Principled Computer System Design

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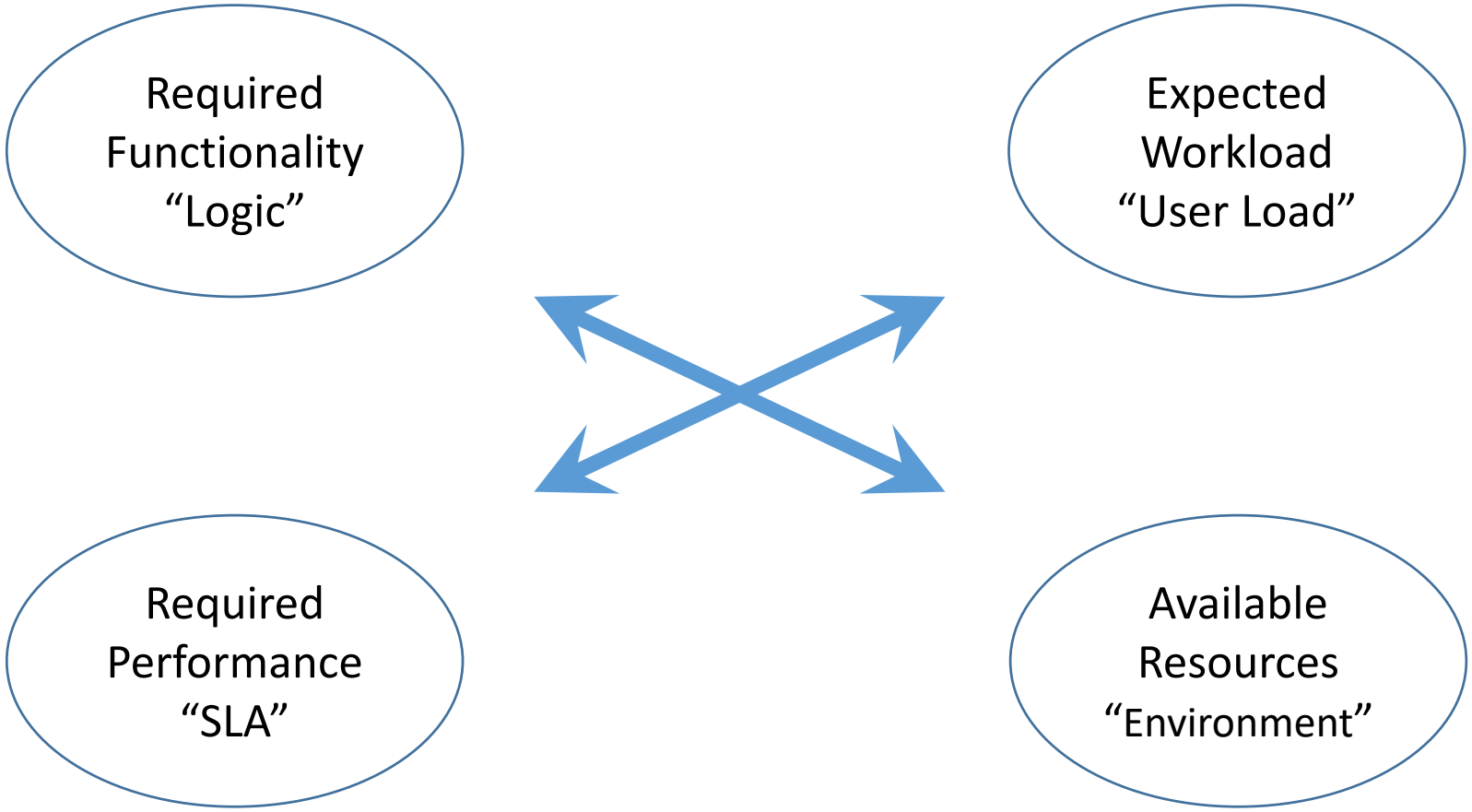
(some material due to Hakim Weatherspoon and probably others)

