UNIVERSITY OF COPENHAGEN

# Advanced Computer Systems (ACS)

Marcos Vaz Salles
Associate Professor, DIKU

# Why study computer systems?

- The IBM/Microsoft/Oracle question

  How can I program large systems with clean interfaces and high performance?

- The Amazon/Facebook/Google question

  How can I understand the guarantees and reliability of scalable services offered to me on the cloud?

- The Cloudera/Vertica/Teradata question

  How do I build systems to process TBs to PBs of data?

# What is the scale of our computer systems?

- Source: Michael Brodie, Computer Science 2.0, presented at VLDB 2007, Vienna, Austria
- **Databases**
  - AT&T has 11 exabytes ($10^7$ TB) of wireline, wireless, Internet data; 2+ trillion calls
  - Google's BigTable (US): 1-2 petabytes,
  - Wal-Mart (US): 500 TB, $10^7$ transactions / day
  - All in 2004

# What is the scale of our computer systems?

- Source: Michael Brodie, Computer Science 2.0, presented at VLDB 2007, Vienna, Austria
- **Internet**
  - 1/2 billion hosts (IP addresses)
  - 1.17 billion users (>4 billion today)
  - or 17.8% of the world's population
- **Web**
  - 109 million distinct web sites
  - 29.7 billion web pages
  - ~5 pages for every man, woman, and child on the planet
  - 7.2 billion Web searches/month (3.9 billion by Google) far exceed the world population

(> 1.8 billion web sites, 100 billion Google searches/ month today)

# What is the scale of our computer systems?

- Source: Michael Brodie, Computer Science 2.0, presented at VLDB 2007, Vienna, Austria
- **Facebook**
  - 1.8 billion photos
  - 41 million active users
  - $10^5$ new users / day
  - 1,800 applications
  - (today > 2.2 billion, ~28% of world population)
- **YouTube**
  - 1.7 billion served / month
  - 1 million streams / day (today billions of views / day)

# What is the scale of our computer systems?

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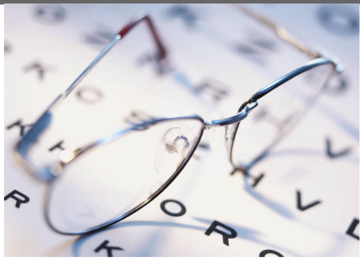
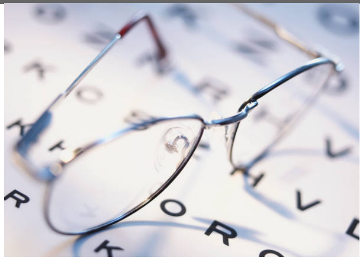
**How can we think about and architect large-scale computer systems?**



# What should we learn in this course?

- Knowledge
    - Describe the design of transactional and distributed systems, including techniques for modularity, performance, and fault tolerance
    - Explain how to employ strong modularity through a client-service abstraction as a paradigm to structure computer systems, while hiding complexity of implementation from clients
    - Explain techniques for large-scale data processing
- Skills
    - Implement systems that include mechanisms for modularity, atomicity, and fault tolerance
    - Structure and conduct experiments to evaluate a system's performance



# What should we learn in this course?

- Competences
  - Discuss design alternatives for a modular computer system, identifying desired system properties as well as describing mechanisms for improving performance while arguing for their correctness
  - Analyze protocols for concurrency control and recovery, as well as for distribution and replication
  - Apply principles of large-scale data processing to analyze concrete information-processing problems

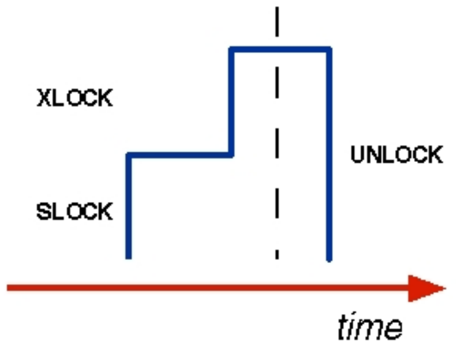
# ACS: What will we study?

