Hints and Principles for Computer System Design

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Abstract

This new short version of my 1983 paper suggests the goals you might have for your system—Simple, Timely, Efficient, Adaptable, Dependable, Yummy (STEADY)—and techniques for achieving them—Approximate, Incremental, Divide & Conquer (AID). It also gives some principles for system design that are more than just hints, and many examples of how to apply the ideas.

1. Introduction

There are three rules for writing a novel. Unfortunately, no one knows what they are. —Somerset Maugham[Q33]

You got to be careful if you don't know where you're going, because you might not get there. —Yogi Berra[Q4]

Designing a computer system is very different from designing an algorithm:

- The external interface (the requirements) is more complicated, fuzzy and changeable.
- The system has much more internal structure, and hence many internal interfaces.
- The measure of success is much less clear.

The designers usually find themselves floundering in a sea of possibilities, unclear about how one choice will limit their freedom to make other choices, or affect the size and performance of the entire system. There probably isn't a 'best' way to build it, or even any major part of it; what's important is to avoid a terrible way, and to have clear division of responsibilities among the parts.

I have designed and built a number of computer systems, some that succeeded and some that didn't. I have also used and studied many other systems, both successes and failures. From this experience come some general hints for designing good ones. Most are part of the folk wisdom of experienced designers, but, "It is not sufficiently considered that men more often need to be reminded than informed."[Q22] There are also some principles (about abstraction and modules) that almost always apply, and some oppositions that suggest different ways to look at things.

There's a longer version of this paper here, about twice the size. Both are successors to a much shorter paper on hints that I wrote in 1983.[R38]

I've organized the hints along three axes, corresponding to three time-honored questions, with a catchy summary: STEADY by AID with ART.

What?	**Goals**	STEADY	— **S**imple, **T**imely, **E**fficient, **A**daptable, **D**ependable, **Y**ummy
How?	**Techniques**	by AID	—**A**pproximate, **I**ncremental, **D**ivide & Conquer
When, who?	**Process**	with ART	—**A**rchitecture, **A**utomate, **R**eview, **T**echniques, **T**est

There are a lot of hints, but here are the most important ones:

- Keep it simple.
- Write a spec.
- Design with independent modules.
- Exploit the ABCs of efficiency.
- Treat state as both being and becoming.
- Use eventual consistency to keep data local.

These are just hints. They are not novel (with a few exceptions), foolproof recipes, guaranteed to work, precisely formulated laws of system design or operation, consistent, or always appropriate and approved by all the leading experts. Skip over the ones you find wrong, useless or boring.

The paper begins with a list of oppositions (simple vs. rich, imperative vs. declarative, etc.), which can help you decide on priorities and structure for a system. §2 presents the principles: abstraction, specs, code, modularity and the value of a point of view. In §3 each goal gets a section on the techniques that support it, followed by one for incremental techniques that didn't fit under a goal. "Efficient" gets by far the most space, followed by "dependable", because locality and concurrency fall naturally under the first and redundancy under the second, and these three are fundamental to today's systems. Finally there's a short nontechnical §4 on process, and a discussion of each opposition in §5. Throughout, short slogans capture the most important points without any nuance, and quotations give a sometimes cynical commentary on the text.

There are lots of examples to illustrate specific points; I've tried to choose ones that are well-known or well-described online. Look for an example that matches your problem; it can help you find a good technique. I've also told some longer stories, marked » and in smaller type. Many things fit in several places, so there are many cross-reference links (for reading online) as well as an index. A term of art is in *italics* the first time it's used, and it's a good starting point for a web search; so are the names of techniques and examples. I've put in explicit references when I think a search won't find what you need.

I'm afraid that what I've written is rather dense—you'll need to think carefully about many of the points to get the most out of them —why I said it that way, what's wrong with obvious alternatives, how it connects to other points. And I've omitted many details and caveats that you can find in the literature. Otherwise there would be a thousand pages, though. If you're reading the short version and find it too terse, try the long one.

1.1 Oppositions and slogans

I've looked at life from both sides now. —Joni Mitchell[Q36]

It often helps to think about design in terms of the opposition between two (or three) extremes. These are not irreconcilable alternatives, but the endpoints of a range of possibilities. Here are some useful ones, each with a few slogans that hint at its (sometimes contradictory) essence. They are ordered by the first goal or technique they serve, and discussed in §5.

Goal	Opposition	Slogans
Principles	Spec ↔ code	Have a spec. Get it right. Keep it clean. Don't hide power. Leave it to the client.
Simple	Simple ↔ rich, fine ↔ features, general ↔ specialized	KISS: Keep It Simple, Stupid. Don't generalize. Do one thing well. Don't hide power. Make it fast. Use brute force.
	Perfect ↔ adequate, exact ↔ tolerant	Good enough. Worse is better. Flaky, springy parts.
	Spec ↔ code	Keep secrets. Free the implementer. Good fences make good neighbors. Embrace nondeterminism. Abstractions leak.
	Imperative ↔ functional ↔ declarative	Make it atomic. Use math. Say what you *want*.
Timely	Precise ↔ approximate software	Get it right. Make it cool.
Efficient		ABCs. Use theory. Latency vs. bandwidth. S^3: shard, stream or struggle.
	Dynamic ↔ static	Stay loose. Pin it down. Split resources.
	Indirect ↔ inline	Take a detour, see the world. Use what you know.
	Lazy ↔ eager ↔ speculative	Put it off. Take a flyer.
	Centralized ↔ distributed, share ↔ copy	Do it again. Make copies. Reach consensus.
Adaptable	Fixed ↔ evolving, monolithic ↔ extensible	The only constant is change. Make it extensible. Flaky, springy parts.
	Policy ↔ mechanism	Change your mind.
Dependable	Consistent ↔ available ↔ partition-tolerant	Safety first. Always ready. Good enough.
	Generate ↔ check	Trust but verify.
Incremental	Being ↔ becoming	How did we get here? Don't copy, share.
	Iterative ↔ recursive, array ↔ tree	Keep doing it. A part is like the whole.
Process		Build on a platform. Keep interfaces stable.

2. Principles

The ideas in this section are not just hints, they are the basic mental tools for system design. But if you are math-averse and section 2.1 puts you off, just skip it.

2.1 Abstraction—Have a spec

The purpose of abstraction is not to be vague, but to create a new semantic level in which one can be absolutely precise. —Edsger Dijkstra[Q14]

Without a specification, a system cannot be wrong, it can only be surprising. —Gary McGraw[Q34]

If you're not writing a program, don't use a programming language. —Leslie Lamport[Q30]

Abstraction is the most important idea in computing. It's the way to make things simple enough that your limited brain can get the machine to do what you want, even though the details of what it does are too complicated for you to track: many, many steps and many, many bits of data. The idea is to have a *specification* for the computer system that tells its clients

- *what*: everything they need to know to use the system,
- but not *how*: nothing about how it works inside—the *code*.

The spec is normally much smaller and clearer than the code, and it decouples the client from the details of the code, so that (a) the client's life is simpler and (b) changes in the code don't affect the client. An abstraction is better if it's simpler and clearer; it's good enough if your limited brain can use it effectively.

A system's *state* is the values of its variables. The spec describes a client's view of the state using basic notions from mathematics, usually relations (sets of ordered pairs) and their special cases: sets, sequences, tuples, functions, and graphs. This is the *abstract* state. For example, a file system spec describes a file as a sequence (array or list) of bytes. Internally the code has index blocks, buffer caches, storage allocators, crash recovery, etc., but none of this appears in the spec. The spec *hides* the complexity of the code from the client and keeps *secret* the details that the client shouldn't depend on because they are irrelevant and might change. Almost always the spec is much simpler, so the client's life is much easier. If it's not, you are probably doing something wrong.

The spec also describes the *actions* that read and change the state; a file has read, write, and set-length actions. The state and actions define a *state machine* or *transition system*. An action a is just a set of possible transitions or *steps* from a pre-state s to a post-state s', so it too can be described by a relation, a predicate $a(s, s')$ on pairs of states that is true exactly when a step from s to s' is one of the action's steps. There are many notations (usually called programming languages) for writing down these relations easily and clearly, but first-order logic underlies all of them. Example: `x:=y` is short for the predicate $x' = y$ **and** $(\forall\, v$ **except** $x \mid v' = v)$; the value of `x` is now `y` and the other variables stay the same. There might be more than one possible next state if an action is nondeterministic, or none if it's blocked. A *behavior* of the system is just a sequence of steps that the system could take.

Why use math in a spec? For clarity and precision. You can also write down the state and the actions in English prose, and this is often a good place to start, but it's surprisingly hard to make an English spec complete and correct. Prose as comments can help the developer's intuition about the system, but when you try to translate it into math you usually find that you overlooked many details, and that you don't even have the right vocabulary to express them clearly and concisely. The computer won't overlook any details.

A spec can be very partial, describing only some aspects of the behavior; then it's often called a *property*. For example, it might just specify "no segfaults" by allowing any step that isn't a segfault. As well as being partial, a spec can be *nondeterministic*: any of a set of results is acceptable; for example, a timing spec such as "Less than 200 ms". And often details *should* be left open: eventual consistency just says that an update will surely be visible by the end of the next sync.

The code should *satisfy* (meet, conform to) the spec. This means that every visible behavior of the code is a visible behavior of the spec: code behaviors are a *subset* of spec behaviors. The "visible" is important; typically the code has internal state that's invisible, and often the spec does too. A partial spec usually has less visible state. This doesn't mean that the code does *everything* the spec allows. In particular, the spec is often nondeterministic where the code takes a single path.

Satisfying is subset, hence it's transitive: if $C \subseteq R$ and $R \subseteq S$ then $C \subseteq S$. So you can get from spec to code in several stages, putting in more details at each stage. You usually stop the formal development once you have correct code for the tricky parts, even if it's still far from executable,[R51] because the bugs that you add in getting from there to something you can ship are much less tricky.

Finding good abstractions is the most important part of designing a system. A language gives you some built-in abstractions: strings, arrays, dictionaries, functions. These are useful, but they are less important than the abstractions in the platform you are building on, such as files, networking, relational data, vectors and matrices, etc. And those in turn are less important than the abstractions specific to the application, such as calendars, protein structure or robot motion.

Which comes first, the spec or the code? In theory the spec should come first, since it reflects what you want done; this is called top-down design, and the code is a *refinement* of the spec. In practice they evolve together, because you can't tell what the spec should be until you see how it affects the code and the system's customers. The first ideas for a spec are usually either too ambitious or too close to the code, providing both more and less than the customers need.

2.1.1 *Safety and liveness*

Any spec is the conjunction of two parts:

- A *safety* spec, which says what the code *may* do, or equivalently, that nothing bad ever happens. If the code violates a safety spec the bad thing happens in a finite number of steps. Safety generalizes partial correctness.
- A *liveness* spec, which says what the code *must* do, or equivalently, that something good eventually happens, usually that it's *fair*: every action allowed by safety eventually

happens. No finite behavior can violate liveness, because the good thing could happen later. Liveness generalizes termination.

For a non-interactive program such as $sort(a{:}\mathbf{seq})$ **returns** sa (one that just takes an input and produces a result), the spec is just the relation between the pre-state and the post-state. The traces are of length two, and safety and liveness are called partial correctness and termination.

Usually safety is what's important, because "eventually" is not very useful; you care about getting a result within two seconds, and that's a safety property (violated after two seconds).

2.2 **Writing a spec**—KISS: Keep It Simple, Stupid.

Seek simplicity, and distrust it. —A.N. Whitehead[Q59]

Reality is that which, when you stop believing in it, doesn't go away. —Philip K. Dick[Q12]

How should you go about writing a spec? There are two steps:

(1) Write down the state of the spec (the **abstract** state).

You have to know the state to even get started, and finding the simplest and clearest abstract state is *always* worth the effort. It's hard, because you have to shake loose from the details of the code you have in mind and think about what your clients really need. The mental tools you need for this are the elementary discrete math of relations, and a good understanding of the clients.

Often people say that the abstract state is not real or that the spec is an illusion; only the RAM bytes, disk blocks and machine instructions are real. I can't understand this; a physicist will say that only the quantum mechanics of electrons in silicon is real. What they probably mean is that the spec doesn't actually describe the behaviors of the system. This can happen in several ways:

- It can be wrong: the code does things the spec doesn't allow. This is a bug that should be fixed.
- It can omit important details: how accurate a sine routine is or what happens if there's a failure.
- It can omit unimportant details by being leaky. This is a matter of judgment.