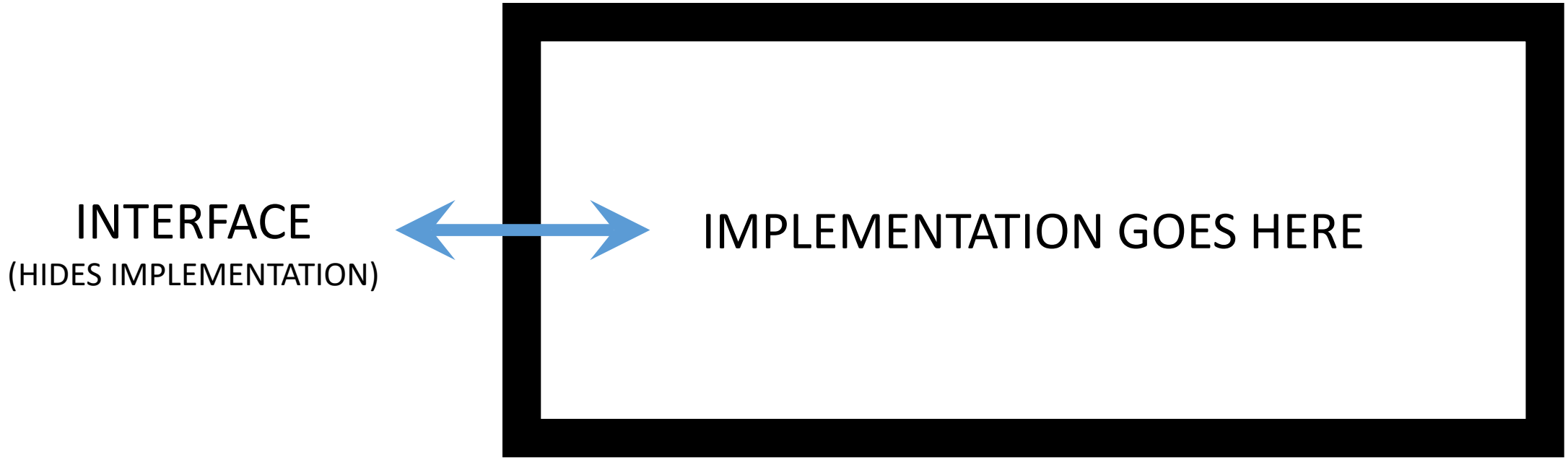
Message from Prof. Weatherspoon

- Please let the class know that they get their own cloud today! Mini Project0 is available, getting started on Fractus: http://www.cs.cornell.edu/courses/cs6410/2016fa/miniprojects.htm
- It is due by tomorrow, but is fun, easy, and quick.

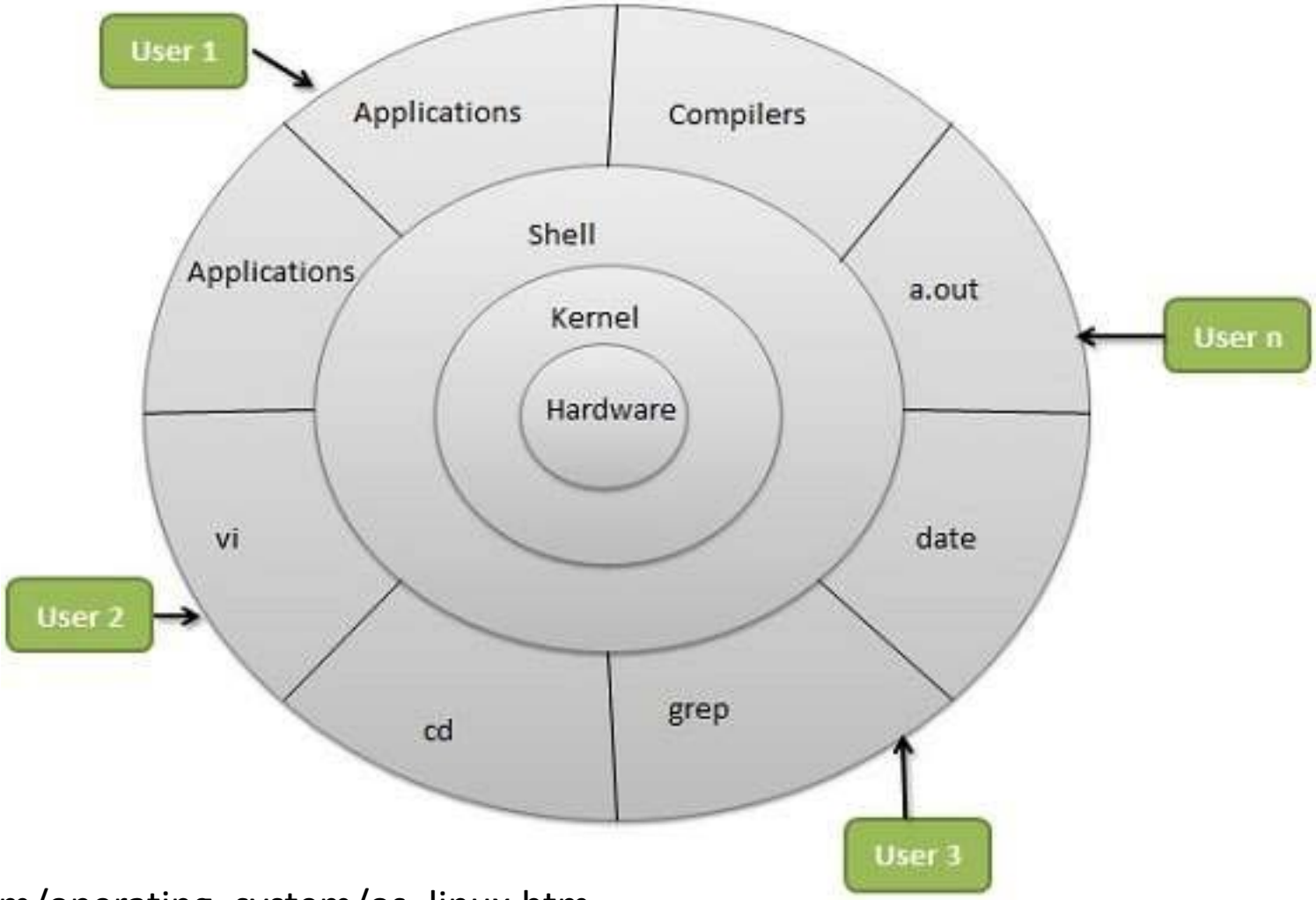
What is System Design: Science, Art, Puzzle?