- Fundamentals
  - Abstractions: interpreters, memory, communication links
  - Modularity with clients and services, RPC
  - Techniques for performance, e.g., concurrency, fast paths, dallying, batching, speculation

Property: Strong Modularity

# ACS: What will we study?

- Concurrency Control and Recovery
  - Two-phase locking
  - Serializability, schedules
  - Optimistic and multi-version approaches to concurrency control
  - Recovery concepts
  - ARIES recovery algorithm




Properties: Atomicity and Durability

# ACS: What will we study?

- Experimental Design
  - Performance metrics, workloads
  - Structuring and conducting simple experiments

# ACS: What will we study?

- Reliability & Distribution
  - Reliability concepts
  - Replication techniques
  - Topics in coordination and distributed transactions
- Communication
  - Message queues, BASE
  - End-to-end argument
  
  (if time allows)

Property: High Availability

# ACS: What will we study?

- Data Processing
  - Operators
  - External sorting
  - Hash- and sort-based techniques for multiple operations (e.g., set operations, joins)
  - Parallelism

Property: Scalability with Data Size

# References & Course Materials

- Course webpage
  - Kurser: http://kurser.ku.dk/course/ndak15006u/
- Course materials in Absalon (Canvas)
  - Tentative course syllabus
    - Includes readings for after each class
  - Slides before each class
  - Assignments & Feedback
  - Discussion forums
- Please always post your questions in Absalon
  - Your colleagues can profit too!

# References & Course Materials

- Book
  - Advanced Computer Systems (ACS): DIKU Course Compendium. Collected references from sources cited therein, organized by Marcos Vaz Salles and Michael Kirkedal Carøe.
  - IMPORTANT: Same compendium as previous year!
- Papers & other references
  - Vast majority listed in the syllabus
  - A few more will come as we go
  - Optional references and videos from recent conferences in computer systems for more depth

# Team

- Lecturers
  - Marcos Antonio Vaz Salles
    - vmarcos@di.ku.dk
  - Yongluan Zhou
    - zhou@di.ku.dk
  - Office hours:
    - By email appointment

- TAs
  - Alexander Richert
  - Lasse Petersen
  - Svend Lund Breddam
  - Yiwen Wang
  - Yuan Liang
  - Meet all of them in the TA sessions on Thursdays!

# Weekly Schedule

- Lectures Tuesdays and Thursdays, 10am-12pm
  - Two 45 min sessions, 15 min break, with lecturer
  - Participation will be encouraged ☺

- TA sessions Thursdays 1pm-3pm
  - TAs will guide most of those
    - Exercises
    - **Feedback** on assignments
    - Assignment work time and Q&A
  - A lecturer will come over for the second hour, walk between classes to answer questions

## Learning is the main goal!

# First Steps

- **Java Warm-up Exercise**
  - If you passed Advanced Java, you do not need it ☺
  - If you did not take Advanced Java, the assignments can be used as warm-up to tell you the level of Java you **need** for this course
- **Group formation**
  - Groups of 2 students recommended for assignments
    - Minimum 1, maximum 2
  - Strategy for group recording using Absalon (Canvas)
    - Groups organized by TAs, every assignment submitted with groups.txt file for validations
    - ***Come to first TA session and let your TA know of your group***
    - TAs will also help people who still need to find groups
    - Self-organize sensibly to spread across TA classes

# First Steps

- **Study group formation with student ambassadors**
  - This Wednesday, **November 21**, 15:00-16:30
  - Either in ML lecture room or DIKU library (to be announced)
- **First TA Session**
  - This Thursday, **November 22**
  - **Group Organization + Assignment introduction + Java best practices**
  - **Optional** Amazon Web Services (AWS) usage through AWS Educate program
    - If interested, enroll; Marcos will periodically check applications against course participants and approve
- **Plus: MSc Elective Course Presentations**
  - Today, at AKB, AUD 03, 12:45-15:15

# Assignments

- **6 take-home assignments**
  - **3 Programming Assignments + 3 Theory Assignments**
  - **Groups: 2 people** strongly recommended
  - Programming Assignment 2 worth two points; all others one point each
  - **5/7 points** must be passed **to qualify** for exam
  - **Resubmission** of Programming Assignments 1 and 2 allowed by December 21
    - You should give the assignments **an honest attempt** to be allowed to resubmit, i.e., you should submit enough that you can get feedback on to address in resubmission
  - **Due dates**
    - **Programming Assignments: November 27, December 6, December 14**
    - **Theory Assignments: December 6, December 17, January 4**

# Exam

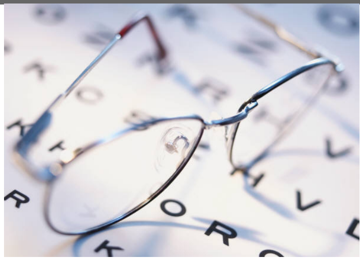
- **Exam format**
  - 4-hour written exam under invigilation with external grading on 7-point scale
  - Exam date is **January 17**
  - The exam is open-book, all aids allowed
  - **The exam must be solved individually**