For the file system example, the spec state has files F, directories D, and inode numbers N. A file is $F = \mathbf{seq}\,\text{Byte}$ (a function $0..l\text{–}1 \rightarrow \text{Byte}$) and a directory is a (partial) function $D = Name \rightarrow N$. The state is a function $s = N \rightarrow (F \textbf{ or } D)$ that gives the current contents of the nodes. The D's must organize the nodes into a graph where the F's are leaf nodes and the D's form a tree or DAG rooted in $s(0)$; an invariant on the state says this.

(2) Write down the spec actions: how each action depends on the state and changes the state. You may need English comments to guide the developer's intuition.

Now you have everything the client needs to know. If you haven't done this much, you probably can't do a decent job of documenting for the client. A spec should be simple, it should be complete enough, and it should admit code that is small and fast enough. Good specs are hard, because each spec is a small programming language with its own types and built-in operations, and language design is hard. Also, the spec mustn't promise more than the code can deliver—not the best possible code, but the code you can actually write.

There is nothing special about concurrency, except that it makes the code (and perhaps the spec) nondeterministic: the current state doesn't determine the next step, which could come from any thread that isn't blocked. Likewise there is nothing special about failures. A crash or the misbehavior of a component is just another action. Crashes cause trouble because they may destroy state that you would prefer to keep, and because they add nondeterminism that's not under your control. But these are facts of life that you have to deal with, not flaws in the method.

2.2.1 *Leaky specs and bad specs*

Specs are usually incomplete or *leaky*. Most notably, specs often don't say much about speed. Sometimes the spec needs to be leaky, in the sense that it exposes some internal secrets, to give clients the access they need to run fast. Being leaky is not necessarily a bad thing, and in general it's unavoidable. But there are other properties of a spec that *are* usually bad:

- *Complexity* is hard for the client to understand, and hard to code. It often comes from being overambitious, ignoring the state-and-actions recipe, or exposing the code's secrets.
- *Brittleness* makes the spec depend on details of the environment that are likely to change, or on details of how it is called that are easy to get wrong.
- *Errors* or *failures* in the code mean that the code won't satisfy the spec, unless the spec gives it a way to report them. A common example is a synchronous API that makes the code look local, fast and reliable even though it's really remote, slow and flaky.
- Similarly, *contention* or overload may keep the code from meeting the spec if there's no way to report these problems or set priorities.
- *De facto specs*, in either function or performance, happen when the code has properties that clients come to depend on even though they are not in the spec.

2.2.2 *Executable specs*

Another kind of spec is *executable*: the machine can run it fast enough for its clients to actually use it, perhaps not to do useful work but at least to see whether they like its functionality.[R33] This has some advantages:

- You can try it out, often a better way than thinking about it to learn whether you like it.
- You can use it as an oracle for testing real code.[R57]
- Perhaps you can evolve it into code that's good enough to ship.

If it's a spec for a module in a bigger system and it's fast enough (perhaps running on a supercomputer), you can run that system before there's real code for the module.

An executable spec also has some drawbacks:

- It may not be simple and clear enough to be useful as a spec; you need powerful primitives and a strong will to keep from putting in too many details.
- Nondeterminism is hard, and a single choice in the spec may constrain the code too much.
- It can't use the full power of mathematics. For example, it can't say, "There exists a path through this network such that …"

A related idea is a *reference implementation*. Sometimes this means an executable spec, but more often it means practical but unoptimized code, intended to make it clear that the spec itself is practical, and often to guide implementers about what to do.

2.3 Writing the code: Correctness—Get it right

Smart companies know reliable software is not cost effective. It's much cheaper to release buggy software and fix the 5-10% of bugs people complain about. (paraphrased) —Bruce Schneier[Q49]

Most of this paper is about how to write the code. But is the code correct? In other words, does it satisfy the spec? (You don't have a spec? Then the question makes no sense.) In theory this question has a yes-or-no answer. If

- the spec is a predicate that describes every allowed or required action (step) of the system,
- the code precisely specifies every action that the system takes, and
- you know which parts of the state are *visible* to the client,

then correctness is a theorem: "Every visible code behavior is a spec behavior," either true or false. This section explains how to prove this theorem; even though it's seldom worthwhile to complete this proof, you can find bugs and get insight into why the code works by writing down the abstraction function and invariants described in step (3) below.

If the theorem is true, a surprising fact is that it has a *simulation proof*: there is an *abstraction function* f from the code state to the spec state that matches each code action with a spec action that has the same visible effect.

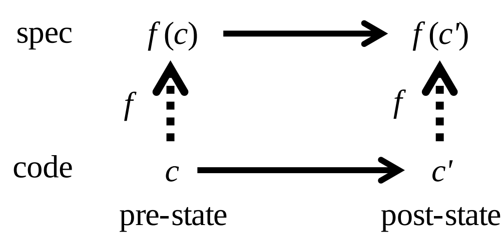

Fig. 1: Inductive step for a simulation proof

Figure 1 is the inductive step in the proof that every visible code behavior is a spec behavior. You might need to add *history* or *prophecy variables* (or use an abstraction relation).[R1]

For a non-interactive system such as $sort(a$:**seq**$)$ **returns** sa the figure is the whole story, since the spec has only two states. The code has lots of internal states as it reorders the sequence, but they all map to the spec's pre-state. For the file system spec action $write(f, i, b)$ (ignoring the complications of crashes) the code does

- a long sequence of internal actions that simulate `skip`s in the spec, to bring into RAM the index block and data block for byte i of the file, allocating new blocks if necessary,
- followed by a visible action to update byte i to b that simulates the $write$ action,
- followed by more internal code actions to write the changed blocks back to disk.

A later $read(f, i)$ will return b. Following this script, once you have the spec (steps (1) and (2) above) and the code state and actions, there are two more steps to connect them:

(3) Find an abstraction function (or relation) from code to spec state.

At the same time, find the *invariants* on the code state, that is, define the states that the code can reach; the proof only needs to deal with actions from reachable states. For example, code that has a sorted array has an invariant that says so, and you need it to show that lookup actually works.

(4) Finally, do the proof that every code action preserves the visible behavior and the invariants.

Step (4) requires reasoning about *every* action in the code from *every* reachable code state, so it's by far the most work. Step (3) requires *understanding* why the code works, and it usually uncovers lots of bugs. Unfortunately, the only way to be sure that you've done it right is to do step (4), which is usually not worthwhile. Writing a spec is always worthwhile, though, because it decouples the client from the code.

An alternative is *model checking*: exploring a subset of the code's state space systematically, looking for behaviors that violate the spec. This doesn't give any guarantee of correctness (unless there are so few behaviors that the checker can try them all), but it finds lots of bugs.[R51,R23]

Testing, model checking, and proof are all much easier when a big system is decomposed into well-specified modules with simple abstract states, because you only have to consider the code state of one module at a time, which is much smaller than the code state of the entire system.

2.3.1 *Types*

Types are a way to express some facts about your code that the machine can understand and check, in particular some stylized preconditions and postconditions. The idea is that

- a value v of type T has an extra `type` field whose value is T,
- if R is a routine with type $T \to U$, its argument must have type T (the precondition): $R(v)$ is an error unless v.type $= T$ (or more generally, v.type is a subtype of T),
- R's result has type U (the postcondition).

With dynamic types the type field is there at runtime (most often it's called a class) and a call of R checks the precondition. In a static system `type` is a "ghost" field not present at runtime, because the compiler knows the type of every expression and does the checks.

Why are static types good? For the same reason that static checking in general is good: the compiler can try to prove theorems about your program, and if it fails you have found a bug early, when it's cheap to fix. Most of the theorems are not very interesting, since they just say that arguments have the right types. But the first draft of a program almost always has lots of errors, most pretty obvious, so type checking finds lots of bugs when it can't prove its trivial theorems.[R55]

2.3.2 *Languages*

What programming language should you use? There is no universal answer to this question, but here are some things to think about:

- How hard is it to write your program so that the language guarantees a safe, bulletproof abstract state, in which a variable always has the expected type and only an explicit write can change its value? Usually this means strong typing and garbage collection. Java is safe in this sense, C++ is not (unless you hide unsafe features behind a safe abstraction),[R65] and JavaScript is in between. If the abstract state isn't bulletproof, debugging is much harder.
- Is the language well matched to your problem domain? Is it easy to say the things that you say frequently? Is it *possible* to say all the things that you need to say?
- What static checking does the compiler do? A bug found at compile time is much easier to fix.
- How hard is it to make your program efficient enough, and to measure how it uses resources?

2.4 Modules and interfaces—Keep it clean. Keep basic interfaces stable.

The only known way to build a large system is to reinforce abstraction with divide and conquer: break the system down into independent abstractions called *modules*. I'll call the running code of a module a *service*; sometimes people call it an object. The spec for a module does two things:

- it *simplifies* the client's life by hiding the complexity of the code (see above), and
- it *decouples* the client from the code, so that the two can evolve independently.

Thus many people can work on the system productively in parallel without needing to talk to each other. Since a spec embodies assumptions that are shared by more than one part of a system, and sometimes by a great many parts, changing it is costly.

It's common to call the spec of a module its *interface*, and I'll do this too. Unfortunately, in common usage an interface is a very incomplete spec that a compiler or loader can process, giving just the data types and the names and (if you're lucky) the parameters of the operations, rather than what the actions do with the state. Even a good description of the state is often missing.

A really successful interface is like an hourglass: the spec is the narrow neck, with many clients above and many codes below; it can live for decades. Examples: CPU ISAs (instruction set architectures such as x86 and ARM), file systems (Posix), reliable messages (TCP), names for Internet services (DNS), web pages (HTTP and HTML). Ousterhout's book on software design[R53] gives many smaller examples, emphasizing how important it is to make the spec much smaller and simpler than the code.

A module boundary doesn't just decouple its *code* from the clients; it can decouple its *execution* and resource consumption as well. If the interface is asynchronous neither side waits for the other, so the service can keep running no matter what the clients are doing, and vice versa. And it can manage the way it consumes storage and other resources independently of its clients. Thus the service is an autonomous agent. How does this show up in the spec? A complete spec doesn't just say enough about the service's internal state to say what results it returns; the spec also describes how it consumes any resources it shares with its clients. An autonomous service doesn't share resources, so its spec is simpler and a system that uses it is more dependable and easier to change. Distributed transactions are an interesting example.

2.4.1 *Classes and objects*

Mathematics is the art of giving the same name to different things. —Henri Poincaré[Q43]

A very popular variation on modules attaches the spec and code to a data item, usually called an *object*. Programs organized this way are called *object-oriented*. You package the specs for a set of routines called *methods* with the same type of first argument into a single spec, here called a *classpec* (it's called an abstract base class in C++ and Python). The code for the classpec is a *class*, a dictionary that maps each method name to its code. An object that has the class attached is an *instance* of the class.

For example, the classpec `Ordered T` might have methods `eq` and `lt`. If `x` is an instance of `Ordered T`, then `x.eq(y)` calls the `eq` method in `x`'s class with arguments `(x,y)`. Adding methods to a class makes a *subclass*, which *inherits* the superclass methods; so `Ordered T` is a subclass of an `Equal T` class that has only the `eq` method. An `Ordered T` instance is also an `Equal T` instance.

2.4.2 *Layers and platforms*

Clients		
Peers	**YOU**	Peers
Host		

A system usually has lots of modules, and when a module's spec changes you need to know who depends on it. To make this easier, put related modules into a *layer*, a single unit that a team or vendor can ship and a client can understand. The layer only exposes chosen interfaces, and a lower layer is not allowed to call a routine in a higher layer. So a layer is a big module, normally a client of its *host*, a single layer below it, with one or more layers as its clients above it. Layers are good for decoupling, but they are not free. Unless you're very careful, there's a significant cost for each level of abstraction. Usually this cost is worth paying, but if performance is important it's prudent to measure it. There are two ways to reduce it: make it cheaper to go from one layer to another, or bypass some layers (making the system a lot more complicated and hard to maintain). The ideas in § 2.4.4 on open systems can also help.

Usually you build a system on a *platform*, a big layer that serves a wider range of clients and comes from a different organization. Common platforms are a browser (the interface is a document object model accessed through JavaScript) or a database system (the interface is SQL), built on an operating system platform (Windows or Linux; the interface is kernel and library calls) built on a hardware platform (Intel x86 or ARM; the interface is the ISA). It's turtles all the way down: the hardware is built on gates and memory cells, which are built on transistors, which are built on electrons . Here is a 2020 example with all the turtles:

Layer	Example
application	Gmail
web framework	Django
database browser	BigTable Chrome
operating system	Windows 10
virtual machine	VMware
ISA	X86
CPU hardware	AMD Ryzen 7 2700X
gates memory	TSMC 7 nm Micron MT40A16G4
transistors	7 nm finFET LPDDR4X-4266
quantum mechanics	electrons

2.4.3 *Components*

Reusing pieces of code is like picking off sentences from other people's stories and trying to make a magazine article. —Bob Frankston[Q17]

It's harder to read code than to write it. —Joel Spolsky[Q51]

A module that is engineered to be reused in several systems is called a *component*. Obviously it's better to find a component that does what you need than to build it yourself (don't reinvent the wheel), but there are some pitfalls:

- You need to *understand* its spec, including its performance.
- You need to be confident that its code actually *satisfies* the spec and will be maintained.
- If it doesn't quite do everything that you want, you have to *fill in the gaps*.
- Your environment must satisfy the *assumptions* the component makes: how it allocates resources, how it handles exceptions, how it's configured, and the interfaces it depends on.

