# Hints and Principles for Computer System Design

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# Overview

- A 32-year update of my 1983 *Hints for Computer Systems*
- These are mostly hints, often not consistent or precise
  - Hints *suggest*—no nitpicking allowed
- **STEADY** by **AID**
  - **What**: **S**imple, **T**imely, **E**fficient, **A**daptable, **D**ependable, **Y**ummy
  - **How**: **A**pproximate, **I**ncremental, **D**ivide & conquer, …
- The future: Engagement with the physical world

*There are three rules for writing a novel. Unfortunately, no one knows what they are*.
—Somerset Maugham
*You got to be careful if you don't know where you're going, because you might not get there.*
—Yogi Berra
*The quest for precision, in words or concepts or meanings, is a wild goose chase*.
—Karl Popper

# What: Goals

- **S**imple
- **T**imely (to market)*
- **E**fficient
- **A**daptable*
- **D**ependable
- **Y**ummy*

**STEADY**

*More important today

First ↔ Fast ↔ Frugal ↔ Flexible ↔ Faithful ↔ Fancy ↔ Fun

TTM ↔ speed ↔ cost ↔ change ↔ trust ↔ features ↔ coolness

*[Data is not information,] Information is not knowledge, Knowledge is not wisdom, Wisdom is not truth, Truth is not beauty, Beauty is not love, Love is not music and Music is THE BEST"* —Frank Zappa

# How: Methods

- **A**pproximate
  - **Good enough**
  - Loose specs
  - Lazy/speculative
- **I**ncremental
  - **Indirect**
  - **Iterate**
  - Extend
- **D**ivide & conquer
  - **Interfaces** to abstractions
  - Recursive
  - Atomic
  - Concurrent
  - Replicated

**AID**

# Kinds of Software

- **Precise** vs. **approximate** software
  - Precise:  Get it **right**
    - avionics, banks, Office
  - Approximate: Get it **soon**, make it **cool**
    - search, shopping, Twitter
- Which kind is yours?
  - One isn't better or worse than the other,
  - but they are *different*.

*Unless in communicating with it* [a computer] *one says exactly what one means, trouble is bound to result.* —Turing

*There's no sense being exact about something if you don't even know what you're talking about.*—von Neumann

# Coordinate Systems and Notation

- Choose the right coordinate system
  - Like center of mass for dynamics, or eigenvectors for matrices
  - Ex: State as being *vs.* becoming, function as code *vs.* table *vs.* overlay
- Choose a good notation
  - This is why domain specific languages succeed
  - Relations cover most needs for design
    - subsuming sets, functions, graphs, programs
    - with composition, transitive closure , union, intersection as primitives

*A point of view is worth 80 points of IQ.* —Alan Kay

*Science is not there to tell us about the Universe,*
*but to tell us how to talk about the Universe.* —Niels Bohr

*A good notation has a subtlety and suggestiveness which at times make it seem almost like a live teacher… and a perfect notation would be a substitute for thought.* —Russell

# Coordinates: State

- State as *being* vs. *becoming*
  - *Being*: map from names → values
  - *Becoming*: initial state + log of updates
- Being is the usual form
- Becoming is good for undo, versions and recovery

| **Example** | **Being** | **Becoming** |
|---|---|---|
| Image | bitmap | display list |
| Document | sequence of characters | sequence of inserts / deletes |
| Database | table + buffer cache | redo-undo log |
| Eventual consistency | names → values read | *any* subset of updates that are commutative and associative |

*Don't ask what it means, but rather how it is used.* —Wittgenstein
*No matter how far down the wrong road you have gone, turn back now.* —Turkish Proverb

# Coordinates: Functions

- Function as code *vs.* table *vs.* overlay
  - Code: execute $f(x)$ to get the result
  - Table: lookup $x$ in a set of (argument, result) pairs
  - Overlay: try $f_1(x)$ , if undefined try $f_2(x)$, …

| **Example** | **Code** | **Table** | **Overlay** |
|---|---|---|---|
| Main memory | — | RAM | write buffer |
| Database | — | data on disk | buffer cache |
| bin for shell cmd | — | /bin directory | search path |
| Function of simple argument | run the code | precomputed results | saved old results |
| Database view | run the query | materialized view | incremental updates |