Academic Integrity
taken very seriously

# Acknowledgements

- Many of the slides in this course are based on or reproduce material kindly made available by Jerome Saltzer & M. Frans Kaashoek & Robert Morris (MIT, PCSD textbook material), Johannes Gehrke (Cornell/Microsoft, Ramakrishnan & Gehrke textbook), Gustavo Alonso (ETH Zurich, EAI course), Michael Freedman (Princeton), Nesime Tatbul (Intel Labs/MIT), James Kurose & Keith Ross (U Mass Amherst & NYU, networking textbook), Jens Dittrich (Saarland University)

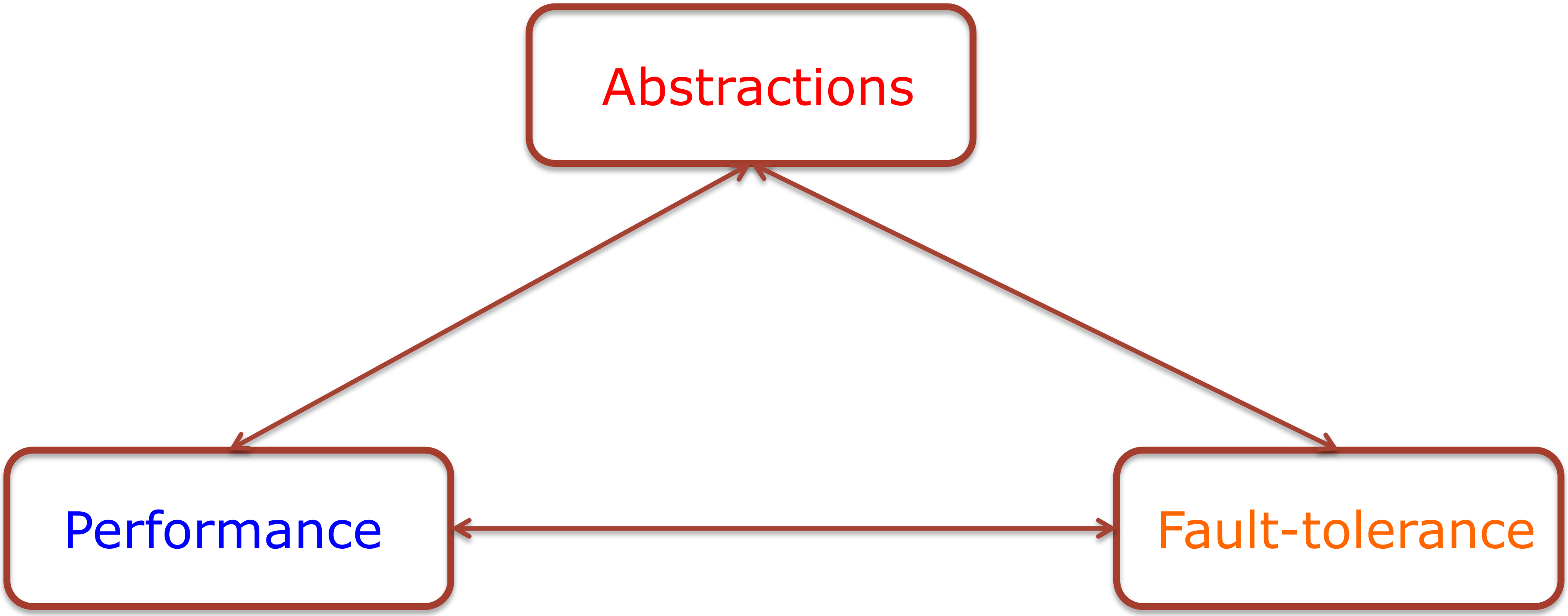
# Questions so far?