There are two ways to keep from falling into one of these pitfalls:

- Copy and paste the module's code into your system and make whatever changes you find necessary. This is usually the right thing to do for a small component, because it avoids the problems listed above. The drawback is that it's hard to keep up with bug fixes or improvements.
- Stick to the very large components usually called platforms. There will only be a few of them to learn about, they encapsulate a lot of hard engineering work, and they stay around for a long time because they have a viable business model (since it's impractical to write your own).[R39] A well-maintained library can also be a source of safe components.

2.4.4 *Open systems*—Don't hide power. Leave it to the client.

The point of an abstraction is to hide how the code is doing its work, but it shouldn't prevent a client from using all the power of its host. An abstraction can preempt decisions that its clients could make; for example, its way of buffering I/O might keep a device from running at its full bandwidth. If it's an ordinary module, a client can always hack into it, but that's not an option if it's an operating system that isolates its clients, or if you want to keep taking bug fixes. The alternative is careful design that doesn't hide power, but gives clients access to all the underlying performance. The Internet's *UDP protocol* is an example; unlike reliable TCP, it gives clients direct access to the basic unreliable, best-efforts packet delivery, which is critical for real-time applications like voice. *Scheduler activations* are less convenient than threads, but give the client control over scheduling and context switching. *Exokernels* carry this idea further to a *library OS*.

Another way to expose an abstraction's power (and also to make it extensible) is to make it programmable, either by *callbacks* to client-supplied functions or by programs written in an application-specific instruction set. A successful abstraction will have many clients depending on all the details of this interface, so choose it carefully. There are many examples of programmability:

- The SQL query language, a functional instruction set.
- JavaScript embedded in data: webpages, documents, database records, etc.
- Display lists and more elaborate programs for GPUs.
- Programmable network interfaces (NICs); leaving it to the client is very important here.[R32]
- Software-defined networking.
- Patching of binaries, or of code written in other languages.

Binary patching was first done in the Informer, a tool for instrumenting an OS kernel; it checked the proposed machine code patch for safety.[R22] Now there are binary modification tools

2.5 Points of view

A point of view is worth 80 points of IQ —Alan Kay[Q25]

A good way of thinking about a system makes things easier, just as the center-of-mass coordinate system simplifies dynamics problems, or statistical mechanics summarizes the behavior of many particles in a few parameters such as temperature and pressure. It's not that one viewpoint is more correct than another, but that it's more convenient for some purpose. Many of the oppositions reflect this idea. Here are some examples of alternative points of view, discussed in more detail later:

- Being vs. becoming: the state is the variable values (a map), or the actions that made it (a log).
- Iterative vs. recursive: do the same thing, or divide into sub-cases until it's really simple.
- Declarative vs. imperative define a result by its properties or by the steps that achieve it.
- Interpreter vs. compiler: different primitives get you different speed, size, or ease of change.

2.5.1 *Notation*

By relieving the brain of all unnecessary work, a good notation sets it free to concentrate on more advanced problems, and in effect increases the mental power of the race. —A.N. Whitehead[Q58]

Notation is closely related to viewpoint, making something that's important easier to think about. Every system has at least some of its own notation: the datatypes and operations it defines, which are a domain-specific language (DSL) without its own syntax. A notation can also be general-purpose: a programming language like C or Python, or a library like the C++ standard template library. Or it can be for a domain: a DSL like the Unix shell (for sequential string processing) or Julia (for numerical computation), or a library like TensorFlow (for machine learning).

A notation consists of:

- *Vocabulary* for naming relevant objects and actions (`grep`, `awk`, `cat`, etc. for the shell). Generic terms make it easier for people: "sort" for different sorting methods, "tree" for partially ordered or recursive structures. In a spec, the foundation should be mathematics, most often relations.
- *Syntax* for stringing them together (in the shell, "`|`" for pipes, ">" for redirect, etc.). In a DSL, syntax is a way to make common things in the domain easy to write and read. By contrast, a library has to live with the syntax of the language, typically method selection and function call.

3. Goals and Techniques

3.1 Overview

The summary is STEADY by AID with ART: reach goals by using techniques with the process.

3.1.1 *Goals—STEADY*

[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[Q61]

By goals I mean general properties that you want your system to have, not the problem it tries to solve. You probably want your system to be STEADY: **S**imple, **T**imely, **E**fficient, **A**daptable, **D**ependable, and **Y**ummy. Since you can't have all these good things at the same time, you need to decide which goals are most important to you; engineering is about trade-offs.

Simple should always be the leading goal, and abstraction is the best tool for making things simpler, but neither one is a panacea. There's no substitute for getting it right. Three other goals are much more important now than in the 1980s: Timely, Adaptable, and Yummy.

- **Timely** (to market) because cheap computer hardware means that both enterprises and consumers use computer systems in every aspect of daily life, and you can deploy a system as soon as the software is ready. If you can't deliver the system quickly, your competitor can.
- **Adaptable** because the Internet means that a system can go from a few dozen users to a few million in a few weeks. Also, user needs can change quickly, and for many applications it's much more important to be agile than to be correct.
- **Yummy**[Q47] because many systems are built to serve consumers, who are much less willing than organizations to work hard to learn a system, and much more interested in features, fashions and fads. Even for professionals, the web, social media and GitHub mean that it's easy for enthusiasm to build up in defiance of formal procurement processes.

Goals	**Simple**	**Timely**	**Efficient**	**Adaptable**	**Dependable**	**Yummy**
As questions	Is it clean?	Is it ready?	Is it fast?	Can it evolve?	Does it work?	Will it sell?
Alliterative	Frugal	First	Fast	Flexible	Faithful	Fashionable
As nouns	Beauty	Time to market	Economy	Evolution	Fidelity	Elegance

3.1.2 *Techniques*—AI^{n}D

Techniques are the ideas and tools that you use to build a system; knowing about them keeps you from reinventing the wheel. The most important ones are about abstraction and specs; those are principles, not just hints. Most of the rest fall under three major headings:

- **Approximate** rather than exact, perfect or optimal results are almost always good enough, and often much easier and cheaper to achieve. Loose rather than tight specs are more likely to be satisfied, especially when there are failures or changes. Lazy or speculative execution helps to match resources with needs.
- **Incremental** design has many aspects; often they begin with "i". The most important is to build the system out of *i*ndependent, *i*solated parts called modules with *i*nterfaces, that you can put together in different ways. Such parts are easier to get right, evolve and secure, and with *i*ndirection and virtualization you can reuse them in many different environments. *I*terating the design rather than deciding everything up front keeps you from getting too far out of touch with customers, and extensibility makes it easy for the system to evolve.
- **Divide and conquer** is the most important idea, especially in the form of abstractions with clean specs for imposing structure on your system. This is the only way to maintain control when the system gets too big for one person's head, now or later. Other aspects: making your system concurrent to exploit your hardware, redundant to handle failures, and recursive to re-use your work. The incremental techniques are other aspects of divide and conquer.

For each technique, many examples show how it's used and emphasize how widely applicable it is. A small number of ideas show up again and again, often concealed by the fact that people use different words for the same thing. The catalog below is both short and surprisingly complete.

The examples can inspire you when you have a design problem; if you find one that's a good match for an important part of your problem, you can see what techniques it uses and how it uses them. A helpful example might be from a very different application domain than yours. For another source of inspiration, look at these links to important techniques:

Simple: abstraction, action, extensible, interface, predictable, relation, spec.
Efficient: algorithm, batch, cache, concurrent, lazy, local, shard, stream, summarize, translate.
Adaptable: dynamic, index, indirect, scale, virtualize.
Dependable: atomic, consensus, eventual, redundant, replicate, retry.
Incremental: becoming, indirect, interface, recursive, tree.

3.2 Simple

I'm sorry I wrote you such a long letter; I didn't have time to write a short one. —Blaise Pascal[Q42]
Everything should be made as simple as it can be, but not simpler. —Albert Einstein[Q16]
Simple things should be simple, complex things should be possible. —Alan Kay[Q26]

The main thing is to keep the spec simple and to divide the system into modules with simple specs, points that I've already discussed. This section is about keeping the code simple.

3.2.1 *Do one thing well*

Figure out how to solve one really tricky sticky problem and then leave the rest of the system straightforward and boring. I call this the "rocket science" pattern. —Terry Crowley[Q10]

There are some insurmountable opportunities around. —Don Mitchell[Q35]

Work expands so as to fill the time available for its completion. —C. Northcote Parkinson[Q41]

Design your system around a small number of *key* modules with simple specs and predictably good performance. If you're lucky you can get these modules from your platform or from a library. If not, you have to build them yourself, but your goal should be the same. Finding this system design and building the key modules is hard work, but it's rewarded throughout the system's life because you can concentrate on the customers' needs; the rest of the code is easy to change, since it won't need any real cleverness. A successful key module will grow over time, improving performance with better algorithms and adding a few features, but building on a solid foundation. Make it fast rather than general or powerful, because then the client can program the function it wants. Slow, powerful operations force the client who doesn't want the power to pay more for the basic function. Usually it turns out that the powerful operation is not the right one. Well-known examples are CISC vs. RISC instruction sets and guaranteed vs. best-efforts packet delivery.

A wide range of examples illustrate this idea:

- The inode structure in a file system represents variable-length byte strings efficiently, even very large ones. Many variations fit in: variable-length extents (ranges of disk blocks) to keep the index small, sharing parts of the byte string for copy-on-write, logs for crash recovery.
- The Unix version 6 operating system separates file directories from inodes, and uses shell programs to connect applications through byte streams.
- The basic Internet protocols (TCP and UDP) provide reliable and best-efforts communication among billions of nodes.
- The BitBlt interface's simplicity make it the standard for raster display applications.
- The eventually consistent hierarchical name space of DNS is the basis of Internet naming. It maps a path name such as `csail.mit.edu` into a set of small "records".
- Relational databases structure very large amounts of data as tables with named columns.

Often a module that succeeds in doing one thing well becomes more elaborate and does several things. This is okay, as long as it continues to do its original job well. If you extend it too much, though, you'll end up with a mess. Only good judgment can protect you from this.

3.2.2 *Brute force*

Entities should not be multiplied beyond necessity. —William of Occam[Q39]

Computers are fast, and specialized hardware is even faster—take advantage of this. Exhaustive search (perhaps only up to some "depth") is a simple brute force technique. Its cost is $O(n)$, and often n is not too big, so always consider it first. Examples: `grep` over a file, model checking, many optimization problems, and a host of attacks on security measures such as password guessing. It's also the only way to query a database if you don't have an index. It works best when you have locality.

Broadcast is another example of brute force. It is to routing as exhaustive search is to indexing, and likewise scales badly. In networking you often need a broadcast to get started. A third example is *polling* for pending work, instead of notification.

3.3 Timely

Building a timely system (one that ships soon enough to meet your time-to-market needs) means making painful choices to give up features and dependability. If it's extensible you can add features later; adding dependability is harder. It's easier to make approximate software timely.

»The web. Perhaps the biggest reason the web is successful is that it doesn't have to work. The model is that the user will try again, switch to an alternative service, or come back tomorrow. It's quite rare to find a web service that is precise. For example, there's no spec for a search engine, since you can't write code for "deliver links to the 10 web pages that best match the customer's intent", and indeed engines are ruthless about ignoring parts of the Internet in order to deliver results faster.

» Uncoordinated software. A more surprising example comes from a major retail web site, where the software is developed as hundreds of modules. Each module is developed by a small team that has complete control over the specs and code. Any module can call any other module. There is no integration testing or release control. Not surprisingly, it's common that a module fails to deliver expected or timely results; this means that its caller must be programmed defensively. Retail customers may notice that some of the web pages they see are incomplete or wrong—the only page that really must be correct is the one with the "Place Your Order" button. Of course, credit card processing uses precise software.

3.4 Efficient—ABCs. Use theory. Latency vs. bandwidth. S^3: shard, stream or struggle.

An efficient program is an exercise in logical brinksmanship. (paraphrased) —Edsger Dijkstra[Q15]

Efficiency is about doing things fast and cheaply. Most of what I have to say about it is in the ABCs below: **A**lgorithms, **A**pproximate, **B**atch, **C**ache, **C**oncurrent, **C**ommute, **S**hard/**S**tream. Bentley's book says more about these ideas and gives many others.[R8] But first some generalities.