*If all you have is a hammer, everything looks like a nail.* —A. Maslow

# Write a Spec: State

- At least, write down the abstract state
  - Abstract state is *real*
  - Example: File system state is `PathName`→`ByteArray`

*The purpose of abstracting is not to be vague,*
*but to create a new semantic level in which one can be absolutely precise.* —Dijkstra

*Beware of bugs in the above code; I have only proved it correct, not tried it.* —Knuth

# Write a Spec: Actions

- At least, write down the state—Abstract state is *real*
  - Example: File system state is `PathName→ByteArray`
- Then, write down the interface actions (APIs),
  - which ones are external, and what each action π does
  - Example: For failures, volatile vs. persistent state
    - On crash, volatile := persistent
    - On sync, persistent := volatile

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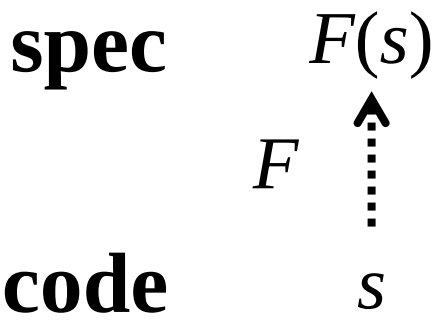
*but to create a new semantic level in which one can be absolutely precise.* —Dijkstra

# Write a Spec: Abstraction Function

- At least, write down the state—Abstract state is *real*
  - Example: File system state is `PathName→ByteArray`
- Then, write down the interface actions (APIs),
  - which ones are external, and what each action π does
- Next, write the *abstraction function F* from code to spec

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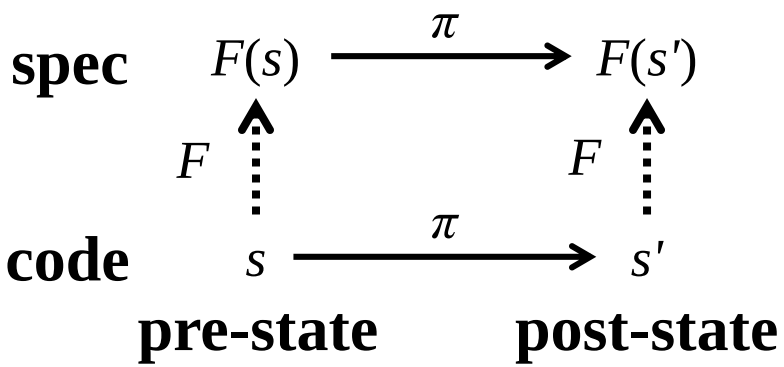
# Write a Spec: Proof

- At least, write down the state—Abstract state is *real*
  - Example: File system state is `PathName→ByteArray`
- Then, write down the interface actions (APIs),
  - which ones are external, and what each action π does
- Next, write the *abstraction function F* from code to spec
- Finally, show that each action π preserves *F*:




Newcombe et al, How Amazon Web Services uses formal methods, *Comm ACM* **58**, 4 (March 2015), pp 66-73

# How: Methods

- **A**pproximate
  - **Good enough**
  - Lazy/speculative
  - Loose specs
- **I**ncremental
  - **Compose (**indirect, virtualize)
  - **Iterate**
  - Extend
- **D**ivide & conquer
  - **Interfaces** to abstractions
  - Recursive
  - Replicated
  - Concurrent

# AID

# AID: Divide & Conquer

- Interfaces to abstractions: Divide by **difference**
  - Limit complexity, liberate parts. TCP/IP, file system, HTML
  - Platform/layers. OS, browser, DB. X86, internet. Math library
    - Need this to ship
  - Declarative. HTML/XML, SQL queries, schemas
    - The program you think about takes only a few steps
  - Synthesize a program from a partial spec. Excel Flashfill
    - Signal + Search → Program

*Civilization advances by extending the number of important operations which we can perform without thinking about them. Operations of thought are like cavalry charges in a battle — they are strictly limited in number, they require fresh horses, and must only be made at decisive moments.* —Whitehead

