The single overriding goal for systems builders is to obtain maximum performance without loss of robustness.

What are the major determinants of performance? Today we will look at:

- The costs of various common operations
- Speed of the various platform technologies
- Caching and other common tricks
- Relationship between caching and replication. Cache consistency issues.
Changing Goals

- Performance goals circa 1980:
  - Focus on getting the compiler to produce the best possible code
  - Forced you to write code with CPU in mind, even to declare “register” variables carefully
  - “Memory mapping and protection boundary crossings” were rare
  - Multithreading was uncommon

Changing goals

- Performance goals circa 1990
  - The Internet became widely deployed
  - 1980 issues remained, but…
    - The network was frequently in the “critical path”
    - Multithreading much more common
  - This changed the emphasis for developers:
    - Often the delay before a message was sent, or received, was central
    - Had to be aware of layers of the operating system and network that each message would traverse and to think about communication relationships.
Changing goals

- Performance goals circa 2000
  - Now we’ve gone to object-oriented architectures and soon, Web Services
- Implications?
  - There are some very slow paths sitting around!
  - Network much more heavily used
- Moreover, the network itself has become more complex.
  - Distinctions between a local area network and the Internet WAN are fading
  - Even a small network has many properties of the shared, public Internet!

“Basic” costs

- A shifting landscape
  - Very dependent on hardware choice
    - CPU speed, but also…
    - Size of L1 cache, cache design
      - E.g. interleaving factors, line size, etc
    - Presence and size of L2 cache
    - Cache hit rates
    - Performance of I/O bus, dev. Controllers
  - Also on O/S architecture
    - Cost of context switching, operating system calls
    - Overall design of the operating system
Two large classes of machines

- Clients: PCs and workstations
  - Sit on your desktop
  - These days, usually run Windows XP or Linux. Sun Solaris a fading option.
  - User application runs here
  - Performance is less of an issue but you need to multithread and exploit pre-built GUI toolkits
- Servers
  - Sit in a data center accessed over net
  - Right now, Linux and other UNIX variants are most popular platform choice. Windows has made minor inroads.
  - Performance is a dominant issue here and demands a great deal of sophistication from the developer
- But often, the real key to performance is the wire itself!

Technology trends

Source: Scientific American, Sept. 1995

Note sudden growth in WAN speeds
Typical latencies (milliseconds)

WAN, disk latencies are fairly constant due to physical limitations

Note dramatic drop in LAN latencies over ATM

Broad observations

- In mid-1990’s a discontinuity occurred as WAN communication speeds suddenly jumped
  - We could see a second such jump if the last hop to the user improves – “home broadband”
  - So far, however, that last hop remains the bottleneck
- In LAN settings picture is stable but could change
  - ATM didn’t make it
  - But Infiniband could bring 10Gb throughput and microsecond latencies over the next decade
  - Issue here is “disruptive” impact of exploiting Infiniband on the Operating System
O/S latency: the most expensive overhead on LAN communication!

![Graph showing O/S overhead as a percentage from 1985-1990 and 1995-2000.]

**Broad observations**

- O/S imposed communication latencies has risen in relative terms over past decade!
- Other performance curves have generally “tracked” one-another
  - Moreover, media objects have grown in size at least as fast as the capacity to move them has risen
  - Disks have “maxed out” and hence are looking slower and slower, especially as DVD-RW gains popularity
  - Due to high latencies, memory of remote computers isn’t currently an appealing resource
- Web Services architecture could impose a 10x growth in overhead on paths that go the whole nine yards!
Performance parameters worth keeping in mind

- Cost of a null system call. Cost of doing a “select” system call.
- Cost of a method invocation to a service running outside your address space
- Context switching overhead for threads and for heavyweight processes
- Maximum TCP transfer rate
- Cost of a remote method invocation
- Round-trip cost to send a small message

Can we reduce performance to a set of rules of thumb?