3.4.1 *Before the ABCs*

The greatest performance improvement of all is when a system goes from not-working to working. —John Ousterhout[Q40]

It's tricky to write an efficient program, so don't do it unless you really need the performance. If a shell script is fast enough to solve your problem, by all means use a shell script.[R9] If you do optimize, remember the rule: make the code correct first and then make it fast. It's a good idea to keep the unoptimized code around as an oracle to test the optimized code against.

The resources you are trying to use efficiently are computing, storage, and communication. The dimensions are time and space: how long something takes and how many resources. For time the parameters are *bandwidth* (or throughput) and *latency* (or response time). Latency is the time to do the work (including communication) plus the time spent waiting for resources because of contention (queuing).

A system design needs to consider efficiency as well as simplicity and functionality, even though it shouldn't involve detailed optimization. To evaluate a design idea, start by working out roughly how much latency, bandwidth and storage it consumes to deliver the performance you need. Then ask whether with optimistic assumptions (including plausible optimizations), you can afford that much. If not, that idea is no good; if so, go on to a more detailed analysis of the possible bottlenecks, and of how sensitive the cost is to the parameters of the platform and workload.

If you can divide the work into independent parts, you can use concurrency to trade more resources (more bandwidth) for less latency. With enough parts the only limit to this is the budget, as cloud services for search, email, etc. demonstrate.

Fast path and bottlenecks

There are two basic ways to reduce latency: concurrency and *fast path*—do the common case fast, leaving the rare cases to be slow. For caching, the fast path is a cache hit. *Amdahl's Law* governs the performance of fast path: if the slow path has probability $p \ll 1$, the fast path takes time f, and the slow path takes time $s \gg f$, then the average time is $f + ps$. The *slowdown* from the slow path is $(f + ps)/f = 1 + p(s/f)$. Thus a RAM cache with $p = 1\%$ (99% hits) and $s/f = 100$ (1 ns to cache, 100 ns to RAM) is $2\times$ slower than a hit every time.

Amdahl invented his law to describe the limit on speedup from concurrency. Here the slow path is the part that must be done serially. The *speedup* from the concurrent fast path is $s/(f + ps) = 1/(f/s + p)$. With n-way concurrency $f/s = 1/n$, and for large n this goes to 0 and the speedup is just $1/p$. If $p = 1\%$ (only 1% is serial), the maximum speedup is $100\times$, no matter how much concurrency there is. Whether you think of the result as a speedup or slowdown depends on your expectations.

Almost the opposite of a fast path is a *bottleneck*, the part of the system that consumes the most time. Look for the bottleneck first. Usually you don't need to look any farther; it dominates the performance, and optimizing anything else wastes your time and adds complexity. Once you've found it, find a fast path that alleviates it. In other words, design your code to use it as little as possible, and measure and control how it's used.

Predictable performance

That, Sir, is the good of counting. It brings everything to a certainty, which before floated in the mind indefinitely. —Samuel Johnson[Q23]

What you measure is what you'll get. Period. —Dan Ariely[Q2]

Your guess about where the time is going is probably wrong. Measure before you optimize. If you depend on something unpredictable, measure it in the running system and either adapt to it, or at least report unexpected values so that developers or operations staff can tell what's going on.

It's often not enough for a spec to describe only the state that the program can name. Resources must be part of the state, including real time, and an action must say roughly (perhaps within a factor of two) what resources it consumes, and especially how long it takes. Ideally this won't depend on the environment or on parameters of the action, but often it does and you need to know how in order to use the action effectively. A module can control many aspects of its performance: internal data structures and algorithms, optimization, compression, etc. But the environment controls other aspects: latency and bandwidth to storage, between address spaces and between machines. This can change as the clients' demands or the underlying platform change, and a robust application must either adapt or report that it can't.[R20]

Don't try to be precise; that's too hard. It's enough to know how to avoid disaster, as in paging, where you just need to keep the working set small enough.

Network access is very unpredictable and you can't control it very well, so it's best to work only on local data (which might be stale) when responding to a user input, unless it's very obvious to the user that the network is involved, for example in a web search. This means that the UI should communicate asynchronously with anything that might be slow.

Locality—Keep data small and close

Because communication is expensive and memory hierarchies are deep, keep the data close to the computation. The L1 cache is the closest it can get, but you just need the data close enough that moving it to the computation doesn't slow things down too much. The two main strategies are:

- Keep the parts that run concurrently as independent as possible, to minimize communication.
- Make the data smaller, so that more of it is local and there's *less* to communicate. Try to get by with a summary of the full dataset.

Often it helps to process data in a stream. To interact with a large object, store it so that all the data needed for computing the display is together.

Contention

If there aren't enough resources to process the instantaneous load there will be *contention*, which shows up as *queuing* for access to a resource and increases the latency. It's hard to understand queuing in general, but the simplest case is important and easy: if a resource is busy (utilized) for u seconds per second and tasks arrive randomly, then a task that uses it for a second will take $1 / (1 - u)$ seconds. For example, at $u = 90\%$ it takes 10 seconds—ouch!

The other simple fact about a single queue is Little's Law, $L = \lambda W$: L is the number of requests being processed, λ the throughput or bandwidth (the rate at which requests arrive and depart), and W the latency or response time for a request; all three are averages.One way to avoid contention is to break a resource into lots of pieces and choose one to use at random; if there are many more pieces than clients, contention is unlikely.

3.4.2 *Algorithms*

[In many areas] performance gains due to improvements in algorithms have vastly exceeded even the dramatic performance gains due to increased processor speed. —PCAST[Q44]

Fancy algorithms are slow when N is small, and N is usually small. —Rob Pike[Q45]

There's been a lot of work both on devising algorithms for important problems and on analyzing their performance. The analysis bounds the running time $t(n)$ asymptotically as the problem size n grows: $t(n) = O(n)$ means that there's a constant k such that $t(n) \leq kn$ as $n \to \infty$. Anything worse than $O(n \log n)$ is bad unless n is sure to be small, but this is not the whole story.

– There can be a large fixed overhead (which is bad when n is small), and k can also be large.
– You might care about the average rather than the worst case.

It's usually best to stick to simple algorithms: a hash table for looking up a key, a B-tree for finding all the keys in a range, a DHT for strong fault tolerance. Books on algorithms[R19] tell you a lot more than you need to know. If you have to solve a harder problem from a well-studied domain such as numerical analysis or graph theory, look for a widely-used library. If n is really large (say the Facebook friends graph), look for a randomized *sublinear* algorithm with time $< O(n)$; for example, the median of a large set of size n is very close to that of a random subset of size $\log n$.

3.4.3 *Approximate*—Flaky, springy parts

It is better to have an approximate answer to the right question than an exact answer to the wrong one. —John Tukey[Q54]

Very often you don't need an exact answer; a good enough approximation is fine. This might be "within 5% of the true answer" or "the chance of a wrong answer is less than 1%." If the "chance" in the latter is truly random and the runs are independent, doing it twice makes it .01%. Sometimes the answer is just a guess (a hint), which you need to validate by watching the running system.

You can approximate the *analysis* rather than the solution; this is "back of the envelope" analysis, and usually it's all you need. How to do it: find the few bottleneck operations that account for most of the cost, estimate the cost and the number of times you do each one, multiply and add. For example, for a program that does 10^{10} memory operations, has a cache hit rate of 95%, and runs on a machine with RAM access time of 100 ns, if memory access is the bottleneck it will take about $10^{10} \times .05 \times 100/10^9 = 50$ sec.[R45]

It often pays to *compress* data so that it's cheaper to store or transmit. The most powerful compression produces a *summary* that is much smaller than the input.

- A *sketch* keeps the most important things about the input. Examples: a low resolution version of an image, a vector of hashes that maps similar documents to nearby points[R14].
- A *Bloom filter* is a bit vector that summarizes a set for testing membership. If a value is in the set the filter will say so; if it's not, the filter will wrongly say that it is with some probability f. With 10 filter bits per set element $f < .01$, with 20 filter bits $f < 10^{-4}$.[R49]
- *Sampling* a data set summarizes it with a much smaller set whose properties are good approximations to properties of the original. Often $\log n$ samples from a set of size n are enough.
- A *classifier* tells you some property of the input, for example, whether it's a picture of a kitten.
- A *Merkle tree* lets you prove that an item i is in a set s in $O(\log n)$ time and space.
- *Abstract interpretation* summarizes the dynamic behavior of a program by making it static, replacing each variable with one whose value only depends on where you are in the program.

Approximate behavior

Another kind of approximation works on a program's *behavior* rather than its data.

- A hint is a value that might be what you want, but you need to check that it's valid; see below.

- In *exponential backoff* an autonomous agent responds to an overload signal by decreasing its offered load (rate) by some factor. Examples: ethernet, Internet TCP, Wi-Fi.
- A randomized algorithm gives an answer with probability $p < 1$ of being wrong. If p isn't small enough, repeat n times and the chance of being wrong is p^n, as small as you like.
- Eventual consistency lets applications operate on stale data.
- Agile software development approximates the system spec to get something running quickly for both developers and users to try out. Their reactions guide the evolution of the spec.

Hints

A hint (in the technical sense) is information that bypasses an expensive computation if it's correct; it's cheap to *check* that it's correct, and there's a *backup* path that will work if it's wrong. There are many examples of hints throughout the paper, but here are some general patterns:

- An approximate index points to an item in a large data set that contains a search term, or more generally that satisfies a query. To check the hint, check that the item does satisfy the query.
- A *predictor* uses past history to guess something. A CPU predicts whether a conditional branch will be taken; the check is to wait for the condition, the backup is to undo any state changes.[R24]
- Routing hints tell you how to forward a packet or message. The backup is rerouting.

3.4.4 *Batch*—Take big gulps

Whenever the overhead for processing b items is much less than b times the overhead for a single item, batching items together will make things faster. If the batch cost is s, the cost per batched item is f and the batch size is b, the total cost is $s + fb$ and the cost per item is $f + s/b$. This is just the fast path formula $f + ps$, with $p = 1/b$; bigger batches are like a smaller chance of taking the slow path. Batching increases bandwidth, at the cost of increased latency.

Here are some examples of batching:

- Buffering many items in a stream (characters, lines, records, etc.) in memory. Usually it's much cheaper to get or put an item from the buffer than from the stream.
- A cache with a line size bigger than the size of the data requested by a load instruction.
- Minibatches for deep learning; each minibatch trains a set of weights that fits in the cache.
- Group commit, packing the commit records for many transactions into one log record.
- Indexing, which pays a big cost upfront to build the index so that later queries will be fast.
- Epochs, batching deletions or other changes to reduce syncing, as in read-copy-update[R48].

The opposite of batching is *fragmenting*, artificially breaking up a big chunk of work into smaller pieces. This is good for load-balancing, especially when either the load or the service time is bursty. Fragmenting bounds the variation in latency, and it also reduces head-of-line blocking: small jobs stuck behind big ones. Fragments in a network are called packets.

3.4.5 *Cache*

The idea of caching is to remember the result of a function evaluation $f(x)$. The best-known application is when $f(x)$ is "the contents of RAM location x"; CPUs implement this in hardware. File and database systems do the same in software, keeping disk pages in RAM. Most references will *hit* in the cache if there's enough locality and it's bigger than the *working set* of frequently referenced locations; otherwise the cache will *thrash*.

The software indexes of databases and search engines are equally important; here $f(x)$ is "the table rows or documents matching x". Without an index you have to scan the entire database to evaluate these functions.

If $f(x)$ depends on the state as well as x, then when state changes cause $f(x)$ to change you must tolerate stale cache values, treat a cache hit as a hint and check it, or invalidate or update a cache entry. The last requires that the source of the change either

- sends a *notification* to any cache entries that depend on it, or
- broadcasts every state change, and the cache watches the broadcasts.

For a RAM cache a state change is another processor's write to an address in the cache, and the two techniques are called *directory* and *snooping*.

Here are some other examples of caching a function:

- Network routing tables, which say what link to use to reach a destination address. These are soft state, updated lazily by a routing protocol such as BGP, OSPF, or ethernet switching.
- Shadow page tables in virtual machines, which cache values of the mapping $(guest\ VM, virtual\ address) \to host\ physical\ address$, the composition of $guest\ VA \to guest\ PA$ and $guest\ PA \to host\ PA$.
- Materialized views in a database, which cache the table that's the result of a query.

3.4.6 *Concurrency*—S^3: shard, stream or struggle. Make it atomic.