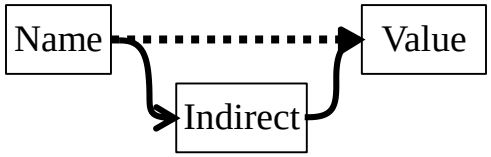
*Don't tie the hands of the implementer.* —Martin Rinard

# AID: Divide & Conquer

- Interfaces: Divide by **difference**
- Recursive: Divide by **structure**. Part ~ whole
  - Quicksort, DHTs, path names. IPV6, file systems
- Replicated: Divide for **redundancy**, in time or space
  - Retry: End to end (TCP). Replicated state machines.
- Concurrent: Divide for **performance**
  - Stripe, stream, or struggle: BitTorrent, MapReduce

*If you come to a fork in the road, take it.* —Yogi Berra
*To iterate is human, to recurse divine.* —Peter Deutsch

# AID: Incremental




- **Indirect:** Control name→value mapping
  - Virtualize/shim: VMs, NAT, USB, app compat, format versions
  - Network: Source route→IP addr→DNS name→service→query
  - Symbolic links, register rename, virtual methods, copy on write
- **Iterate** design, actions, components
  - **Redo:** Log, replicated state machines (state as becoming)
  - **Undo.** File system snapshots, transaction abort
  - **Scale.** Internet, clusters, I/O devices
- **Extend.** HTML, Ethernet

*Any problem in computing can be solved by another level of indirection.* —David Wheeler
*Compatible, adj. Different.* —The Devil's Dictionary of Computing

# AID: Approximate

- **Good enough**. Web, search engines, IP packets
  - Eventual consistency. DNS, Dynamo, file/email sync
- **Loose coupling**: springy flaky parts. Email, Fedwire
- **Brute force**. Overprovision, broadcast, scan, crash fast
  - Strengthen (do more than is needed). Redo log, coarse locks
- **Relax**: small steps converge to desired result
  - Routing protocols, daily builds, exponential backoff
- **Hints**: Trust, but verify

*I may be inconsistent. But not all the time.*—Anonymous

# What: Goals

- **S**imple
- **T**imely (to market)*
- **E**fficient
- **A**daptable*
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- **Y**ummy*

**STEADY**

- First↔Fast↔Frugal↔Flexible↔Faithful↔Fancy↔Fun
- Need tradeoffs—You can't get *all* these good things

# STEADY: Simple, Timely

- **Simple** is important because we can't do much
  - Simple enough? I can still understand it
    - But when it evolves, only abstraction and interfaces can save me
  - Simple is hard, often not rewarded—"That's obvious."
    - Why didn't computer scientists invent the web?
- **Timely**: Good enough is good enough
  - The web is successful because it doesn't have to work.
  - Learn what customers really want—Iterative development

*Less is more.* —Browning
*Everything should be as simple as possible, but no simpler.* —Einstein
*I'm sorry I wrote you such a long letter; I didn't have time to write a short one.* —Pascal

*The best is the enemy of the good.* —Voltaire
*If you don't think too good, don't think too much.* —Ted Williams

*And the users exclaimed with a laugh and a taunt,*
*"It's just what we asked for but not what we want."* —Anonymous

# STEADY: Efficient, Adaptable

- **Efficient** has two faces: for the implementer, for the client
  - Not unrelated: the client wants it fast and cheap enough
  - Efficient *enough*, not optimal
- **Adaptable**–Plan for success
  - Evolution/scaling: Successful systems live a long time
    - 2015 PC = 100,000 × Xerox Alto, Web grew from 100 users to $10^9$
  - Incremental update: Big things change a little at a time

*An efficient program is an exercise in logical brinkmanship.* —Dijkstra
*I see how it* [the phone] *works. It rings, and you have to get up.* —Degas
*That, Sir, is the good of counting. It brings everything to a certainty, which before floated in the mind indefinitely.*—Samuel Johnson

*Success is never final.* —Churchill (attributed)
*APL is like a diamond; Lisp is like a ball of mud.* —Joel Moses