- There are a number of generic performance tricks worth knowing
- On a given platform you need to design tiny little stand-alone code loops to figure out what really matters
- Gprof and Ethereal are very helpful tools! The more you know the more you can focus on the bottlenecks
Generic insight #1

- System calls are expensive
  - Many developers are casual about using “select”, hence core loop could require 3 or 4 system calls per operation performed
  - Often, it turns out that select is the most costly operation you can do!
- So… think hard about your “main loop”

Example

- A common style
  - Non-blocking select
  - Allocate just the right size object
  - Then fetch msg
  - Map IP address to name
  - Note arrival time
  - select(....);
  - msg_body = malloc(...);
  - recvmsg(...);
  - gettimeofday(...);
  - nis_lookup(...):

- Better options?
  - Use one thread per incoming socket and do blocking rcvs
  - Another separate thread can use select and check time, putting it in a shared global variable
  - NIS lookup can usually be avoided by caching results
  - If we have some single maximum size for messages, can allocate off a free list from a pool
Generic insight #2

- Threads can be very costly
  - Context switching can be slow
  - Thread scheduling (and mis-scheduling) a common problem!
  - Each thread will need a lot of memory for the stack and other overheads
    - C, C++: Your program soon starts to thrash!
    - Java and C# avoid this but they have other forms of high overhead

Example?

- Formula for really bad performance: have multiple threads on run queue when in fact only one thread can “do anything”
  - E.g. thread a wakes up thread b, then blocks on a semaphore only after thread b is runnable.
  - O/S will often get the context switching wrong, running b, then a, then b again (if not worse)

```c
Signal(B.sema);
wait(A.sema);
wait(B.sema);
Signal(A.sema);
wait(B.sema);
```
Threads and sockets

- You saw socket interface in Paul’s lecture on Monday
- Thread model and socket model were never thought out in a clear side-by-side way
- Today we live with a messy legacy of this initially haphazard design!

Thread issues on UNIX/Linux

- Problem here relates to mismatch between threads and “select”
  - Select can be used as a blocking or a non-blocking call
  - But UNIX never thought of threads as a first-class O/S construct
  - Hence if anything blocks, the whole address space blocks
Why is this such an issue?

- Suppose that an application interacts with many external data sources
  - Sockets connected to TCP
  - Events from the windowing layer
  - Timers associated with timeouts
  - Exception handlers
- Now it issues a blocking select… what happens?

Blocking select on UNIX

- Only some events can interrupt a select
  - So until the select unblocks, those events will block
  - Timer interrupt is the big issue
- Why are timers such a problem?
  - Costly to use timers in “clock tick” style
  - But otherwise, can be tricky to figure out how to set the select timeout parameter!
Issues with true threads?

- Suppose that your “main program” is waiting
  - Either for an incoming message
  - Or for a request from the user
- You decide to use multithreading and your version of the O/S supports this
- But how can live thread A “break through” the select to wake thread B?

What about on Windows?

- Windows originally used an event model popularized in old Digital Equipment VAX VMS O/S
- Everything is a small “message”
- Delivery of such a message is an “event”
- Application registers event handlers and can also wait for an event in one or more classes (like select)
Here the issue arises when mixing models

- Winsock used a more Unix-like model
- Very awkward to combine Winsock with the normal event-style of Windows main loop!
- So this can get sloppy and complex too, easily
- In modern languages like C#, all unified in an event model

Best option?

- Have one thread per event “source”
- It loops (or does whatever you do) waiting for events of that type to happen
- Then can queue the event up on a “main loop” thread input queue
  - Main loop thus uses “wait”, not any sort of blocking O/S system call!
- And it dispatches the work while your event source thread waits for the next one
Example?

- Event queue
- Wait for next event
- Blocking `recv` then enqueue "new message" event
- Blocking thread sleep, then enqueue "new time" event
- User keyboard event? Create a new event object and enqueue it too!

Seems inefficient?

- Actually not... having a main dispatch thread can be very useful
  - The main program is only concurrent when you want it to be
  - And it can “stop” looking at inputs while doing something messy without actually freezing up
- But beware situations where that main loop might hang!
Summary of this insight?