Now that single-stream general-purpose processors are not getting faster,[R43] there are only three ways to speed up a computation: using fewer instructions or cache misses (by better algorithms or tighter code), specialized hardware, and concurrency. Only the latter is reasonably general-purpose, but it has two major problems:

- It's hard to reason about concurrent computations that make arbitrary state changes, because the concurrent steps can be interleaved in so many ways. Hence the S^3 slogan.
- To run fast, data must be either immutable or local, because when a remote variable changes, getting its current value is costly. Fast computations need P&L: parallelism and locality.

The other reason for concurrency is that part of the computation is slow. Disk accesses, network services, external physical devices, and user interaction take billions of processor cycles. And when the slow part is done it has to get the attention of the fast part, usually by some form of *notification*: interrupt a running thread, wake up a waiting thread, post to a queue that some thread will eventually look at, or run a dispatcher thread that creates a new thread.

Sharding is really easy concurrency that breaks the state into n pieces that change *independently*. A single thread touches only one shard, so the steps of threads that touch different shards don't depend on the interleaving. A *key* determines which shard to use. The simplest example is disk striping: a few bits of the address are the key that chooses the disk to store a given block, and all the disks read or write in parallel. Fancier is a sharded key-value store with ordered keys; $n - 1$ *pivot* values divide the keys into n roughly equal chunks. To look up a key, use the pivot table to find its shard.

Often there's a *combining function* for results from several shards. A simple example is sampling, which just takes the union of a small subset from each shard.

Streaming is the other really easy kind of concurrency: divide the work for a single item into k sequential steps, put one step on each processor, and pass work items along the chain. This scheme generalizes to *dataflow*, where the work flows through a DAG. The number of distinct processing steps limits concurrency. Use batching to reduce the per-item overhead. Map-reduce combines these two techniques, alternating a sharded map phase with a combining reduce phase that also redistributes the data into shards that are good for the next phase. You can reuse the same machines for each phase, or stream the data through a DAG of machines.

Beyond shards and streams—struggle

Do I contradict myself? Very well then I contradict myself, (I am large, I contain multitudes.) —Walt Whitman[Q60]

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

If you can't shard or stream, you will have to struggle. It helps to first show that a general nondeterministic program is correct, and then let performance constrain the choices: scheduling (including timeouts, interleaving, losses), table sizes, etc. If the abstract state is not bulletproof (at least type and memory safe) you'll struggle more.

There are four kinds of concurrency; the first three provide *consistency*, the same result as running the actions sequentially in some order (this isn't the ACID consistency of transactions).

- **Really easy**: pure sharding or streaming. Either actions are *independent*, sharing no state except when you combine shards, or they communicate only by *producer-consumer* buffers.
- **Easy**: make a complex action *atomic* so that it behaves as if the entire action happened sequentially (serially). To do this, group the actions into sets that don't commute (and hence break atomicity if they run concurrently), such as reads and writes of the same variable. Have a *lock* variable to protect each set, with the rules that:
  - Before running an action, a thread must acquire its lock.
  - Two locks in different threads *conflict* if their actions don't commute. For example, writes of the same variable don't commute with reads or other writes.
  - A thread must wait to acquire a lock if another thread holds a conflicting lock.
- **Hard**: anything else. With hard concurrency you can choose: do a formal **proof** or have a **bug**.

- **Eventual**: all updates commute, so you get the same eventual result regardless of the order they are applied, but you have to tolerate stale data. This is easy to code:
  - Make updates commute. The usual case is a blind write $v \coloneqq \mathtt{constant}$ to a variable v. To make two writes to v commute, timestamp them and let the last writer win.
  - Broadcast the updates to all the nodes.

  It's also highly available, since you can always run using only local data. The apps pay the piper: they must deal with stale data. Three of many examples are name services like DNS, key-value stores like Dynamo, and "relaxed consistency" memory[R4].

An important special case of easy concurrency is *epochs*, a batching technique that maintains some invariant on the state except in between epochs. An epoch holds a global lock on certain changes, so that they can only occur when the epoch ends. The code follows these rules by convention; there's no lock variable that's acquired and released. Most often the change that is locked is deleting an object, so that objects won't disappear unexpectedly. Sometimes the global lock prevents *any* changes to certain objects, keeping them immutable during the epoch.

Locks don't work well in a distributed system because they don't play nice with partial failures. Leases can be a workaround. The only meaningful content in an asynchronous message is facts that are *stable*: once they are true, they are true forever. For example, a lease implies "P holds until time t," which is stable. "P holds until Q" might be stable too, but a failure can make Q inaccessible. A fact from an eventually consistent system is stable only if it has been synced.

A good rule of thumb is the *scalable commutativity rule*: if the specs of two actions commute, then it's possible to write code in which they run concurrently, which is important for keeping all the cores busy on modern CPUs. For example, Posix file `open` returns the *smallest* unused file descriptor; if it returned an *arbitrary* unused descriptor, two `open`s could commute.[R16]

3.5 Adaptable

There are many things your system might need to adapt to during its lifetime:

- Changes in the **clients' needs**: new features or data formats, higher bandwidth, lower latency, better availability.
- Changes in the host **platform**: new interfaces or versions, better or worse performance.
- Changes in **regulation** or in security **threats**: privacy or other compliance requirements, data sovereignty, broken cryptography, new malware.
- Changes in **scale**, from 100 clients to 100 million or from storing text to storing video.

Such changes may force major rework, but usually a well-designed system can adapt less painfully. An old rule of thumb says that a $10\times$ change in scale requires a new design, but the Internet and the web are striking counterexamples.

The keys to adapting to functional changes are modularity and extension points in the design. The keys to adapting to scaling are modularity, automation, and concurrency.

Interface changes can be incompatible: unless the client and service specs change at the same time, there's a mismatch. This is okay if the new service spec is a superset of the old one. Ethernet, the Internet, many ISAs, some programming languages, and basic HTML have done this, and 40-year-old clients still work. The alternative is indirection: an *adapter* or *shim* that satisfies the old spec and is a client of the new one. When the new one is dramatically different this is *virtualization*.

3.5.1 *Scaling*

Expanding on the catchwords above, scaling requires:

- Modularity for algorithms, so it's easy to change to one that scales better.
- Automating everything, both fault tolerance and operations, so that a human never touches just one machine (except to replace it if the hardware fails).
- Concurrency that scales with the load by sharding: different shards are independent because they don't share variables or resources: all communication is asynchronous.

The independent shards sometimes have to come back together. There are two aspects to this:

- Combining the independent outputs or synchronizing the shard states.
- Naming the shards, using big random numbers (which must be indexed) or path names.

If the shards already exist, use federation to put them into a single name space by making a new root with all of them as children.

- In a file system this is called *mounting*, and the shards stay independent.
- In a source code control system the shards are *branches* and synchronization is *merging*.

3.5.2 *Inflection points*—Seize the moment. Ride the curve.

History never repeats itself, but it rhymes. —John Robert Colombo[Q8]

Why do great new technologies often fail? They are great when compared with the current incarnation of the boring old technology, but during the 3 to 5 years that it takes to ship the new thing, the old one improves enough that it's no longer worthwhile to switch. This typically happens with new hardware storage technologies, such as thin film memories and optical disks.

The reverse happens when a new idea has some fundamental advantage that couldn't be fully exploited in yesterday's world, but conditions have changed so that it now pays off:

- Packets replaced circuits for communication when the computing needed to do the switching got cheap enough, and bandwidth got cheap enough for bursty data traffic to overwhelm voice.
- Ted Nelson invented the web in the 1960s (he called it hypertext), but it didn't catch on until the 1990s, when the Internet got big enough to make it worthwhile to build web pages.

3.6 Dependable

The price of reliability is the pursuit of the utmost simplicity. It is a price which the very rich find most hard to pay. —Tony Hoare[Q21]

A system is dependable if it is:

- **Reliable**—it gives the right answers in spite of partial failures and doesn't lose data.
- **Available**—it delivers answers promptly in spite of partial failures.
- **Secure**—it's reliable and available in spite of malicious adversaries.

The secret of reliability and availability is fault tolerance by *redundancy*: doing things independently enough times that at least one succeeds. Redundancy can be in time or in space.

- Redundancy in **time** is *retry* or *redo*: doing the same thing again. You have to detect the need for a retry, deal with any partial state changes, make sure the inputs are still available, and avoid confusion if more than one try succeeds. The main design tool is end-to-end validation.
- Redundancy in **space** is *replication*: doing the same thing in several places. The challenges are giving all the places the same input and making the computation deterministic so that the outputs agree. The main tool is *consensus*.

It's very important for the redundancy to mostly use the *same* code as the normal case, since that code is tested and exercised much more, and hence has many fewer bugs. And of course redundancy won't do any good if a deterministic bug (a *Bohrbug*) caused the failure. On the other hand, many bugs are infrequent nondeterministic *Heisenbugs*, usually caused by concurrency.[R28]

Redundancy by itself is not enough; you also need *repair*. If one of two redundant copies fails the system continues to run, but it's no longer fault-tolerant. Similarly, if a component is failing half the time and a single retry costs three times as much as a success, the operation takes six times as long as it should.

The idea of redundancy is to have no *single points of failure*. This means a distributed system, which inherently is concurrent and has *partial failures*. Hence there are many more rare states, which is why a distributed system is harder to get right than a centralized one, in which many errors just reset the whole system to a known state. A Bohrbug is also a single point of failure, unless the redundancy includes different code.

»Arpanet partitioning. On December 12, 1986, New England was cut off from the Arpanet for half a day. The map showed that there were seven connections to the rest of the network, but it didn't show that all seven of them went through the same fiber-optic cable between Newark and White Plains.[R31] In theory carriers can now guarantee that two connections share no physical structure.

»Cellphone disconnected. I tried to call a friend at the Microsoft campus on his office phone. It didn't work because it was a VOIP phone and his building's Internet connection was down. So I tried his cellphone, and that didn't work either because his building had a local cell base station, which used the building's Internet to connect to the carrier and was too stupid to shut itself off when it could no longer connect.

3.6.1 *Correctness*

The best way to get your code to be correct is to keep it simple, and the best way to do that is to structure your system so that the most critical parts of the spec depend only on a small, well-isolated part of the code. This is the *trusted computing base* (TCB), invented to keep computer systems secure but applicable much more broadly. It's a good idea, but there are some difficulties:

- Keeping the TCB isolated from bad behavior in the rest of the system.
- Keeping the "most critical" parts of the spec from growing to be all of it (mission creep).
- Maintaining the structure as spec and code change.

The single best tool for making a TCB is the *end-to-end* principle;[R59] its underlying idea is that the client is in control. Specifically, if the client can easily *check* whether an answer is correct and has a *backup* procedure, then the code that *generates* the answer isn't in the TCB, and indeed doesn't need to be reliable at all. To use this idea you need a check for failure; if you're just sending a message this is a strong checksum of the contents, and a timeout in case the message never arrives. The checksum also works for storage.

You probably don't want to give up if the check fails, so you need the backup; end-to-end says that this decision is up to the client, not the abstraction. You need to undo any visible state change caused by the failure,. After that, if the failure is nondeterministic retrying is a good backup. The canonical example is TCP, which makes the flaky best-efforts packet service of the raw Internet into a reliable congestion-controlled byte stream. Other possibilities are trying something more expensive, especially if it was a hint that failed, or running in a degraded mode such as eventual consistency (with or without notice to the client). There may be no backup; encryption, for example, can't prevent a denial of service attack, though it can guarantee secrecy and integrity.

Fault tolerance means that the code doesn't run sequentially, because it can be redirected at any point by a fault. Instead you should think of it as a collection of atomic actions, each one enabled by some predicate on the state that is not just "PC = x," much like a concurrent program. In fact, a fault tolerant program *is* a concurrent program, in which you don't have much control over the concurrency. An example is a crash-tolerant file system, where every chunk of code that ends with a write to the disk is an atomic action, after which recovery might run instead of the next sequential action.

3.6.2 *Retry—Do it again*

If you can tell whether something worked, and after it fails there's a good chance that it will work better the second time, then retry is the redundancy you want. This applies especially to networking, where often you don't have good control of the communication, and even if you do it's much cheaper to tolerate some errors. Retry is based on the end-to-end principle, and in most applications you expect it to succeed eventually unless the network is partitioned or the party you are talking to has failed. Retry is a form of slow path: success on the first try is the fast path, with cost f, and if p is the chance of failure and r is the cost for one retry (the time it takes to detect a failure—usually a timeout—and try again), the cost of the slow path is $s = r(1 + p + p^2 + \cdots) = r/(1 - p)$. As usual, the slowdown caused by retries is $1 + p(s/f)$. For example, if a retry costs $10 \times$ a success ($r = 10f$), then you need $p \ll 10\%$ to make the slowdown from retries small.