Something to do with “Abstraction”



Also, “Layering” (layered modules)

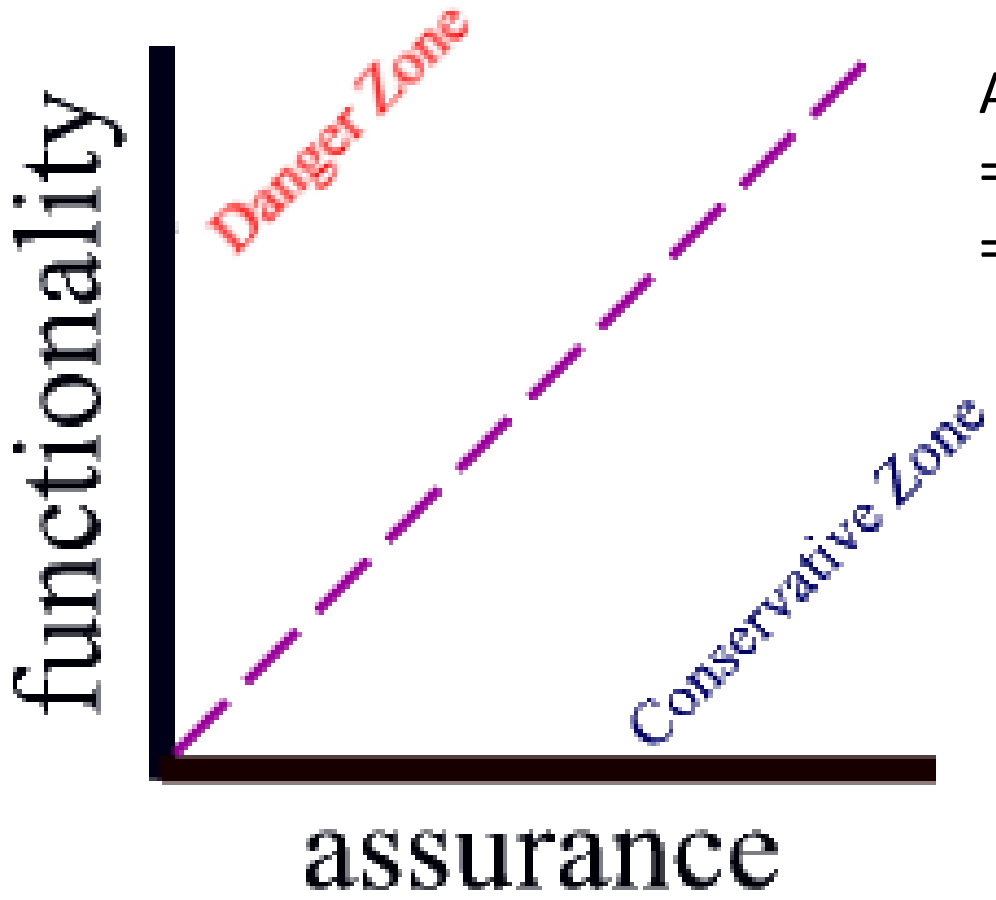


From: http://www.tutorialspoint.com/operating_system/os_linux.htm

Any problem in computer science can be solved with another level of indirection

- Attributed to David Wheeler (by Butler Lampson)