# What should we learn today?

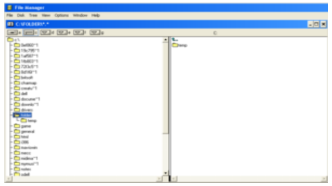
- Identify the fundamental abstractions in computer systems and their APIs, including memory, interpreters, communication links
- Explain how names are used in the fundamental abstractions
- Design a top-level abstraction, respecting its correspondent API, based on lower-level abstractions
- Discuss performance and fault-tolerance aspects of such a design

# The Central Trade-off: Abstractions, Performance, Fault-Tolerance



# Fundamental abstractions

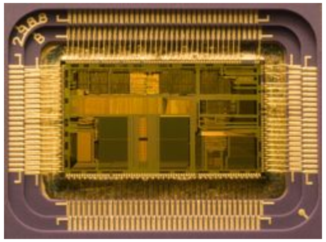




- ***Memory***
  - Read/write
- ***Interpreters***
  - Instruction repertoire
  - Environment
  - Instruction pointer
- ***Communication links***
  - Send/receive

(loop (print (eval (read))))

Names make connections



Source: Saltzer & Kaashoek & Morris (partial)

# Examples of Names

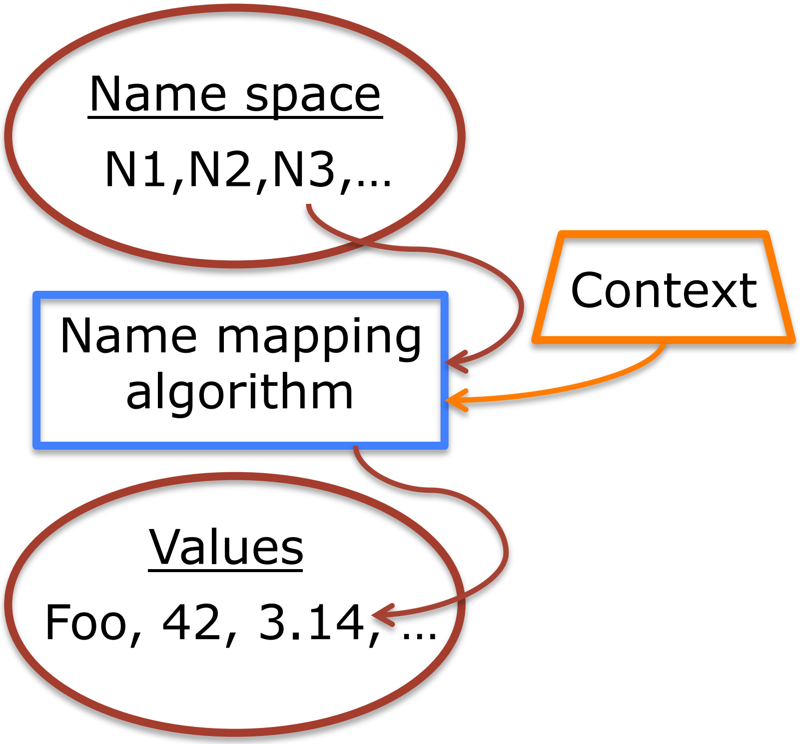
- R1
- 1742
- 18.7.22.69
- web.mit.edu
- http://web.mit.edu/6.033
- 6.033-staff@mit.edu
- amsterdam
- /mit/6.033/www
- foo.c
- .. (as in cd .. or ls ..)
- wc
- (617)253-7149, x37149
- 021-84-2030

address is overloaded name with location info (e.g., LOAD 1742, R1)

Names require a mapping scheme

Source: Saltzer & Kaashoek & Morris (partial)

# Name Mapping

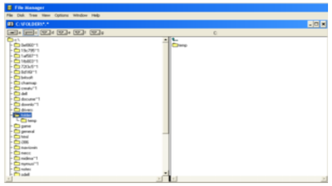



- How can we map names?

- Table lookup
  - Files inside directories
- Recursive lookup
  - Path names in file systems or URLs
- Multiple lookup
  - Java class loading

# Fundamental abstractions

- ***Memory***
  - Read/write

- ***Interpreters***
  - Instruction repertoire
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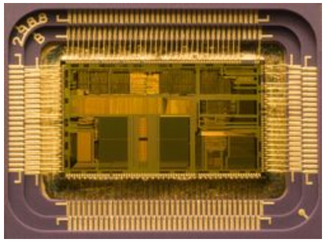
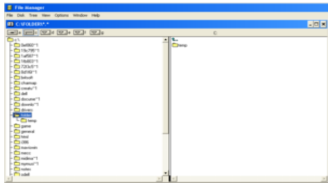


- ***Communication links***
  - Send/receive

Source: Saltzer & Kaashoek & Morris (partial)