If p is too big (perhaps because the chance of corrupting a message bit is too great), you can make it smaller with forward error correction (an error-correcting code). Or make r smaller by fragmenting: breaking the work into smaller chunks that fail and retry independently.

A retry that succeeds is supposed to yield the same final state as a single try (as long as there are no concurrent actions that don't commute with this one); this is *idempotence*. Some actions are intrinsically idempotent, notably a *blind write* of the form $x \coloneqq$ constant. To make an arbitrary action such as $x \coloneqq x + 1$ idempotent, make it *testable*: give it a unique ID, remember the ID of a completed action (often as the version of a variable), and discard any redundant retries. In communication this is discarding duplicate messages at the receiver; it's called *at-most-once* messaging. The reason that the payment pages of online commerce often say “don’t hit the back button and retry” is that they do this wrong.

Another form of retry is redo recovery from a log after a crash. If every pair of actions a and b in the log either commute ($a; b = b; a$) or absorb ($a; b = b$), then redoing prefixes of the log repeatedly (which happens if there are crashes during recovery), followed by redoing the whole log, is equivalent to redoing the whole log once. This is *log idempotence*. A blind write absorbs an earlier write to x and commutes with a write to any other variable. A testable action absorbs itself.

3.6.3 *Replication*—Make copies

The simplest kind of replication is several copies of the bits that represent the state, but it’s very tricky to make this work when there are failures because you can’t update all the copies atomically. The most powerful kind of replication is a log that records the sequence of operations that produced the current state. With this and a checkpoint of some past state, you can reconstruct the current state by redoing the operations. There are many variations on this idea.

The strongest variation provides uninterrupted service even when there are failures. It is a *replicated state machine* (RSM), a way to do a fully general fault-tolerant computation using the ideas of being and becoming. You make several replicas of the host, all running the same code, start them in the same state, and feed them the same sequence of deterministic commands, either in real time or from a log. Then they will produce the same outputs and end up in the same state. Any of the outputs will do as the output of the RSM, or the replicas can vote if there are at least three of them and a minority might be Byzantine.

Of course there are some complications:

- The replicas must all see the same sequence: they must all agree about the first command, the second command, etc. The *Paxos* algorithm for distributed asynchronous consensus does this; it guarantees that replicas will never disagree about commands, and it makes progress as long as a suitable quorum of replicas can communicate for long enough. a retry is forced to
- The commands must be deterministic; this requires some care.
- To restore a failed replica, you can redo the whole sequence of commands from scratch, or copy the state of some other replica and redo recent commands.

Reads must go through the RSM as well, which is expensive. To avoid this cost, use the reliable communication channel called real time. One replica takes out a time-limited lock called a *lease* on part of the state through the RSM; this stops anyone else from changing that state. Drawbacks are that the leaseholder can be a bottleneck, and if it fails everyone must wait for the lease to expire unless you can reliably detect the failure.

The usual way to do replication is as *primary-backup*: one replica is the primary, chosen by the RSM, and it has a lease on the whole state so that it can do fast reads and batch many writes into one RSM command. The backups see all the writes because of the RSM, and they update their state to be ready in case the primary fails. The RSM needs three replicas, but they only need to store the commands; only two have to store the entire state.

Replication can make things faster as well as fault tolerant, since you can read from any replica that you know is up to date, such as a cache. This only helps if there are a lot more reads than writes from different writers, since a replicated write costs more.

»Ariane 5. The first flight of the European Space Agency's Ariane 5 rocket self-destructed because both inertial reference system computers failed. The computers shut down because of an uncaught exception from an overflow. Shutdown seemed reasonable to engineers familiar with random hardware failures rather than software Bohrbugs.[R10] Lesson: independence is tricky.

3.6.4 *Detecting failures: real time*

Real time is not just for leases. It's the only way to detect that a service is not merely slow but has failed—it hasn't responded for too long. (Another way is for the service to tell you about it, but it might be wrong or dead.) How to decide how long is too long? Choose a timeout, and when it expires either retry or declare a failure and run recovery; in both cases report the problem. For a client device the report goes to the human user, who can decide to keep trying or give up. For a service it ultimately goes to the operations staff.

How do you choose a timeout? If it's too short there will be unnecessary retries, failovers or whatever. If it's too long the overall system latency will be too long. If the service reports the progress it's making, that might help you to choose well. This story applies to a *fail-stop* system, which either satisfies its spec or does nothing. After a *Byzantine* failure the system might do anything. These are trickier to handle, and out of scope here.

3.6.5 *Recovery and repair*

It's common to describe availability by counting nines: 5 nines is 99.999% available, which is five minutes of downtime per year. A good approximation is $MTTR/MTTF$, mean time to repair over mean time to failure (how long the system runs before it fails to serve its clients promptly enough). When part of a fault-tolerant system fails, $MTTR$ is the time to fail over to a redundant component, not the time to fix the failing part. In a well-engineered system failover is less than the specified response time, so the *system* doesn't fail at all; this is why it's important to make failover fast. Repair is also important.

»Memory errors. At Xerox Parc in 1971 we built a medium-sized computer called Maxc, using the new Intel 1103 1024-bit dynamic RAM chip. We didn't really know whether this chip worked, but with single bit error correction we never *saw* any failures in the running system. So we used the same chips in the Alto, but we decided to just have parity. Everything was fine until we ran the first serious application, the Bravo full-screen editor, and we started to get parity errors. Why? It turned out that 1103's are pattern-sensitive. Although Maxc hardware reported a corrected error, there was no software to read the reports, and there were quite a few of them. Lesson: Measure failures and do repairs.

We got the problem under control using a random memory test program. Two years later we built the Alto 2, using 4k RAM chips and error correction. The machine seemed to work flawlessly, but after another two years we found that in one quarter of the memory neither error correction nor parity worked at all, because of a design error. Why did it take us two years to notice? The 4k chips were much better than 1103's, and most bits in RAM don't matter much. This is why consumer PCs don't have parity: chips are pretty reliable, parity adds cost, and parity errors make the PC manufacturer look bad, but if random things happen Microsoft gets blamed. Lesson: Different parties may have different interests.

3.6.6 *Transactions*—Make it atomic

In bacon and eggs, the chicken is involved, the pig is committed. —Anonymous

If a complex action is atomic (either happens or doesn't), it's much easier to reason about. The slogan for this is ACID: Atomic, Consistent, Isolated, Durable.

- Atomic: Redo recovery makes it atomic with respect to *crashes*: after a crash either the whole action has happened, or none of it.
- Consistent: If each transaction leaves the system in a good state when running sequentially, then the whole system does so in spite of concurrency or failures. In addition, the transaction can decide to *abort* before committing, which undoes any state changes and so makes it atomic with respect to its *own* work. So it only needs to leave the system in a good state (consistent) if it commits.
- Isolated: The locks of easy concurrency make it atomic with respect to *concurrent* actions.
- Durable: A committed transaction writes its changes to persistent storage, usually in several copies, so that they survive anything short of a truly catastrophic failure.

Transaction processing systems ensure all these properties by draconian control over the transaction's application code.

Atomic transactions don't scale across organizations, because they can force you to hold locks until another agent's work is done, and usually an organization won't give up that much control.

»Pixie dust. Transaction processing systems are the pixie dust of computing. They take an application that understands nothing about fault tolerance, concurrency, undo, storage or load-balancing, and magically make it atomic, abortable, immune to crashes, and easy to distribute across a cluster of machines.

3.6.7 *Security*

But who will watch the watchers? She'll begin with them and buy their silence. —Juvenal[Q24]
If you want security, you must be prepared for inconvenience. —Gen. Benjamin Chidlaw[Q7]

Computer security is hard because of the conflict between *isolation* and *sharing*. People don't want outsiders to mess with their computing, but they do want to share data, programs and resources. In the early days isolation was physical and there was no sharing except by reading paper tape, punch cards or magtape. Today there's a lot more valuable stuff in your computers, and the Internet enables sharing with people all over the world. The job of security is to say "No," and people like to hear "Yes," so naturally they weaken the security until they actually get into trouble.

Here are the most important things to do for security (which all add inconvenience):

- **Focus**: figure out what you really need to protect.
- **Lower aspirations**: secure only things so important that you'll tolerate the inconvenience.
- **Isolation**: sanitize outside stuff to keep it from hurting you, or don't share dangerous stuff.
- **Whitelisting**: decide what you do trust, rather than blacklisting what you don't.

There are basically two approaches to security: *high assurance* and fixing bugs. The former tries to build a that is simple enough to be formally verified or thoroughly tested. This has proved easier to say than to do; the closest approximations that are widely deployed are hypervisors.

Everyone practices the latter for want of anything better, but decades of experience tell you that there are always more bugs. Defense in depth can help.

It's traditional to describe the goals of security as *confidentiality* (secrecy), *integrity* and *availability*; the acronym is CIA. Integrity means that only authorized agents can change the state. In practice, systems that keep track of money or other critical data do use authorization, but they rely on detecting and undoing bad changes, rather than always preventing them, because even authorized agents sometimes make mistakes or do bad things; this is an example of the end-to-end principle, and the data is only eventually consistent. If you can't undo something, such as a wire to Russia, you must be much more careful in allowing it. Long-lived systems have levels of undo, ending with bankruptcy court.

The mechanisms of security are *isolation* and the gold standard of *authentication* (who is making a request), *authorization* (who can access a resource), and *auditing* (what happened). A decentralized system also has to establish *trust*, which you do by indirection: you come to trust someone by asking someone else that you already trust. Thus to answer questions like, "What is the public key for `billg@microsoft.com`," you trust a statement from `microsoft.com` that says, "The public key for `billg@microsoft.com` is K."[R40]

What are the points of failure? For security they are called a *threat model*, especially important because there are so many possible attacks (hardware, operating system, browser, insiders, phishing, …) and because security is fractal: there's always a more subtle attack. For example, how do you know that your adversary hasn't hacked the BIOS on your PC, or installed a Trojan Horse in the hardware?[R73] So you need to be very clear about what you are defending against and what you are not worrying about. The TCB is the dual of the threat model; it's just what you need to defend against the threats. The end-to-end principle makes the TCB smaller: encryption can make a secure channel between the two ends, so that the stuff in the middle is not a threat to secrecy or integrity.

Code for security is often tricky; don't roll your own. For secure channels, use TLS. For parsing text input to complex modules like SQL or the shell, use standard libraries to block SQL injection and similar attacks. Similarly for encrypting data; it's easy to make mistakes in coding crypto algorithms, managing keys, and blocking side channels.

» Outrunning a bear. Two hunters run into a grizzly bear in the woods. One says, "We'd better run!" The other objects, "You can't outrun a grizzly." The first replies, "But I only need to outrun *you*." Lesson: Be a harder target than someone else who's just as rich.

3.7 Yummy

The Mac is the first personal computer good enough to be criticized. —Alan Kay[Q27]

A system is much easier to sell if it's yummy, that is, if customers are enthusiastic about it. There are some good examples:

- Apple makes consumer products that people love to use, sacrificing functionality for completeness, coherence and elegance. The Macintosh, the iPod and the iPhone are well known.
- Amazon's mission statement is, "To be Earth's most customer-centric company," and they approach a project by "working backwards": first write the press release, then the FAQ.[R71]

- People use and love the web as soon as they see it. Writing for it is less yummy, though.
- Spreadsheets are loved (especially by accountants and list-makers); VisiCalc is what made PCs take off.
- Porsches, Corvettes and Teslas are yummy.

By contrast, Microsoft Word, and the Honda Accord are good products, but not yummy. Linux is yummy for developers, but not for users.

So what—is it important for your system to be yummy? If it's a consumer product it certainly helps a lot, and it might be crucial. For an enterprise product, staying power is more important. Clearly there's a lot of noise, but to cheaply boost your chances of making a yummy system, Amazon's approach is best. Much more expensive, but even better, is to study the users deeply. This is much easier if the designers are also users; this isn't always possible, but when it is the resulting system is much more likely to succeed. Unix, Bravo and the Internet are obvious examples.

3.7.1 *User interfaces*

And the users exclaimed with a snarl and a taunt, "It's just what we asked for but not what we want." —Anonymous[Q63]

People think that good user interfaces are all about dialog boxes, animations, pretty colors and so forth. Two things are much more important:

- The *user model* of the system: is there a way for the user to think about what the system is doing that makes sense, is faithful to what it actually does, and is easy to remember?
- *Completeness and coherence* of the interface: can the user see clearly how to get their whole job done, rather than just some piece of it? Are there generic operations like copy and paste that tell the user what operations are possible? Do the parts look and feel like a coherent design?

