System Design

An Engineering Approach to Computer Networking

What is system design?

- A computer network provides computation, storage and transmission resources
- System design is the art and science of putting together these resources into a harmonious whole
- Extract the most from what you have

Goal

- In any system, some resources are more freely available than others
  - high-end PC connected to Internet by a 28.8 modem
  - *constrained* resource is link bandwidth
  - PC CPU and and memory are *unconstrained*
- Maximize a set of performance metrics given a set of resource constraints
- Explicitly identifying constraints and metrics helps in designing efficient systems
- Example
  - maximize reliability and MPG for a car that costs less than $10,000 to manufacture

System design in real life

- Can’t always quantify and control all aspects of a system
- Criteria such as scalability, modularity, extensibility, and elegance are important, but unquantifiable
- Rapid technological change can add or remove resource constraints (example?)
  - an ideal design is ‘future proof’
- Market conditions may dictate changes to design halfway through the process
- International standards, which themselves change, also impose constraints
- Nevertheless, still possible to identify some principles

Some common resources

- Most resources are a combination of
  - time
  - space
  - computation
  - money
  - labor

Time

- Shows up in many constraints
  - deadline for task completion
  - time to market
  - mean time between failures
- Metrics
  - *response time*: mean time to complete a task
  - *throughput*: number of tasks completed per unit time
  - *degree of parallelism* = response time * throughput
    - 20 tasks complete in 10 seconds, and each task takes 3 seconds
    - => degree of parallelism = 3 * 20/10 = 6

Space

- Shows up as
  - limit to available memory (kilobytes)
  - bandwidth (kilobits)
    - 1 kilobit/s = 1000 bits/sec, but 1 kilobyte/s = 1024 bits/sec!

Computation

- Amount of processing that can be done in unit time
- Can increase computing power by
  - using more processors
  - waiting for a while!

Money

- Constrains
  - what components can be used
  - what price users are willing to pay for a service
  - the number of engineers available to complete a task

Labor

- Human effort required to design and build a system
- Constrains what can be done, and how fast

Social constraints

- Standards
  - force design to conform to requirements that may or may not make sense
  - underspecified standard can faulty and non-interoperable implementations
- Market requirements
  - products may need to be backwards compatible
  - may need to use a particular operating system
  - example
    - GUI-centric design

Scaling

- A design constraint, rather than a resource constraint
- Can use any centralized elements in the design
  - forces the use of complicated distributed algorithms
- Hard to measure
  - but necessary for success

Common design techniques

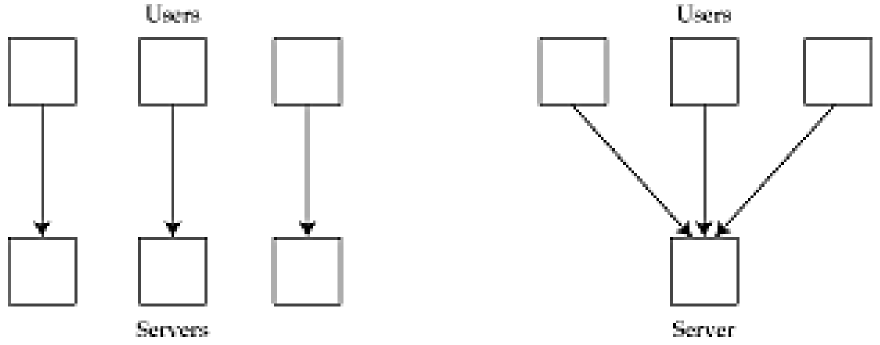
- Key concept: *bottleneck*
  - the most constrained element in a system
- System performance improves by removing bottleneck
  - but creates new bottlenecks
- In a *balanced* system, all resources are simultaneously bottlenecked
  - this is optimal
  - but nearly impossible to achieve
  - in practice, bottlenecks move from one part of the system to another
  - example: Ford Model T

Top level goal

- Use unconstrained resources to alleviate bottleneck
- How to do this?
- Several standard techniques allow us to trade off one resource for another

Multiplexing

- Another word for sharing
- Trades time and space for money
- Users see an increased response time, and take up space when waiting, but the system costs less
  - economies of scale



Multiplexing (contd.)

- Examples
  - multiplexed links
  - shared memory
- Another way to look at a shared resource
  - *unshared virtual resource*
- *Server* controls access to the shared resource
  - uses a *schedule* to resolve contention
  - choice of scheduling critical in proving quality of service guarantees

Statistical multiplexing

- Suppose resource has capacity C
- Shared by N identical tasks
- Each task requires capacity c
- If Nc <= C, then the resource is underloaded
- If at most 10% of tasks active, then C >= Nc/10 is enough
  - we have used statistical knowledge of users to reduce system cost
  - this is *statistical multiplexing gain*

Statistical multiplexing (contd.)