# STEADY: Dependable, Yummy

- **Dependable:** Reliable, Available, Secure
  - Reliable: Gives the right answer (safe)
  - Available: Gives the answer promptly (live)
  - Secure: Works in spite of bad guys
- Often dependable **undo** is the most important thing

- **Yummy**: Users really want it
  - Function: Spreadsheets, the web, smartphones
  - Design: Apple's forté

*But who will watch the watchers? She'll just begin with them and buy their silence.* —Juvenal

*The unavoidable price of reliability is simplicity. It is a price which the very rich find most hard to pay.* —Tony Hoare

# The Future: What Do Computers Do?

| | | |
|---|---|---|
| **Simulate** | 1950-ongoing | nuclear weapons, payroll, protein folding, games, virtual reality |
| **Connect** (and store) | 1980-ongoing | email, airline tickets, books, movies, Bing, Virtual Earth |
| **Engage** (with physical world) | 2010-... | factories, cars, robots, smart dust: *Embodiment* |

*The future ain't what it used to be*.—Yogi Berra

*Reality is that which, when you stop believing in it, doesn't go away.*—Philip K. Dick

# Big Trends

- Connectivity—cloud and data everywhere
- Ubiquity, invisibility: systems everywhere
- Scaling—billions of users, billions of gigabytes
- Approximation—good enough is good enough

- AI and systems are converging
- Reusable components are finally catching on

- **Uncertainty**—fundamental to engagement
- **Dependability**—critical systems have to work

*They always say time changes things, but you actually have to change them yourself.*
—Andy Warhol

*You see things; and you say, 'Why?' But I dream of things that never were; and I say 'Why not?'*
—Shaw

# Grand Challenge: Zero Traffic Deaths

- Cars have to drive themselves
  - A pure computer science problem
- Needs
  - Computer vision
  - World models for roads and vehicles
  - *Dealing with uncertainty* about sensor inputs, vehicle performance, changing environment
  - *Dependability*
- DARPA Challenges, Google cars a start
- Huge economic impact
- Safety trumps liability

*Problems worthy of attack prove their worth by hitting back.*—Piet Hein

# Dealing with Uncertainty

- Unavoidable in the physical world
  - Need good models of what's possible, and their limits
- Unavoidable for "natural" user interfaces: speech, writing, language
  - The machine must guess; what if it guesses wrong?
- Paradigm?: Probability distributions
  - Distributions as a standard data type?
    - Parameterized over the domain (like lists). What are the operations?
  - A start: Microsoft Infer.Net, probabilistic programming

*Logic, like whiskey, loses its beneficial effect when taken in too large quantities*.—Lord Dunsany

*Do I contradict myself? Very well then I contradict myself. (I am large, I contain multitudes.)* —Whitman

# Dependable ⇒ No Catastrophes

- A realistic way to reduce aspirations
  - Focus on what's *really* important
- What's a catastrophe? It has to be *very* serious
  - USS Yorktown: database failure → can't run engines
  - Terac 25 and other medical equipment: Patients die
- Architecture: Normal vs. catastrophe mode
  - Catastrophe mode ⇒ high assurance CCB
- Catastrophe mode requires limited goals = limited function
  - And strict bounds on complexity
    - Less than 50k lines of code? Can verify? Examples: Ironclad, FSCQ

*If you can't make it fast and correct, make it fast*.—Luca Cardelli

*As a rule, software systems do not work well until they have been used, and have failed repeatedly, in real applications*.—David Parnas

# Summary

- **STEADY** by **AID**
  - What: **S**imple, **T**imely, **E**fficient, **A**daptable, **D**ependable, **Y**ummy
  - How: **A**pproximate, **I**ncremental, **D**ivide & conquer
- If you only remember three things:
  - Keep it simple
  - Interfaces to abstractions
  - Write a spec
- The future: Engagement with the physical world

*If I have seen further than others, it is because I have stood on the shoulders of giants.* —Schoolmen of Chartres, via Newton

*The only thing new in the world is the history you don't know.* —Harry Truman

*History doesn't repeat, but it rhymes.* —Mark Twain