User models and coherence are hard because it's hard to find out what the users really need. You can't just ask them, because they are paid to *do* their jobs, not to *explain* them—no user would have asked for the iPhone. The only way is to watch them at their work or play for a long time. A much cheaper substitute is to make up scenarios or use cases, but it's hard to ensure that they are both common and complete.

Here are some examples of good user models:

- Files and folders on the desktop.
- The web, with links that you click on to navigate.
- Web search, which pretty often finds what you're looking for.
- Spreadsheets, which can do complex calculations without any notion of successive steps.

And here are some less good examples:

- Microsoft Word, with styles, sections, pages, and other things interacting confusingly.
- The user interface to security—there's no intelligible story about what's going on.
- System administration, where the sound idea that the user should describe the desired state by a few parameters is badly compromised by poor engineering of the components.

»Bravo and Gypsy. The most successful application on the Alto was the Bravo editor, the first What You See Is What You Get editor. When Charles Simonyi and I designed it, we made a deliberate decision not to work seriously on the user interface, because we knew it was hard and we didn't have the resources to both build an editing engine and invent a new UI. Larry Tesler and Tim Mott came along with their Gypsy system for the book editors at Ginn. Their first step was to spend several weeks watching their customers at their daily work. They completely replaced our UI, and they invented modeless commands and copy/paste, the basis of all modern UIs.[R67]

3.8 Incremental

There are three aspects to incremental:

- *small* steps—otherwise it wouldn't be incremental,
- *useful* steps—you make some progress each time, and
- steps *proportionate* to the size of the change—you don't have to start over.

Incremental steps are easier than big steps to understand, easier to get right, less disruptive, and more likely to be useful building blocks. But it's important to start with a good idea; Alan Kay says, "It's hard to tinker a great sculpture from malleable clay just by debugging."[Q28]

Increments can be qualitative or quantitative. Qualitative ones are being and becoming, indirection, subclassing, path names and many other techniques. Quantitative ones add elements:

- Nodes to the Internet or a LAN (and you don't even have to take it down).
- Peripherals to a computer.
- Applications to an OS installation or extensions to a browser.

3.8.1 *Being and becoming*

This is an opposition: being is a **map** that tells you the values of the variables, becoming a **log** of the actions that got you here. Some examples:

- A bitmap can represent an image directly, but a "display list" of drawing commands can produce the image; this generalizes to an arbitrary program, as in PostScript.
- A log-structured file system uses the log to store the data bytes, with an index just like the one in an ordinary file system except that the leaf nodes are in the log, which is enough to reconstruct the index. Amazon's Aurora pushes this to a limit.
- Checkpoints and deltas can compress a long sequence of states, such as the frames of a video or successive versions of a file. The checkpoints are a few complete states (called key frames for MPEG videos), and the deltas are actions that take one state to the next.
- Becoming lets you do time travel, since you can recover any previous state by replaying the log. Checkpoints make this faster.
- The standard way to recover from failures in a data storage system is to apply a redo log that produces the current state from a persistent state that reflects only some prefix of the actions.
- A more general approach to fault tolerance uses a replicated state machine, which applies the same log to several identical copies of the state.

How do you find the value of a variable v (that is, construct a bit of the map) from the log? Read the log backward, asking for each logged action u how it relates to the action r that reads v. If u is a blind write $m(v') \coloneqq x$ then either u and r commute (if $v \neq v'$) or u determines that $v = x$ and you don't need to look farther back in the log. Other kinds of u need ad hoc treatment.»Bravo undo. How do you undo some actions to get back to a previous version v? Simply replay the log up through the last action that made v. We did this in Bravo, logging the user commands, although our original motivation was not undo but reproducing bugs, so the replay command was called `BravoBug`. I've never understood why later systems didn't copy this; perhaps they didn't want to admit that they had bugs.[R42]

Optimizations

There are many variations on these ideas. To keep a log from growing indefinitely you can take a *checkpoint*, which is a map as of some point in the log. You can *share* parts that don't change among multiple versions; a copy-on-write file system does this, as does a library for immutable data like `immutablejs`.

There's a common idea behind these optimizations: deconstruct the map, moving it closer to a log, by putting it together out of independent parts. The base case that the hardware provides is a fixed-size finite array of bytes in RAM, pages on disk or whatever; here the variables are integers called addresses A. Call this a store $S: A_S \to V$ and represent it abstractly by a hierarchical structure $S = A_S \to \big(V \textbf{ or } (T, A_T)\big)$, where A_T is an address in a lower level store T. Each level takes an address and either produces the desired value or returns a lower level store and address. Index blocks in file systems are an obvious example, but often you can think of this as a way to compress or index a log of updates, as in log structured memory or copy on write file systems.

To efficiently build a store S on top of lower-level stores T_1, T_2, ..., build an index from (ranges of) S addresses $[a_S, a_S + \Delta]$ to pairs $\left(T_i, a_{T_i}\right)$; each entry in this index is a *piece*. A write changes the index for the range of addresses being written (fig. 2a). There are many data structures that can hold the index: a sorted array, a hash table, a balanced tree of some kind.

Since the T_i are stores themselves, this idea works recursively. And the indexes can be partial overlays, with a sequence of stores $S_n, S_{n-1}, \ldots S_0$; if a is undefined in $S_n, \ldots, S_i$ then you look in S_{i-1}. Several successive writes can appear explicitly or you can collapse them to a single level (fig. 2b, with just S_2 and S_0, like CPU write buffers), or all the way to an index that maps every address (fig. 2c, like a copy-on-write file system).

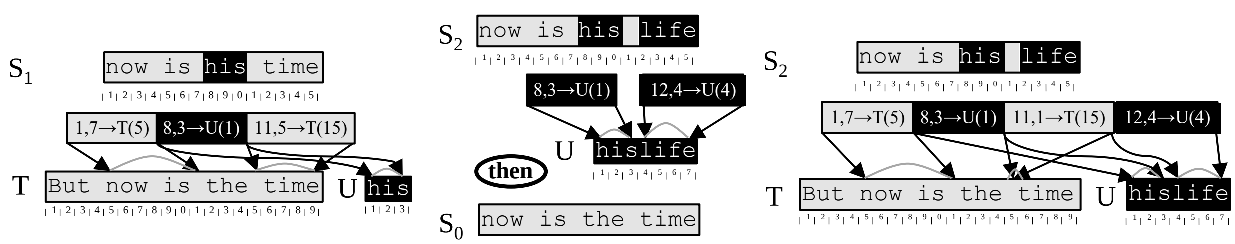

Fig. 2a: Writing "his" in place

Fig. 2b: A single discontinuous write

Fig. 2c: Back to a full index for S_2

Amazon Aurora applies many of these techniques to a cloud database, separating storage completely from the database code. It treats the redo records that contain database writes as the truth; when the database reads a page, storage reconstructs it from the redo records. If there are many of them, it takes a checkpoint just for that page. This drastically reduces write bandwidth.[R70]

3.8.2 *Indirection*—Take a detour, see the world.

Indirection is in opposition to inlining, but there are many other examples, often having to do with binding a client resource less tightly to the code or objects that implement it. Indirection replaces the direct connection between a variable and its value, $v \to x$, with an indirect connection or link, $v \to u \to x$. This means that you go through u to get to the object, and u can do all kinds of things. It can *multiplex* x onto some bigger object or *federate* it with y so that its own identity becomes invisible. It can *encapsulate* x, giving it a different interface to make it more portable or more secure. It can *virtualize* x, giving it properties its creators never dreamt of. It can *interpose* between v and x to instrument the connection. It can act as a *name* for x, decoupling x from its clients and making it easy to switch v to a different x.

Multiplexing divides up a resource into parts. The classic example is dividing a communication channel into subchannels, either statically by time, frequency, or code division multiplexing, or dynamically by packet switching. An OS multiplexes files onto a disk or processes onto a CPU. Routing does this repeatedly; Internet packets, email messages and web page requests all go through several indirections.

Federation is almost the opposite, combining several resources into a single one: several disks into one volume, several filesystems into a bigger one by mounting, a sea of networks into the Internet. Load-balancing federates servers: each client sees a single resource, but there are many clients and the balancer spreads the load across many servers.

Encapsulation isolates a resource from its host, as a *secure enclave* that keeps the resource safe from the host or a *sandbox* that keeps the host safe from an app.

Virtualization converts a "physical" host resource into a "logical" guest one that is less limited (virtual memory much bigger than physical memory, missing instructions trapped and done in software) and easier to move (virtual machines not bound to hardware). It can also change the interface, for example with a different ISA on the guest so you can run old programs (*emulation*) or for portability, as with the Java Virtual Machine (JVM). An interpreter can run the guest ISA by executing instructions of the host, or a compiler can translate guest programs to the host ISA either statically, or dynamically using JIT. Other examples: virtual hard disks, overlay networks, the C library. An adapter can handle a smaller interface change.

Interposing splices more or less arbitrary code between a client and a service, often to log audit records or to collect information about performance. It's easy to do this for a class, but it's always possible by patching, even at the level of machine instructions. Proxies and content distribution networks such as Akamai do this on a larger scale to distribute load and improve locality.

Naming decouples a service such as Twitter from the physical machines that implement it. Such a service uses several levels of indirection: DNS maps `twitter.com` to an IP address, and the Internet delivers packets with that address to a machine. You can name a *group*: a style in a word processor names a group of character or paragraph properties, decoupling the markup from the appearance, and a mailing list, security group or role names a group of people, decoupling the structure of an organization from the current membership. An index makes name lookup or search cheaper. Indirection makes it easier to have *aliasing*: several different v's that map to the same x.

Certificates use indirection to establish trust.

4. Process

The most important single aspect of software development is to be clear about what you are trying to build. —Bjarne Stroustrup[Q52]

Systems resemble the organizations that produce them (paraphrased). —Melvin Conway[Q9]

If you can't be a good example, then you'll just have to be a horrible warning. —Catherine Aird[Q1]

SOFTWARE IS HARD. … Good software … requires a longer attention span than other intellectual tasks. —Donald Knuth[Q29]

The summary is STEADY by AID with ART: **A**rchitecture, **A**utomation, **R**eview, **T**echniques, and **T**esting are the essentials of process. I don't have much personal experience with this. But I have watched a lot of systems being developed, with teams that range in size from six to several thousand people. If you find yourself working on a team that breaks the rules in this section, look for another job.

You can build a small system with willpower: one person keeps the whole design in their head and controls all the changes. You can even do without a spec. But a system that's bigger (or lives for a long time) needs process. Otherwise it's broken code and broken schedules. Process means:

- Architecture: Design that really gets done, and documented so that everyone can learn it.
- Automation: Code analysis tools (very cheap for the errors they can catch) and build tools.
- Review: Design review—manual, but a much cheaper way to catch errors than testing.
- Review: Code review—manual, but still cheaper than testing.
- Testing: Unit and component tests; stress and performance tests; end-to-end scenarios.[R11]

None of this will help, though, if the goal is badly conceived. If your system isn't going to be yummy, it had better at least be useful. If it's entering a crowded field, it needs to be a *lot* better than the market leaders. If there's a strong ecosystem of languages and applications in place, build on it rather than fighting it. And usually simplicity is key: if your system does one thing well, it's easier to sell and easier to build. If it's successful it will expand later. Some well- known examples:

- Dropbox just syncs a subtree of the file system.
- The C language stays as close to the machine as possible.
- The original HTML gives you links, text with simple formatting, and bitmap images.
- Twitter gives you short tweets that can go to millions of followers.

The symbiotic relationship between a platform and its applications can take one of two forms:

- **Controlled**: The platform only accepts applications that fit its self-image, with the goal of coherence and predictability for the whole ecosystem. Apple does it this way.

- **Wild and free**: The platform accepts anything, and it's up to the market to provide whatever coherence there is. Windows does it this way. Android is in the middle.

Successful systems last, and you want your system to succeed, right? You don't get to rewrite it from scratch; that's not compatible with agile development and shipping frequently. And the shipping code reflects lots of hard-won knowledge, much of which isn't written down and has slipped out of the team's heads (or the team has changed). This is why it pays to think through the initial design, and to put as much code as possible into modules with clean interfaces, especially performance-critical code. It also pays to clean up messy code when you need to change it; IDE tools can help. If the system is too slow, first measure and then work on the few modules need to be fast and predictable. Your system doesn't have that structure? Then you have incurred *technical debt*.[R44] The solution is to change it until it does; those changes are expensive, but they have enduring value. Then keep it that way. And keep shipping.[R63]

»Intel Itanium. When Intel made a big bet on a VLIW (Very Long Instruction Word) design for its 64 bit Itanium architecture to replace the x86, the performance predictions were apparently based on a single hand-coded inner loop, 30 instructions long, since they didn't have the optimizing compiler working.[R18] Most real programs turned out to be much less amenable. Usually chip designs are based on extensive simulation of real workloads.

