CS514: Intermediate Course in Operating Systems

Professor Ken Birman
Vivek Vishnumurthy: TA

Recap

- We started by thinking about Web Services
  - Basically, a standardized architecture that clients client systems talk to servers
  - Uses XML and other Web protocols
  - And will be widely popular ("ubiquitous")
- Our goal is to build "trustworthy" systems using these standard, off-the-shelf techniques
- So we started to look at the issues top down

Things data centers need

- Front ends to build pages and run business logic for both human and computer clients
- A means for clients to "discover" a good server (close by… not overloaded… affinity)
- Tools for building the data center itself: communication, replication, load-balancing, self-monitoring and management, etc

Recap

- With this model in mind we looked at naming/discovery
- We asked what decisions need to be made
  - Client needs to pick the right service
    - I want this particular database, or display device
  - Service may have a high-level routing decision
    - Send "East Coast" requests to the New Jersey center
  - Service also makes lower-level decisions
    - John Smith is doing a transaction; send requests to the same node if possible to benefit from caching
  - And finally the network does routing

Recap

- In the case of naming/discovery
  - We observed that the architecture doesn't really offer "slots" for the associated logic
  - Developers can solve these problems
    - I.e. by using the DNS to redirect requests
    - But the solutions feel like hacks
  - Ideally Web Services should address such issues.
    - One day it will, by generalizing the content distribution "model" popularized by Akamai

Recap

- Next we looked at scalability issues
  - We imagined that we're building a service and want to increase load on it
  - Led us to think about threading, staged event queuing (SEDA)
  - Eventually leads us to a clustered architecture with load-balancers
- Again, found that WS lacks key features

Trustworthy Web Services

- To have confidence in solutions we need rigorous technical answers
  - To questions like "tracking membership" or "data replication" or "recovery after crash"
- And we need these embodied into WS
  - For example, would want best-of-breed answers in some sort of discovery "tool" that applications can exploit

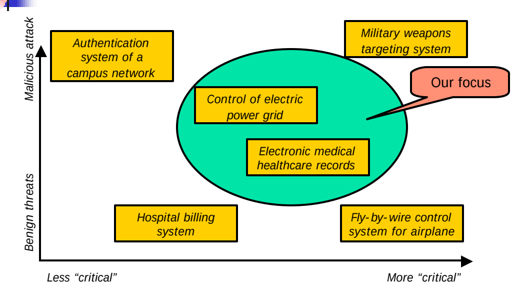
Trustworthy Computing

- Overall, we want to feel confident that the systems we build are "trustworthy"
- But what should this mean, and how realistic a goal is it?
- Today
  - Discuss some interpretations of the term
  - Settle on the "model" within which we'll work during the remainder of the term

Categories of systems…

- Roles computing systems play vary widely
  - Most computing systems aren't critical in a minute-by-minute sense
  - … but some systems matter more; if they are down, the enterprise is losing money
  - … and very rarely, we need to build ultra-reliable systems for mission-critical uses

Examples



Techniques vary!

- Less critical systems that face accident (not attack) lend themselves to cheaper solutions
  - Particularly if we don't mind outages when something crashes
  - High or continuous availability is harder
- The mixture of *time-critical, very secure, very high availability* is particularly difficult
  - Solutions don't integrate well with standard tools
  - "Secure and highly available" can also be *slow*

Importance of "COTS"

- The term means "commercial off the shelf"
- To understand importance of COTS we need to understand history of computing
  - Prior to 1980, "roll your own" was common
  - But then with CORBA (and its predecessors) well-supported standards won the day
  - Productivity benefits of using standards are *enormous:* better development tools, better system management support, better feature sets
- Today, most projects mandate COTS

The dilemma

- But major products have been relaxed about:
  - Many aspects of security
  - Reliability
  - Time-critical computing (not the same as "fast")
- Jim Gray: "*Microsoft is mostly interested in multi-billion dollar markets. And it isn't feasible to make 100% of our customers happy. If we can make 80% of them happy 90% of the time, we're doing just fine.*"

Are COTS trustworthy?

- Security is improving but still pretty weak
  - Data is rarely protected "on the wire"
  - Systems are not designed with the threat of overt attack in mind
  - Often limited to perimeter security; if the attacker gets past the firewall, she's home free
- Auditing and system management functions are frequently inadequate

Are COTS trustworthy?

