us that any digital system could run into conditions where it jams. We already knew that, due to partitioning.

On the other hand, it also has a problematic "implication". It makes it very hard to prove the correctness of real systems using a pure logic formulation. We need probabilistic assumptions and goals, and only can show some high likelihood of progress.

IMPLICATION?

If we can't do perfect failure sensing, we need to make do with something imperfect.

This ties back to the idea of a system that manages its own membership.

If the manager layer can't be sure that some process is healthy, it is allowed to just declare that the process has failed!

HOW TO "WORK AROUND" FLP

It was very simple.
I poisoned both
glasses of wine.

HOW DOES DERECHO DO IT?

It has a virtually synchronous self-managed membership service, sort of like Zookeeper.

Recall that we discussed the term virtual synchrony at the time: it centers on ordering of membership views (epochs), state transfers and multicast.

Originally used in Isis Distributed Toolkit in 1980's, but then explored in many papers and books.

HOW DOES DERECHO DO IT?

Periodic “heartbeat” messages are sent by healthy processes.

Each process watches for these heartbeats. A timeout triggers “failure suspicion”. Also, if a TCP connection <u>breaks</u>, the live process will immediately deem the other endpoint as having crashed.

At the core is a form of Paxos. It prevents split-brain behavior if leader failure is suspected. Zookeeper is very similar.

BUT CAN VIRTUAL SYNCHRONY AVOID THE FLP PROBLEM?

FLP is not directly applicable: in FLP, a healthy process *must be allowed to vote*.

In systems like Zookeeper, *a healthy process might be "killed" by accident, but this keeps the system alive when it might otherwise freeze up).*

Anyhow, this still leaves partitioning as a risk. We can't evade the risk of freezing up – we can only evade the FLP "scenario" for that happening.

A THEORY PERSON WOULD ARGUE THAT NO SOLUTION CAN EVADE THE FLP THEOREM

The distributed systems theory community considers the FLP theorem to be the bottom line.

No system that can solve consensus is able to guarantee progress.

They also understand that in practical cloud settings, we may not be worried about the FLP scenario, or even the partitioning scenario (we can design a redundant network to minimize that risk…)

A PRACTICAL PERSON… WOULD AGREE!

FLP is a law of nature.

But a practical person would then say that well, systems like Derecho and Cascade and Paxos – and Zookeeper – aren't *guaranteeing* progress. They make a best effort

Both can freeze up if a system partitions and neither side has the majority of the servers. Freezing up because of FLP is actually, far less likely!

IN EFFECT, THEY DON’T AVOID FLP

The bottom line is that “fault tolerance is impossible” and yet “we solve it!”

It is almost as if we finesse the meaning of the word “impossible”, so that we take it to mean “usually possible, but not always.”

This is good enough because after all, the whole data center could have a leaky roof and shut down. Guaranteed progress isn’t always meaningful.

WHAT ABOUT HADOOP?

How does it deal with failures?

HDFS USE OF ZOOKEEPER VIEWS

Recall that in HDFS every file has one or more replicas. It uses chain replication, with Zookeeper tracking the chain members!

If a chain member fails, HDFS still has a healthy replica and reads can continue. It restarts the failed member or launches some new node to take on the same role, and copies data from a healthy replica if needed to repair the failed replica.

If all replicas fail, HDFS will wait for recoveries. But in the normal case, HDFS itself stays available for reads.

BIG CHALLENGE: HADOOP (MAPREDUCE)

Failures could cause some tasks to disappear.

MapReduce and Hadoop will automatically restart the failed task on some other node (they will even run extra copies of very slow task, "just in case")

Whichever task finishes first, successfully, is considered to have completed that step and the others are terminated if any are still running. If they do produce output, it is ignored.

HADOOP IS "AT MOST ONCE" RELIABLE

This basic task fault handling ensures that each Hadoop task will be performed at least once, but at most one output will be preserved.

What if a task fails while writing files?

RECALL THAT HDFS IS APPEND-ONLY

We discussed the rule that HDFS uses for file updates: either create a whole new file version or append to a file. You can't update the middle of a file – seek into the middle of an HDFS file will cause writes to fail.

… so, if some task has to be restarted, HDFS can just restore any files that task was writing to back to the length they had before the task started!

This works well because in Hadoop, every object can be constructed from some other object by some kind of repeatable ("idempotent") computation