# Memory

- ***Memory***
  - `READ(name) → value`
  - `WRITE(name, value)`

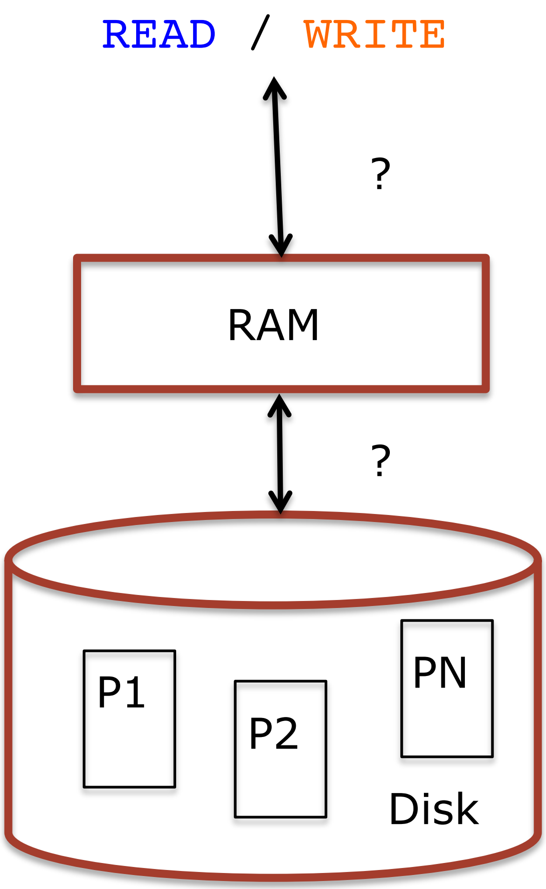
- Examples of Memory
  - Physical memory (RAM)
  - Multi-level memory hierarchy (registers, caches, RAM, flash, disk, tape)
  - Address spaces and virtual memory with paging
  - Key-value stores (e.g., Cassandra, Dynamo)
  - Database storage engines

Source: Saltzer & Kaashoek & Morris (partial)

# How would you design a two-level memory abstraction consolidating disk and RAM?

- Characteristics of storage technologies
  - **RAM**: high cost per gigabyte, low latency, volatile
  - **Disk**: low cost per gigabyte, high latency, nonvolatile

- Design top-level abstraction respecting *Memory API*
- Abstraction must:
  - Address as much data as fits in disk
  - Use fixed-size pages for disk transfers
  - Use RAM efficiently to provide for low latency (on average)
  - Neither disk nor memory directly exposed, only READ/WRITE API




Write the pseudocode down!

# Address Space Mapping

- Address spaces modular way to multiplex memory
- Naming scheme translating virtual into physical addresses
- Page map
  - Updated by kernel code
  - Lookup implemented in hardware
  - Concerns: Protection (Pr), representation, efficiency

**Page Map**

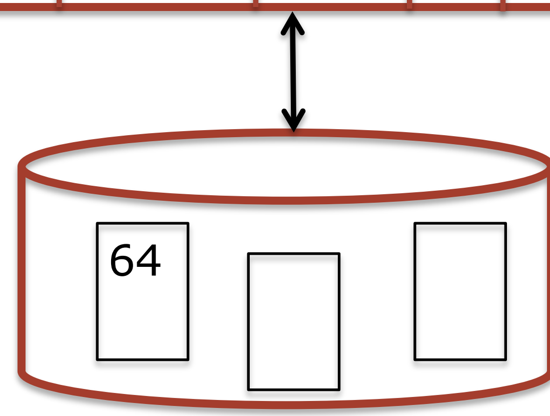
| Page# | Block# | Pr |
|---|---|---|
| 42 | 2 | RX |
| 53 | 45 | R |
| 64 | 97 | RW |
| … | … | … |

# Address Space Mapping: Introducing Disks

- Use disk to store more blocks
- Pages may be either in memory or on disk
- Resident bit (R)
  - Access to non-resident pages results in page faults
- Page Fault
  - An indirection exception for missing pages

**Page Map**

| Page# | Block# | Pr | R | D | P |
|---|---|---|---|---|---|
| 42 | 2 | RX | 1 | 1 | 0 |
| 53 | 45 | R | 1 | 0 | 1 |
| 64 | (D-42) | RW | 0 | 0 | 0 |
| … | … | … | … | … | … |



# Address Space Mapping: Introducing Disks

- Handling page faults
  - Trap to OS handler
  - Handler loads block from disk and updates mapping
  - If memory full, must choose some *victim* block for replacement
  - Page replacement algorithm, e.g., LRU
- Other metadata
  - *Dirty bit (D)*: Only write page back when it has changed!
  - *Pin bit (P)*: do not remove certain pages (e.g., code of OS handler itself)