- Most COTS technologies do anticipate crashes and the need to restart
  - You can usually ask the system to watch your application and relaunch after failure
  - You can even ask for a restart on a different node... but there won't be any protection against split-brain problems
- So-called "transactional" model can help
  - Alternatively can make checkpoints, or replicate critical data, but without platform help

Is this enough?

- The way COTS systems provide restart is potentially slow
  - Transactional "model" can't offer high availability (we'll see why later)
  - Often must wait for failed machine to reboot, clean up its data structures, relaunch its main applications, etc
- In big commercial systems could be minutes or even hours
- Not enough... if we want high availability

Are COTS trustworthy?

- Security... reliability... what about:
  - Time-critical applications, where we want to guarantee a response within some bounded time (and know that the <u>application</u> is fast enough... but worry about platform overheads and delays)
  - Issues of system administration and management and upgrade

SoS and SOAs

- The trend is towards
  - Systems of Systems (SoS): federation of big existing technologies
  - Service Oriented Architectures (SOAs).
    - Object oriented or Web Services systems
    - Components declare their interfaces using an interface definition language (IDL) or a description language (WSDL)
    - Implementation is "hidden" from clients

Example: the Air Force JBI

Globally Interoperable Information "Space" that …

Aggregates, fuses, and disseminates tailored battlespace information to all echelons of a JTF

Decision-Quality Information

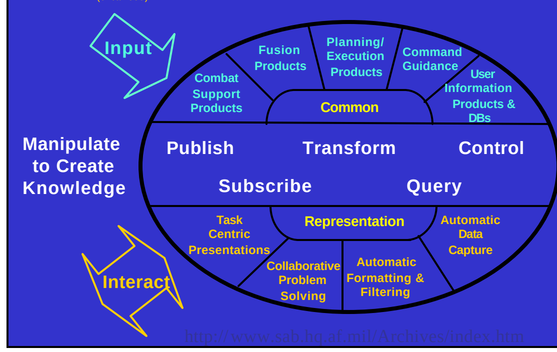
Links JTF sensors, systems & users together for unity of effort

Integrates legacy C2 resources

Focuses on Decision-Making | Enables Affordable Technology Refresh | Leverages Emerging Commercial Technologies

Inside the Battlespace InfoSphere

(circa 1999)



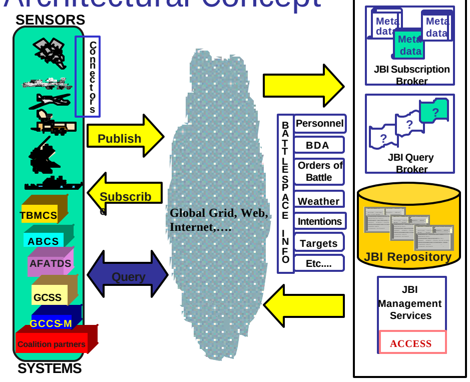
JBI Basics

The JBI is a system of systems that integrates, aggregates, & distributes information to users at all echelons, from the command center to the battlefield.

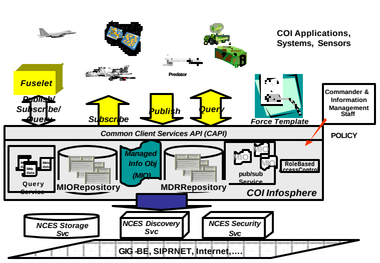
The JBI is built on four key technologies:

- Information exchange
  - **Publish/Subscribe/Query**
- Transforming data to knowledge
  - **Fuselets**
- Distributed collaboration
  - **Shared, updateable knowledge objects**
- Force/Unit interfaces
  - **Templates**
    - **Operational capability**
    - **Information inputs**
    - **Information requirements**

Architectural Concept



A fusion of BIG systems



Observations?

- Everyone is starting to think big, not just the US Air Force
- Big systems are staggeringly complex
  - They won't be easy to build
  - And will be even harder to operate and repair when problems occur
- Yet the payoff is huge and we often have no choice except to push forward!

Implications of bigness?