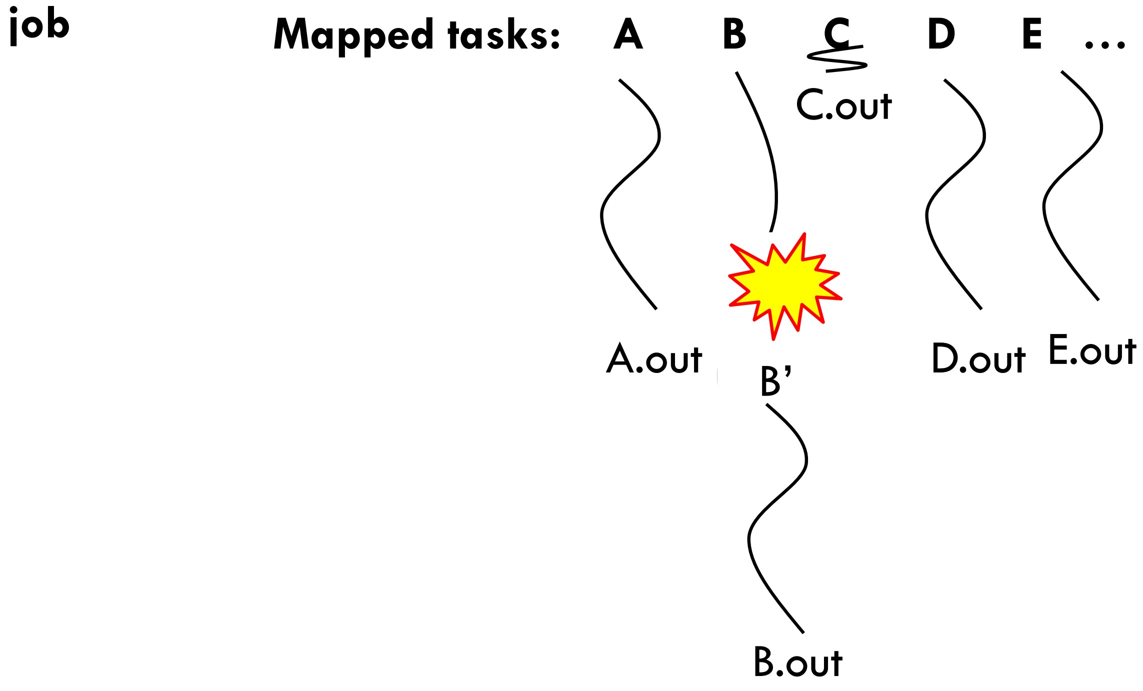
CHECKPOINTS

HDFS adds a "checkpoint" feature to what POSIX normally can support.

The checkpoint is just a file that contains the names, version numbers and lengths of the files your Hadoop application is using. To "roll back" it just truncates files back to the size they had and restores any deleted files.

This assumes that deleted file versions are kept around for a little while.

VISUALIZING HADOOP FAILURES IN IMAGES



Normal case: A, B… E just run, create output (key,value collections in HDFS files), then the reduce step can run.

Failure case (B crashes). Now Hadoop just rolls back any files B was appending to and runs B', to repeat the task.

WHY SUCH A FOCUS ON FILES?

In fact <u>everything in Hadoop is kept in files</u>, even key,value tuples created by the tasks running on behalf of map, the shuffled data, the sorted version that are input to reduce, and the output from reduce.

This makes it much easier to deal with MapReduce cleanup after a failure: it just tracks what files are created by a task (it deletes the new version), and what files were extended (it restores the old length, truncating any extra data that was being written when the task failed).

BUT TASKS CAN ALSO BE DISRUPTED BY FAILURES

Apache also has to worry about Hadoop jobs that might be running exactly when the failure occurred.

Very often such a job could be disrupted in some way, hence active tasks shouldn't be allowed to continue running "as is".

Hadoop kills all the user-generated tasks, removes any files they may have created and restores any then deleted, then reruns the failed tasks. (Somehow, Hadoop must also be waiting for HDFS to self-repair)

THIS CONCEPT WORKS IN ALL OF APACHE

The whole Apache infrastructure centers on mapping all forms of failure handling to Zookeeper, HDFS files with this form of "rollback", and task restart!

It has similar effect to an abort/restart in a database system, but doesn't involve contention for locks and transactions, so Jim Gray's observations wouldn't apply. Apache tools scale well (except for Zookeeper itself, but it is fast enough for the ways it gets used).

WHAT ABOUT AIR TRAFFIC CONTROL?

These systems have a system-wide virtual synchrony view manager.

The role of the view manager is to atomically report to all components when any failure disrupts any component. When a view changes, all components instantly "wedge" and adjust to the new view

The system briefly (seconds… not minutes) freezes up and repairs itself, and when it resumes, every component is back to a healthy state.

COMPARE WITH APACHE?

Air traffic control might have state in a few places, but it helps that the flight plan records reside in a single database that every other process simply mirrors, read-only.

The key thing is to ensure that we never have parts of the system using one set of flight plans, or one set of configuration files, while the remainder is using a different set. And this property is very carefully verified.

BOTTOM LINE?

The cloud is highly available, because it has layers of backups– even backup datacenters and backups at geographic scale.

IoT data managed by the cloud *can* be strongly consistent. This doesn't really reduce availability and in fact doesn't even reduce performance.

It leads to a style of coding in which membership is managed for you. But many parts of the existing cloud are using weaker consistency today, and you need to be aware of the risks when you use those tools.

EFFECTS OF BOTTOM LINE?

Today’s cloud is remarkably robust.

We use CAP and weaken consistency in outer layers, but this is partly because doing so actually simplifies the solutions we create. Fault tolerance is easy when you don’t worry about consistency.

Systems that do need consistency use the “timeline”: they have a standard way to detect failure. Every component learns of any fault relevant to it. Disrupted components pause their work queues while they self-repair.