Functionality vs Assurance



Assurance
== Required Performance (Speed, Fault Tolerance)
== Service Level Agreement (SLA)

“Hints for Computer System Design” --- Butler Lampson, 1983

- Based on author’s experience in systems design
- Founding member of Xerox PARC (1970)
- Currently Technical Fellow at MSR and adjunct prof. at MIT
- Winner of ACM Turing Award (1994). IEEE Von Neumann Medal (2001)
- Was involved in the design of many famous systems, including databases and networks

System Design Hints organized along two axes: Why and Where

- Why:
  - Functionality: does it work?
  - Speed: is it fast enough?
  - Fault-tolerance: does it keep working?
- Where:
  - Completeness
  - Interface
  - Implementation

Hints for Computer System Design - Butler Lampson

Why?	*Functionality* Does it work?	*Speed* Is it fast enough?	*Fault-tolerance* Does it keep working?
Where?			
Completeness	Separate normal and worst case	Shed load End-to-end Safety first	End-to-end
Interface	Do one thing well: Don't generalize Get it right Don't hide power Use procedure arguments Leave it to the client Keep basic interfaces stable Keep a place to stand	Make it fast Split resources Static analysis Dynamic translation	End-to-end Log updates Make actions atomic
Implementation	Plan to throw one away Keep secrets Use a good idea again Divide and conquer	Cache answers Use hints Use brute force Compute in background Batch processing	Make actions atomic Use hints

Figure 1: Summary of the slogans

FUNCTIONALITY

- Interface
  - Between user and implementation of an abstraction
  - Contract, consisting of a set of assumptions about participants
    - Assume-Guarantees specification
  - Same interface may have multiple implementations
- Requirements:
  - Simple but complete
  - Admit efficient implementation
- Examples: Posix File System Interface, Network Sockets, SQL, …

- Lampson: “Interface is a small programming language”
  - Do we agree with this?

Keep it Simple Stupid (KISS Principle)

- Attributed to aircraft engineer Kelly Johnson (1910—1990)
- Based on observation: systems work best if they are kept simple
- Related:
  - *Make everything as simple as possible, but not simpler* (Einstein)
  - *It seems that perfection is reached not when there is nothing left to add, but when there is nothing left to take away* (Antoine de Saint Exupéry)
  - *If in doubt, leave it out* (Anon.)
  - *Complexity is the Enemy: Exterminate Features* (Charles Thacker)
  - *The unavoidable price of reliability is simplicity* (Tony Hoare)

Do one thing at a time, and do it well
Don’t generalize
Get it right!

- A complex interface is hard to implement correctly, efficiently
- Don’t penalize all for wishes by just a few
- Basic (fast) operations rather than generic/powerful (slow) ones
- Good interface admits implementation that is
  - Correct
  - Efficient
  - Predictable Performance
- Simple does not imply good
  - A simple but badly designed interface makes it hard to build applications that perform well and/or predictably

Make it Fast
Leave it to the Client
Don’t Hide Power
Keep Secrets

- Design basic interfaces that admit implementations that are fast
  - Consider monolithic O.S. vs. microkernels
- Clients can implement the rest
- Abstraction should hide only undesirable properties
  - What are examples of undesirable?
    - Non-portable
- Don’t tell clients about implementation details they can exploit
  - Leads to non-portability, applications breaking when modules are updated, etc.
  - Bad example: TCP

Use procedure arguments

- High-level functions passed as arguments
  - Requires some kind of interpreter within the abstraction
  - Hard to secure
    - Requires safe language or sandboxing

Keep basic interfaces stable
Keep a place to stand

- Ideally do not change interfaces
  - Extensions are ok
- If you have to change the interface, provide a backward compatibility option
  - Good example: Microsoft Windows