- We'll need to ensure that if our big components crash, their restart is "clean"
  - Leads to what is called the transactional model
  - But transactions can't guarantee high availability
- We'll also "wrap" components with new services that
  - Exploit clustered scalability, high availability, etc
  - May act as message queuing intermediaries
  - Often cache data from the big components

Trusting multi-component systems

- Let's tackle a representative question
- We want our systems to be trustworthy even when things malfunction
  - This could be benign or malignant
- What does it mean to "tolerate" a failure, while giving sensible, consistent behavior?

CS514 threat model

- For CS514 we need to make some assumptions that will carry us through the whole course
  - What's a "process"? A "message"?
  - How does a network behave?
  - How do processes and networks fail?
  - How do attackers and intruders behave?

Our model

- *Non-deterministic processes,* interacting by *message passing*
  - The non-determinism comes from use of threads packages, reading the clock, "event" delivery to the app, connections to multiple I/O channels
  - Messages can be large and we won't worry about how the data is encoded
  - 1-1 and 1-many (multicast) comm. patterns
- The non-determinism assumption makes a very big difference. Must keep it in mind.

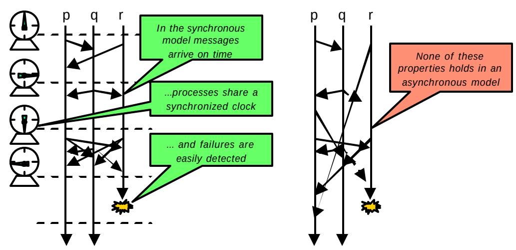
Network model

- We'll assume your vanilla, nasty, IP network:
  - A machine can have multiple names or IP addresses and not every machine can connect to every other machine
  - Network packets can be lost, duplicated, delivered very late or out of order, spied upon, replayed, corrupted, source or destination address can lie
- We can use UDP, TCP or UDP-multicast in the application layer

Execution model: asynchronous

- Historically, researchers distinguished asynchronous and synchronous models
  - Synchronous distributed systems: global clock; execution in lock-step with time to exchange messages during each step. Failures detectable
  - Asynchronous distributed systems: no synchronized clocks or time-bounds on message delays. Failures undetectable

Synchronous and Asynchronous Executions



Reality: neither one

- Real distributed systems aren't synchronous
  - Although a flight control computer can come close
- Nor are they asynchronous
  - Software often treats them as asynchronous
  - In reality, clocks work well... so in practice we often use time cautiously and can even put limits on message delays
- For our purposes we usually start with an asynchronous model
  - Subsequently enrich it with sources of time when useful.
  - We sometimes assume a "public key" system. This lets us sign or encrypt data where need arises

Failure model

- How do real systems fail?
  - Bugs in applications are a big source of crashes. Often associated with non-determinism, which makes debugging hard
  - Software or hardware failures that crash the whole computer are also common
  - Network outages cause spikes of high packet loss or complete disconnection
  - Overload is a surprisingly important risk, too

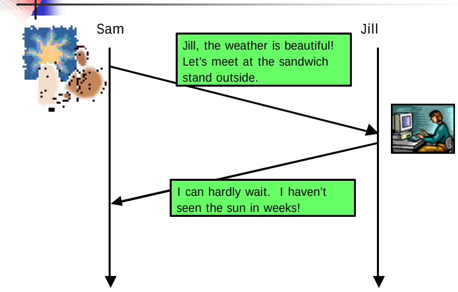
Detecting failures

- This can be hard!
  - An unresponsive machine might be working but temporarily "partitioned" away
  - A faulty program may continue to respond to some kinds of requests (it just gives incorrect responses)
  - Timeouts can be triggered by overloads
  - One core problem can cascade to trigger many others
- We usually know when things are working but rarely know what went wrong

Thought problem

- Jill and Sam will meet for lunch. They'll eat in the cafeteria unless both are sure that the weather is good
  - Jill's cubicle is inside, so Sam will send email
  - Both have lots of meetings, and might not read email. So she'll acknowledge his message.
  - They'll meet inside if one or the other is away from their desk and misses the email.
- Sam sees sun. Sends email. Jill acks's. Can they meet outside?