**Page Map**

| Page# | Block# | Pr | R | D | P |
|---|---|---|---|---|---|
| 42 | 2 | RX | 1 | 1 | 0 |
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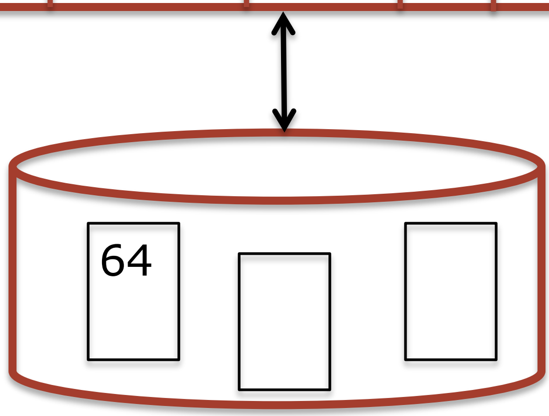

# Virtual Memory with Paging: Abstractions, Performance, Fault-Tolerance

- ***Abstraction:*** Do we have any guarantees on two concurrent threads writing to the same memory?
- ***Performance:*** Do we get average latency close to RAM latency?
- ***Fault-Tolerance:*** What happens on failure? Do we have any guarantees about the state that is on disk?

**Page Map**

| Page# | Block# | Pr | R | D | P |
|---|---|---|---|---|---|
| 42 | 2 | RX | 1 | 1 | 0 |
| 53 | 45 | R | 1 | 0 | 1 |
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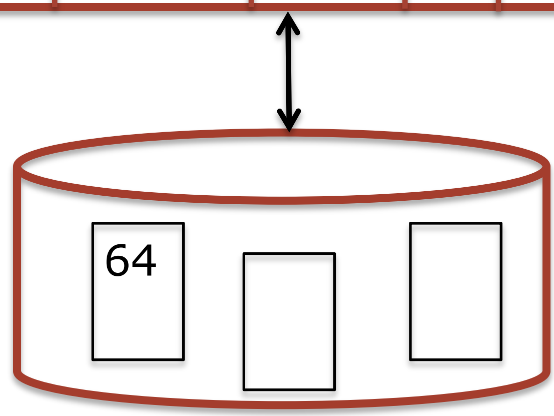
| … | … | … | … | … | … |



# Interpreters

- ***Interpreter***
  - Instruction repertoire
  - Environment
  - Instruction pointer

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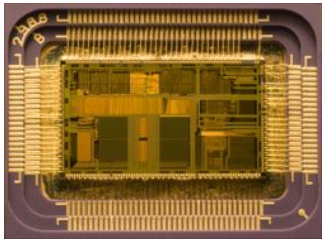


```
procedure INTERPRET()
    do forever
        instruction ← READ(instruction_pointer)
        perform instruction in environment context
        if interrupt_signal = TRUE then
        instruction_pointer ← entry of INTERRUPT_HANDLER
        environment ← environment of INTERRUPT_HANDLER
```

- Examples of Interpreters
  - Processors (CPU)
  - Programming language interpreters
  - Frameworks, e.g., MapReduce or Spark
  - Your own (layered) programs! (RPCs)

Source: Saltzer & Kaashoek & Morris (partial)

# Communication links

- ***Communication links***
  - `SEND(linkName, outgoingMessageBuffer)`
  - `RECEIVE(linkName, incomingMessageBuffer)`


- Examples of Communication Links
  - Ethernet interface
  - IP datagram service
  - TCP sockets
  - Message-Oriented Middleware (MOM)
  - Multicast (e.g., CATOCS: Causal and Totally-Ordered Communication System)

Source: Saltzer & Kaashoek & Morris (partial)

# Memory, Interpreters, Communication Links: Is that all there is?

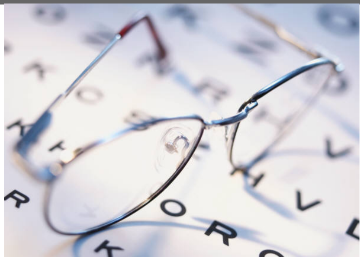
- Other abstractions also useful!

- ***Synchronization***
  - Locks
  - Condition variables & monitors

  (see, e.g., Chubby lock service from Google)

- ***Data processing***
  - Data transformations
  - Operators

  (see, e.g., data-parallel implementations)



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