Plan to throw one away
Use a good idea again

- Prototyping is often a good strategy in system design
- You end up building a series of prototypes
- The same good idea may be usable in multiple contexts
- Example: Unix developed this way, leading to Linux, Mac OS X, and several others

Divide and Conquer

- Several forms:
  - Recursion
  - Stepwise Refinement
  - Modularization
- Lampson only talks about recursion
- Stepwise refinement is a useful technique to contain complexity of systems
- Modules contain complexity
  - Principle of “Separation of Concerns” (Edsger Dijkstra)

Handle normal and worst case separately

- Use a highly optimized code path for normal case
- Just try to implement handling the worst case correctly
- Sometimes optimizing normal case hurts worst case performance!
  - And sometimes good worst case performance is more important than optimal normal case performance
- Example: normal case in TCP/IP highly optimized

SPEED

- Lampson talks mostly about making systems *fast*
- Other, perhaps more subtle considerations include
  - Predictable performance
  - Meeting service-level objectives
  - Cheap to run in terms of resources

Split resources
Safety first

- Partitioning may result in better performance than sharing
  - but not always..
    - for example: a shared cache would result in better overall utilization typically than a partitioned cache
    - but a partitioned cache may give more predictable performance to any particular user
  - most low-level resources these days tend to be shared…
- Prioritize safety over optimality

Static analysis
Dynamic translation

- No, this is not a PL course
- If you know something about the workload, exploit it!
  - For example, workload might exhibit locality, periodicity, etc.
  - Related to “normal case” handling
- Prefetching allows I/O and compute to overlap
- Examples: paging and scheduling algorithms

Cache answers
Use hints

- Caching answers to expensive computations trades storage for other resources (CPU, network, etc.)
  - What does “expensive” mean in this context?
- “Hints” are typically caches of potentially wrong information
  - Example: DNS uses this extensively to provide scalability
  - Should be easy to check if hint works, and correct for it if not

When in doubt, use brute force

- Related idea: don’t optimize blindly
  1. build the system “stupidly”
  2. identify bottlenecks through profiling
  3. eliminate bottlenecks
  4. go back to Step 2 if necessary
- If the system is modular, such “adjustments” are typically easy to make
  - If not, difficult refactoring might be necessary
  - Related: building series of prototypes

Compute in background
Use batch processing
Shed load

- “Compute in background” essentially means to do I/O and compute in parallel
  - examples: paging, GC, …
  - in this day and age, we do everything in parallel…
- Batching multiple small jobs into a larger one can significantly improve throughput
  - although often at the expense of latency
  - example: TCP
- Avoid overload by admission control
  - example: TCP

Fault Tolerance

- We expect 24x7x365.25 reliability these days
- In spite of what Lampson says, it’s pretty hard…

Log updates
Make actions atomic or restartable

- Cheap: many storage devices optimal or optimized for append-only
- Useful: after a crash, state can be restored by replaying log
  - helps if updates are “idempotent” or restartable
  - example: ARIES “WAL” (Write-Ahead Log)
- Atomic (trans-)actions simplify reliable system design
  - group of low-level operations that either complete as a unit or have no effect
- Isolation and Durability are also very useful properties!

End-to-End arguments in System Design –
Jerry H. Saltzer, David P. Reed, David D. Clark (MIT)

- Jerry H. Saltzer
  - A leader of Multics, key developer of the Internet, and a LAN (local area network) ring topology, project Athena