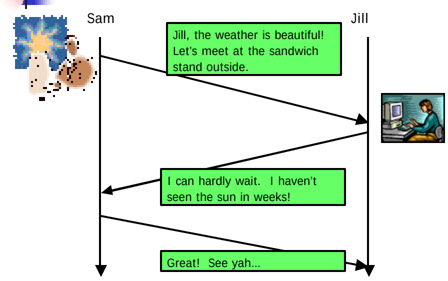
Sam and Jill



They eat *inside!* Sam reasons:

- "Jill sent an acknowledgement but doesn't know if I read it
- "If I didn't get her acknowledgement I'll assume she didn't get my email
- "In that case I'll go to the cafeteria
- "She's uncertain, so she'll meet me there

Sam had better send an Ack



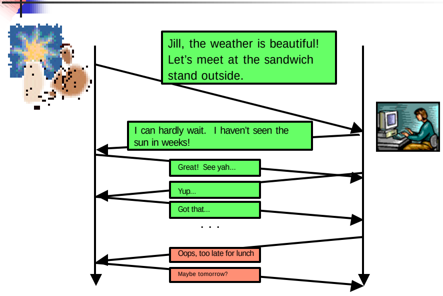
Why didn't this help?

- Jill got the ack… but she realizes that Sam won't be sure she got it
- Being unsure, he's in the same state as before
- So he'll go to the cafeteria, being dull and logical. And so she meets him there.

New and improved protocol

- Jill sends an ack. Sam acks the ack. Jill acks the ack of the ack….
- Suppose that noon arrives and Jill has sent her 117'th ack.
  - Should she assume that lunch is outside in the sun, or inside in the cafeteria?

How Sam and Jill's romance ended



Things we just can't do

- We can't detect failures in a trustworthy, consistent manner
- We can't reach a state of "common knowledge" concerning something not agreed upon in the first place
- We can't guarantee agreement on things (election of a leader, update to a replicated variable) in a way certain to tolerate failures

Consistency

- At the core of the notion of trust is a fundamental concept: “distributed consistency”
  - Our SoS has multiple components
  - Yet they behave as a single system: many components mimic a single one
- Examples:
  - Replicating data in a primary-backup server
  - Collection of clients agreeing on which to use
  - Jill and Sam agreeing on where to meet for lunch

Does this matter in big systems?

- Where were Jill and Sam in the JBI?
  - Well, JBI is supposed to coordinate military tacticians and fighters…
    - Jill and Sam are trying to coordinate too.
    - If they can’t solve a problem, how can the JBI?
    - Illustrates value of looking at questions in abstracted form!
  - Generalize: our big system can only solve “solvable” consistency problems!

Why is this important?

- Trustworthy systems, at their core, behave in a “consistent” way even when disrupted by failures, other stress
- Hence to achieve our goals we need to ask what the best we can do might be
  - If we set an impossible goal, we’ll fail!
  - But if we ignore consistency, we’ll also fail!

A bad news story?

- Jill and Sam set out to solve an impossible problem
  - So for this story, yes, bad news
- Fortunately, there <u>are</u> practical options
  - If we pose goals carefully, stay out of trouble
  - Then solve problems and prove solutions correct!
- And insights from “small worlds” can often be applied to very big systems of systems

Trust and Consistency

- To be trustworthy, a system must provide guarantees and enforce rules
- When this entails actions at multiple places (or, equivalently, updating replicated data) we require consistency
- If a mechanism ensures that an observer can’t distinguish the distributed system from a non-distributed one, we’ll say it behaves consistently

Looking ahead

- We’ll start from the ground and work our way up, building a notion of consistency
  - First, consistency about temporal words like “A happened before B”, or “When A happened, process P believed that Q…”
  - Then we’ll look at a simple application of this to checkpoint/rollback
  - And then we’ll work up to a full-fledged mechanism for replicating data and coordinating actions in a big system

Homework (don't hand it in)

- We've skipped Parts I and II of the book
  - I'm assuming that most of you know how TCP works, etc, and how Web Services behave
  - There's good material on performance… please review it, although we won't have time to cover it.
- Think about TCP failure detection and the notion of distributed consistency
  - Thought puzzle: If we were to specify the behavior of TCP and the behavior of UDP, can TCP really be said to be "more reliable" than UDP?