- Threads are
  - Inevitable
  - Poorly integrated with applications that handle lots of events from many kinds of sources
  - Far more costly than you would expect!

Generic insight #3

- Messages costs are independent of size
  - Most people assume that a small message is cheap and a big one is costly…
  - In fact, beyond IP packet (1400 bytes) this is partly true – think of costs “per IP packet”
  - Still, the major costs of sending or receiving a message are dominated by overhead
- So… try and accumulate many chunks of information into each message, if you can!
Example: In “better” approach, A and B get 3 times as much work done per O/S delay they incur!

- Avoid
  - Program A
  - Program B

- Better
  - Program A
  - Program B

Downside?
- When your application crashes, there can be many important messages sitting in the output buffer
  - Be sensitive to need to “flush” if something important happens
  - Also, don’t let the sender and receiver get too far out of sync (could “thrash”)
  - Use a high water/low water model, as TCP does in its windowing scheme
Generic insight #4

- Latency is the biggest problem in modern systems
  - Network throughputs have been rising slowly and in most settings are getting good
  - But round-trip latency often sucks and delays of 50 or 100ms are common!
- So... modern systems must cache and replicate important objects!
- Also should try to build systems to run asynchronously – message “round trips” are very slow if the user is waiting and watching

Example:

- Avoid
- Better (within limits)
Caching is an instance of this insight, too

- If you can find an object locally and are able to use it, the win is huge!
- But caching *isn’t* replication!
  - When we replicate, we end up with a true copy
  - A cached copy (by definition) can be stale
  - And checking validity can be just as costly as fetching a new copy!
- Also, not everything can be cached
  - Much content is produced on demand…

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Caching

- Avoid
  ```
  Program A     Program B
  [DELAY] ABC    [DELAY] ABC
  [DELAY] XYZ    [DELAY] XYZ
  [DELAY] ABC?   [DELAY] ABC?
  ```
- Better
  ```
  Program A     Program B
  [ABC] ABC
  [XYZ] XYZ
  [ABC?] ABC?
  ```
We’ll look at caching in more detail during next lecture

- Often done at multiple levels even in a single system!
  - Your application can cache in user space
  - The O/S may cache too
  - And there could be an “edge” cache near your system
  - And the server itself may have cached data in some form of proxy on its side
  - Plus it may cache in its own user memory
  - And the disk on which it runs could be caching objects too!
- Main issue with caching concerns stale data
  - How can we tell?
  - Who is responsible for updating or invalidating?

Generic insight #5

- Think about the critical path first!
  - Often the “speed” of a system is an illusion determined by how long it takes before the user sees a response
  - All sorts of background work can be taken off the critical path
  - User will then see snappy performance without system having “speeded up” at all!
- But this also has led to some dreadful reliability compromises, like log-based database replication
Critical paths

Program A
- Main prog
- Invoke remote method
- DB
- DB

Tricks?
- Often can delay some “work” until a message has already been sent
- In fact may be able to do some work in anticipation of the next message
  - Van Renesse: “Ask yourself how much of the work of sending a message actually depends on its contents”
  - Can you guess what the next message will look like?
Critical paths

Do postprocessing after dispatching response to user

Move “preprocessing” to end of handling of previous message!

Sync with backup offline

Questions to ask

- By moving the synchronization with backup offline, did we lose fault-tolerance?
  - Two “systems” know about request
    - Client system
    - Server
  - To tolerate one failure we need to be sure that both will be “checked” for any pending requests
  - Also need to know that outcome of request will be predictable to backup if it hears about it only after primary has gone down
Another approach

User sends request to the backup which forwards it to the primary. This ensures that the backup and primary both know about the request and also the request ordering!

Move "preprocessing" to the end of handling of previous message!

Do postprocessing after dispatching response to user.

One hop really helps!