- David P. Reed
  - Early development of TCP/IP, designer of UDP

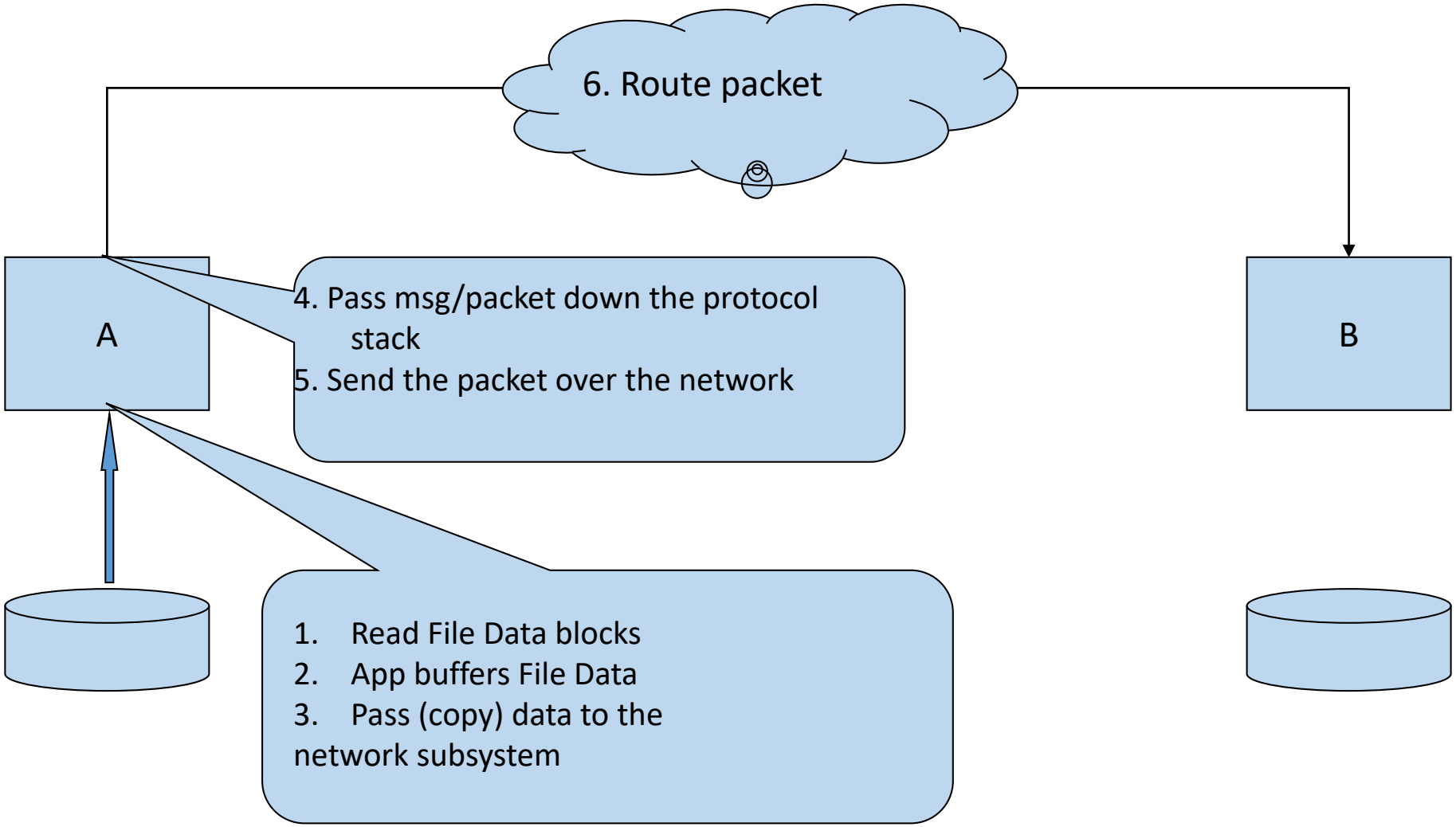
- David D. Clark
  - I/O of Multics, Protocol architect of Internet

    "We reject: kings, presidents and voting.
    We believe in: rough consensus and running code."

End-to-End argument

- Helps guide function placement among modules of a *distributed* system
- Argument
  - implement the functionality in the lower layer only if
    - a large number of higher layers / applications use this functionality and implementing it at the lower layer improves the *performance* of many of them, AND
    - does not hurt the remaining applications

Example : File Transfer (A to B)