- Two types: spatial and temporal
- Spatial
  - we expect only a fraction of tasks to be simultaneously active
- Temporal
  - we expect a task to be active only part of the time
    - e.g silence periods during a voice call

Example of statistical multiplexing gain

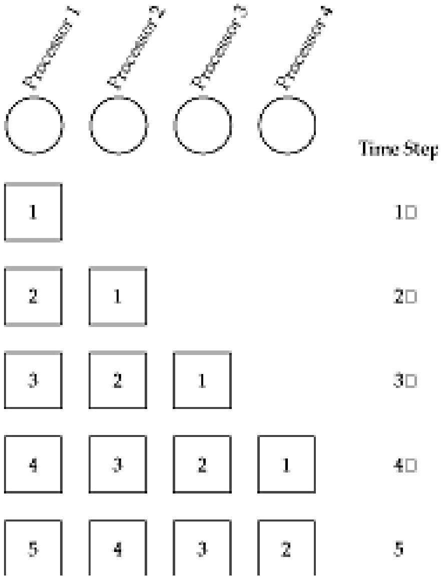
- Consider a 100 room hotel
- How many external phone lines does it need?
  - each line costs money to install and rent
  - tradeoff
- What if a voice call is active only 40% of the time?
  - can get both spatial and temporal statistical multiplexing gain
  - but only in a packet-switched network (why?)
- Remember
  - to get SMG, we need good statistics!
  - if statistics are incorrect or change over time, we’re in trouble
  - example: road system

Pipelining

- Suppose you wanted to complete a task in less time
- Could you use more processors to do so?
- Yes, if you can break up the task into *independent* subtasks
  - such as downloading images into a browser
  - optimal if all subtasks take the same time
- What if subtasks are dependent?
  - for instance, a subtask may not begin execution before another ends
  - such as in cooking
- Then, having more processors doesn’t always help (example?)

Pipelining (contd.)

- Special case of *serially dependent* subtasks
  - a subtask depends only on previous one in execution chain
- Can use a *pipeline*
  - think of an assembly



Pipelining (contd.)

- What is the best decomposition?
- If sum of times taken by all stages = R
- Slowest stage takes time S
- Throughput = 1/S
- Response time = R
- Degree of parallelism = R/S
- Maximize parallelism when R/S = N, so that S = R/N => equal stages
  - *balanced pipeline*

Batching

- Group tasks together to amortize overhead
- Only works when overhead for N tasks < N time overhead for one task (i.e. *nonlinear*)
- Also, time taken to accumulate a batch shouldn’t be too long
- We’re trading off reduced overhead for a longer worst case response time and increased throughput

Exploiting locality

- If the system accessed some data at a given time, it is likely that it will access the same or ‘nearby’ data ‘soon’
- Nearby => spatial
- Soon => temporal
- Both may coexist
- Exploit it if you can
  - caching
    - get the speed of RAM and the capacity of disk

Optimizing the common case

- 80/20 rule
  - 80% of the time is spent in 20% of the code
- Optimize the 20% that counts
  - need to measure first!
  - RISC
- How much does it help?
  - Amdahl's law
  - Execution time after improvement = (execution affected by improvement / amount of improvement) + execution unaffected
  - beyond a point, speeding up the common case doesn't help

Hierarchy

- Recursive decomposition of a system into smaller pieces that depend only on parent for proper execution
- No single point of control
- Highly scaleable
- Leaf-to-leaf communication can be expensive
  - shortcuts help

Binding and indirection

- Abstraction is good
  - allows generality of description
  - e.g. mail aliases
- Binding: translation from an abstraction to an instance
- If translation table is stored in a well known place, we can bind automatically
  - indirection
- Examples
  - mail alias file
  - page table
  - telephone numbers in a cellular system

Virtualization

- A combination of indirection and multiplexing
- Refer to a virtual resource that gets matched to an instance at run time
- Build system as if real resource were available
  - virtual memory
  - virtual modem
  - Santa Claus
- Can cleanly and dynamically reconfigure system

Randomization

- Allows us to break a tie fairly
- A powerful tool
- Examples
  - resolving contention in a broadcast medium
  - choosing multicast timeouts

Soft state

- State: memory in the system that influences future behavior
  - for instance, VCI translation table
- State is created in many different ways
  - signaling
  - network management
  - routing
- How to delete it?
- Soft state => delete on a timer
- If you want to keep it, refresh
- Automatically cleans up after a failure
  - but increases bandwidth requirement

Exchanging state explicitly

- Network elements often need to exchange state
- Can do this implicitly or explicitly
- Where possible, use explicit state exchange

Hysteresis

- Suppose system changes state depending on whether a variable is above or below a threshold
- Problem if variable fluctuates near threshold
  - rapid fluctuations in system state
- Use state-dependent threshold, or *hysteresis*

Separating data and control

- Divide actions that happen once per data transfer from actions that happen once per packet
  - Data path and control path
- Can increase throughput by minimizing actions in data path
- Example
  - connection-oriented networks
- On the other hand, keeping control information in data element has its advantages
  - per-packet QoS

Extensibility

- Always a good idea to leave hooks that allow for future growth
- Examples
  - Version field in header
  - Modem negotiation

Performance analysis and tuning

- Use the techniques discussed to tune existing systems
- Steps
  - measure
  - characterize workload
  - build a system model
  - analyze
  - implement