- Since backup can maintain an accurately ordered request list, it has a better chance of reproducing identical decisions to the ones made by the primary.
- And the latency impact will be quite small.
- Illustrates both a performance trick and also the kind of thinking required if you don’t want to lose reliability!
Generic insight #6

- Memory allocation costs a fortune.
  Garbage collection is a disaster
  - Modern languages are very casual about allocation and freeing of objects
  - But in fact, costs are extremely high!
- Maintain a free-list for your common object types.
  - Once an object is allocated, put it on the free list and never actually “free” it again

Free lists

```c
Msg *m_freelst;

Msg* m_alloc()
{
  if(Msg *m = m_freelst)
  {
    m_freelst = m->msg_next;
    return(m);
  }
  return(Msg* malloc(sizeof(Msg))); // Actual allocation code
}

void m_free(Msg* m)
{
  m->msg_next = m_freelst;
  m_freelist = m;
}
```
Generic insight #7

- Modern processors all lie about their speed
  - The vendor may claim 2.5GHz
  - You’ll be lucky to squeeze 10MIPs out of it
- The problem is L1 and L2 cache misses, which stall the processor
  - For raw speed you’ll need to work hard on fine-grained performance tuning!
  - But for this kind of work, code in C or abandon all hope of setting speed records

Generic insight #8

- Hidden costs of background mechanisms can be a scaling problem
  - Many modern systems are using costly distributed mechanisms
  - But those costs may not be incurred continuously. Instead, they have a “periodic cleanup mechanism”
  - Be very wary of the scalability issues these periodic mechanisms face!
- Later in semester we’ll look at “scalable reliable multicast” (SRM)
  - Background overhead kills SRM scalability!!
What are “background” mechanisms?

- In many distributed systems we have
  - A primary “data path” used for most work and most operations
  - A background task used to
    - Rebuild data structures
    - Handle unusual failure cases
    - Deal with unlikely conflicts or deadlocks

- The issue is that
  - Frequency of background work grows with system size
  - And the amount of time or messages may also
  - ... giving a form of \( O(n^2) \) background cost!

- Becomes noticeable only in large settings!

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Generic insight #9

- Languages like Java and C# are really best as scripting languages
  - Think of them as orchestrating control of large components doing “big” things
  - Huge productivity wins. Only way to go for fancy GUI design or to talk to a database
  - But for demanding, high-performance applications, they are too sluggish

- C++ has similar issues! “Hidden costs” when you make use of inheritance and garbage collection.

- C on UNIX remains the best choice if you really care about raw speed
Generic insight #10

- Stateless, loosely coupled architectures are usually faster
  - We’ll face tough choices: “consistent” replication versus weaker forms of caching, hints versus accurate data
  - Loose replication is often the key to building scalable “farms” running cloned servers
  - Experience with fine-grained, tight replication is more problematic.
- But remember Einstein: “Make things as simple as possible, but no simpler”

Server farms are common

- Stateful Database
- Load Balancer
- Cloned servers handle “soft” state
How File Systems use such ideas

- File systems illustrate many of our points
  - They make extensive use of caching
    - In the application itself
    - In the file system buffer pool on client and server side (write-through policies, some even use write-back invalidation)
  - They multi-thread on both client and server side
  - Critical path is hand coded in C, often inside the O/S. Great attention to scheduling…

Clever recent trick

- In mobile file systems, bandwidth is a serious constraint
- So researchers at … looked at file system “blocks”
  - Traditionally, on 1k, 4k or 8k boundary
  - Thus a small change in a file can “shift” data so that whole file changes
- Concluded that even if most updates change just a few bytes, whole file always gets moved!
Clever recent trick

- ... so they had the idea of cutting files into irregular sized blocks using a mathematical coding function
  - This function cuts at the same spots even if the file gains or loses some bytes in the front or middle
  - Notice the decision to do more computing “on board” in order to reduce network I/O
- Effect? Updates only modify a small subset of the blocks! So update traffic was slashed...

Summary?

- Performance is a huge challenge to the systems builder
- Modern architectures won’t help at all!
- Most tricks for gaining performance also add complexity
- Yet opportunity often exists for speedups of 50x or more relative to what the usual tools simply spit out...