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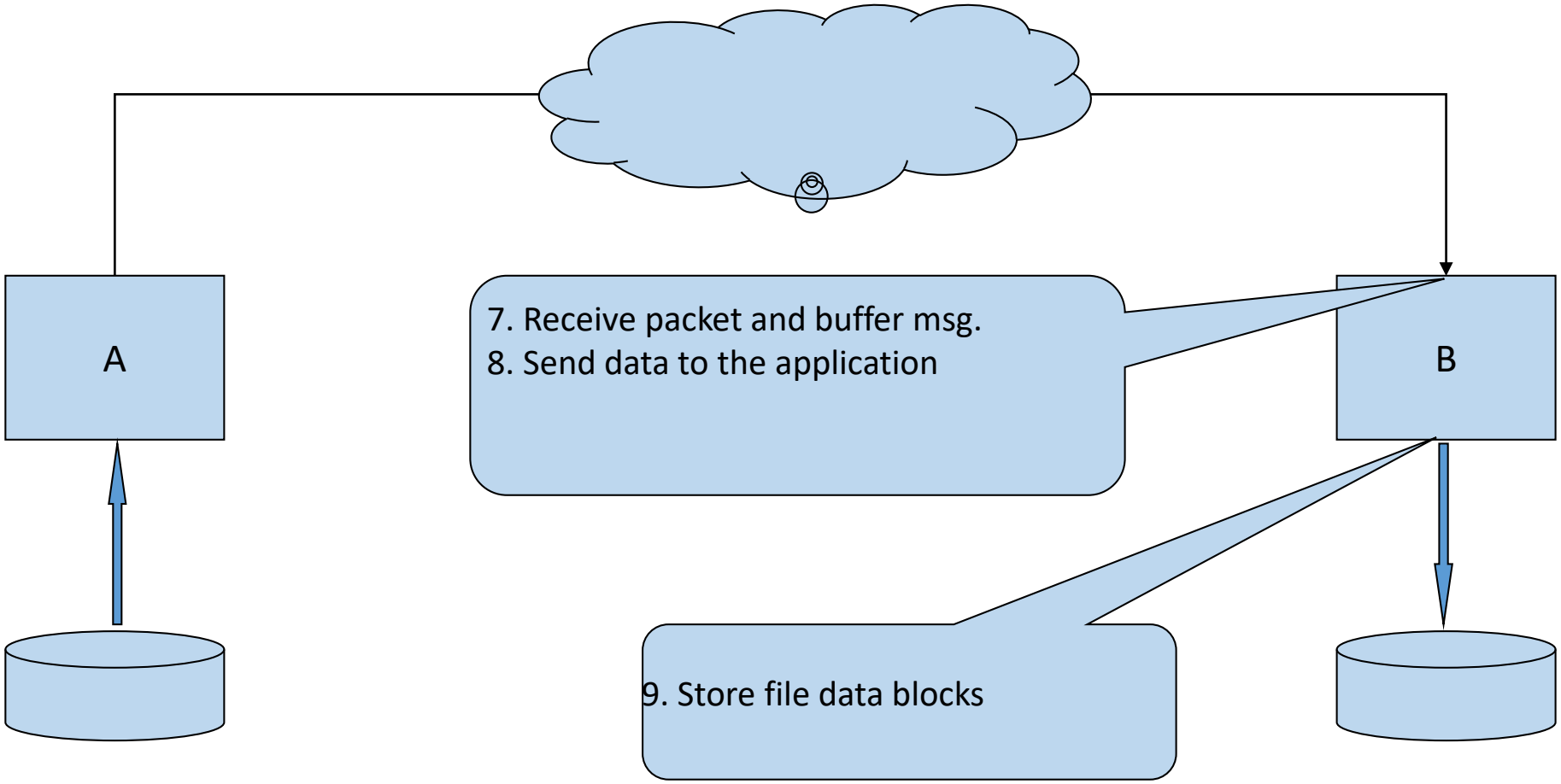

Possible failures

- Reading and writing to disk
- Transient errors in the memory chip while buffering and copying
- network might drop packets, modify bits, deliver duplicates
- OS buffer overflow at the sender or the receiver
- Either of the hosts may crash

Solution: make the network reliable?

- Packet checksums, sequence numbers, retry, duplicate elimination
  - Example: TCP
- Solves only the network problem
- What about the other problems listed?
- Not *sufficient* and not *necessary*

Solution: end-to-end retransmission?

- Introduce file checksums and verify once transfer completes – *end-to-end check*.
  - On failure – retransmit file
  - Works! (modulo rotting bits on disk)

Is network-level reliability useful?

- Per-link retransmission leads to faster recovery from dropped packets than end-to-end
- Seems particularly useful in wireless networks or very high latency networks
- But this may not benefit all applications
  - Huge unnecessary overhead for, say, Real-Time speech transmission

TCP/IP

- Transmission Control Protocol (TCP)
  - It is a transport protocol providing error detection, retransmission, congestion control, and flow control
  - TCP is almost-end-to-almost-end
    - kernel-to-kernel, socket-to-socket, but not app-to-app
- Internet Protocol (IP)
  - IP is a simple ("dumb"), stateless protocol that moves datagrams across the network
  - The network itself (the routers) needs only to support the simple, lightweight IP; the endpoints run the heavier TCP on top of it when needed.

Other end-to-end examples

- End-to-end authentication
  - TLS, SSL
- Duplicate msg suppression

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