5. Oppositions

Finally, here is a brief discussion of each opposition. These are not alternatives but extremes; the text explores the range of possibilities between the extremes. The brackets refer to relevant goals.

Simple ↔ rich, fine ↔ features, general ↔ specialized [S Y]

—KISS: Keep It Simple, Stupid. Do one thing well. Don't generalize.

—Don't hide power. Leave it to the client. Make it fast. Use brute force.

If in doubt, leave it out. —Anonymous

The cost of adding a feature isn't just the time it takes to code it, [it's the] obstacle to future expansion. ... Pick the features that don't fight each other. —John Carmack[Q6]

Systems are complicated because it's hard work to make them simple, and because people want them to do many different things. You can read a lot about software bloat, the proliferation of features in browsers and in rich applications like Word and Excel. But almost every feature has hundreds of thousands of users at least. The tension between keeping things simple and doing a lot is real, and there is no single right answer, especially for applications that interact with users.

Still, it's best to add features and generality slowly, because:

- You're assuming that you know the customers' long-term needs, and you're probably wrong. It's hard enough to learn and meet their immediate needs.
- It takes time to get it right, but once it's shipped legacy customers make it hard to change.
- More features mean more to test, and more for a bad guy to attack.

So why do systems get overambitious? Because there are no clear boundaries,[Q5] as there are with bridges for example, and programmers are creative and eager to tackle the next challenge.

But features that have a lot in common can add power without adding too much complexity; the best design is a single mechanism that takes different parameters for the different features. So a search engine can index many different data types, a webpage can include text, images and video, or an email program can keep a calendar. A user interface feature that just invokes a sequence of existing features is less dangerous because it only complicates the UI, not the rest of the system.

For software whose clients are other programs, the solution is building programs on components. A single component should do one thing, and its code should do it well and predictably so that clients can confidently treat it as a primitive building block; beware of components that don't have these properties. Building one of these components is a lot of work. It's worth doing if the component is critical for your system, or if it's part of a platform like an operating system, a browser or a library where it will have lots of clients.

Even better is a complete set of such components, with both the functionality and the performance you need to write programs for a significant application domain. Then a client can do a lot without writing much code and without much cleverness. Some examples:

- key-value stores;
- Unix shell programming on top of primitives like `diff`, `sort`, `grep`;
- graphics on top of BitBlt, spline curves, and compositing;
- mathematics systems like Mathematica and Julia.

This takes both lots of work and deep insight into the application domain, but the payoff is big.

Perfect ↔ adequate, exact ↔ tolerant [S T D] —Good enough. Flaky, springy parts.

Worse is better. —Richard Gabriel[Q18]
The best is the enemy of the good. —Voltaire[Q56]

This is not about whether there is a precise spec, but about how close the answer needs to be to an ideal result. "Close" can take different forms: a tolerance or a probability of being right, results that may just be wrong in some difficult cases, or a system that behaves well as long as its environment does. Some examples:

Tolerance or probability:

- Available 99.5% of the time (down no more than one hour per week), rather than 100%.
- Response time less than 200 ms with 99% probability, rather than always.
- A 98% hit rate in the cache on the Spec benchmark, rather than 100%.

Such properties usually come as statistics derived from measuring a running system, or from a randomized algorithm.

Wrong in difficult cases:

- Words are hyphenated if they appear in a hyphenation dictionary, rather than always.

- Internet packets are discardedwhen there’s too much congestion.
- Changes to DNS may not appear immediately (because it uses eventual consistency).
- A database system may fail, but it recovers without losing any committed work.

Friendly environment:

Every system at least depends on its host to execute its instructions correctly, but often the system can be simpler or cheaper by assuming more about its environment:

- Data is not lost as long as the power doesn’t fail.
- Your files are available if you have a connection to the Internet.
- Faces are recognized reliably if the lighting is good enough.

The environment is not just the host you depend on; it’s also your clients. If they are not too demanding, your system may be adequate even if it doesn’t satisfy an ideal spec.

Spec ↔ code [P S]

—Keep secrets. Good fences make good neighbors. Free the implementer.
—Embrace nondeterminism. Abstractions leak.

Don’t tie the hands of the implementer. —Martin Rinard[Q46]
Writing is nature’s way of letting you know how sloppy your thinking is. —Richard Guindon[Q19]

A spec tells you *what* a system is supposed to do, and the code tells you *how*. Both are described by actions; how do they differ? A spec constrains the visible behavior of the system by saying what behaviors (sequences of steps) are acceptable or required. A spec is not a program, and the right language for writing it is either English (if the design ideas are still too vague to be expressed precisely) or mathematics.

The code is executable, but it still may not be a program you can run; it may be an algorithm such as Quicksort or Paxos, described in pseudocode that abstracts from the details of how the machine represents and acts on data. Pseudocode can have a precise definition and a toolchain.[R37]

Imperative ↔ functional ↔ declarative [S E] —Make it atomic. Use math. Say what you *want*.

The many styles of programming can be grouped into three broad classes: imperative, functional and declarative.

An imperative program (for example, one written in Java or C) has a sequence of steps and a program counter, as well as named variables that the program can read or write. Interesting programs take lots of steps thanks to loops or recursion. Most computing hardware is imperative.

A functional program (perhaps written in the functional subset of Haskell) has function calls instead of steps, and immutable values bound to function parameters or returned from the calls instead of state variables. Interesting programs have recursive functions, so they can make lots of calls. Real languages aren’t purely functional because small changes to big values are too expensive, but you can embed immutable data structures in an imperative language, and a library like `immutablejs` can make this efficient. The most widely used programming languages are functional: spreadsheets and database query systems. However, they are special-purpose.

The literature doesn't say what a declarative program is, but I think it's a program with few steps; people are not very good at understanding long sequences of steps. Often it's also easier to optimize, since it doesn't commit to the sequence of steps the machine should take. Powerful primitives help to make a program declarative; for example, code to compute a transitive closure has lots of steps, but a transitive closure primitive is a single easy step. The SQL query language for relational databases has many such primitives, as does HTML as an abstract description of a desired webpage.

Precise ↔ approximate software [T D] —Get it right. Make it cool. Shipping is a feature.[Q38]

Unless in communicating with [a computer] one says exactly what one means, trouble is bound to result. —Alan Turing[Q55]

It is better to be vaguely right than precisely wrong. —Leonard Lodish[Q32]

Broadly speaking, there are two kinds of software, precise and approximate, with the contrasting goals "Get it right" and "Get it soon and make it cool."

Precise software has a specification (even if it's not written down very precisely), and the customer is unhappy if the software doesn't satisfy its spec. Obviously software for controlling airplanes or nuclear reactors is precise, but so are word processors, spreadsheets, software for handling money, and the Internet packet protocol. The spec might be nondeterministic (the Internet might drop packets), partial (Excel should evaluate its formulas correctly) or opaque (Word should generate the same paragraph numbers today that it did 10 years ago), but that doesn't make it imprecise.

Approximate software, on the other hand, has a very loose spec, or none at all; the slogan is "Good enough." Web search, retail shopping, face recognition, and social media are approximate.

Approximate software is not better or worse than precise, but they are very different, and it's important to know which kind you are writing. If you wrongly think it's precise, you'll do extra work that the customers won't value and it will take too long. If you wrongly think it's approximate, the customers will be angry when code doesn't satisfy the (unwritten) spec they counted on.

Dynamic ↔ static [E A] —Stay loose. Pin it down. Shed load. Split resources.

A computer is infinitely flexible, but a program is not; both what it does (the spec) and how (the code) are more specialized. Yet the code can be more or less able to adapt to changes in itself or in the environment. Flexibility costs because you have to check more things at runtime, but it can save if the checks let you skip some work. Code that takes advantage of things that stay constant is more efficient if they really are constant, and static checking automatically proves theorems about your code before you ship it. To some extent you can have both with *just-in-time* (JIT): make a static system based on the current code and environment, and remake it if there are changes.

There are (at least) four aspects of this opposition: interpret vs. compile, indirect vs. inline, scalable vs. fixed, and online vs. preplanned resource allocation.

Compiling commits the code to running on a host that is usually closer to the hardware. The compiler chooses how data is represented, and often it infers properties of the code (example: at this point $v = 3$ always) and uses them to optimize. It may do *trace scheduling*, using information from past runs or heuristics to predict code properties (in this JavaScript program, i is usually an integer).[R26] These predictions must be treated as hints and checked at runtime, with fallback to slower code when they are wrong. Together with JIT, trace scheduling can adapt a very general program to run efficiently in common cases.

A different aspect of the dynamic-static opposition is resource allocation, and scheduling in particular. CPUs and operating systems can allocate resources online to a sequence of tasks that's not known in advance (using caches, branch prediction, asynchronous concurrency, etc.), but if you know the sequence you can do this work just once. Examples: resources reserved for a real-time application, and a *systolic* array in which work items pass through a sequence of processors with no queuing.[R35] Storage allocation is similar; static allocation (splitting up the storage) is cheaper if you know the sizes in advance or can guess them well. And when it fails, it's much easier to figure out why.

Indirect ↔ inline [E I] —Take a detour, see the world. Use what you know.

Any problem in computing can be solved by another level of indirection. —David Wheeler[Q57]

Indirection is a special case of abstraction that replaces the direct connection between a variable and its value, $v \to x$, with an *indirect* connection $v \to u \to x$, often called a *link*; the idea is that ordinary lookups to find the value of v don't see u, so that clients of v don't see the indirection. You can change the value of v by changing u, without changing x. Often u is some sort of service, for example the code of a function, reached indirectly by jumping to the code for the function; this gives the most flexibility, since you can run arbitrary code in the service. The link doesn't have to be explicit; it could be an *overlay* that maps only some of the possible v's, like a TLB or a cache.

Inlining replaces a variable v with its value x. This saves the cost of looking up v, and the code can exploit knowing x. For example, if $x = 3$ then $x + 1 = 4$; this saves an addition at runtime. If v is a function you can inline its code, avoiding the control transfer and argument passing, and now you can specialize to this particular argument. But inlining takes more space and makes it hard to change the function's code.

Lazy ↔ eager ↔ speculative [E] —Put it off. Take a flyer.

When you come to a fork in the road, take it. —Fort Gibson New Era[Q62]

The common theme is to improve efficiency by reordering work. The base case is *eager* execution, which does work just when the sequential flow of the program demands it; this is the simplest to program. **Lazy** execution *defers* work until it must be done to produce an output, gambling that it will never be needed. It can pay off in lower latency because it first does the work that produces output, and in less work if a result turns out not to be needed at all.

Indirection is lazy as well as dynamic—if you never need the value of the name, you never pay the cost of following the link. Other examples of laziness are write buffers, which defer writes from a cache to its backing store; redo logging, which replays the log only after a crash; eventual consistency, which applies updates lazily and in an arbitrary order until there's a need for a consistent result.

More generally, it's lazy to represent a function by code rather than as a set of ordered pairs. Of course if the set is infinite then code is the only option. Pushing this idea farther, to defer the execution of some code, wrap it in a function and don't invoke it until the result is needed.

Speculative execution does work *in advance*, gambling that it will be useful. This makes sense if you have resources that are otherwise idle, or to reduce latency in the future. Prediction is the most common form of speculation, for example when a storage system prefetches data from memory to cache, or when a CPU predicts which way a branch instruction will go. Caching speculates that an entry will be used before it has to be replaced. Exponential backoff in networks and optimistic concurrency control in databases speculate that there will be little contention.

Usually laziness or speculation keeps the program's results unchanged. This is simplest if the parts being reordered commute. They do in a functional program, but code with side effects may not. Sometimes you settle for sloppy results, for example with eventual consistency.

Centralized ↔ distributed, share ↔ copy [E D] —Do it again. Make copies. Reach consensus.

A distributed system is one in which the failure of a computer you didn't even know existed can render your own computer unusable. —Leslie Lamport[Q31]

If you have a choice, it's better to be centralized. Distributed systems are more complicated because they have inherent concurrency and partial failures, and they have to pay for communication. But they are essential for serious fault tolerance, and for scaling beyond what you can get in a single box. A distributed system needs fault tolerance because it has to deal with *partial failures*; you don't want to crash the whole system when one part fails. But even a very large system can be centrally managed (in a fault-tolerant way) because management doesn't require that much computing or data; this is how big cloud systems like AWS and Azure work.

Fixed ↔ evolving, monolithic ↔ extensible [A I]

—The only constant is change. Make it extensible. Flaky, springy parts.

No matter how far down the wrong road you have gone, turn back now. —Turkish proverb

Always design your program as a member of a whole family of programs, including those that are likely to succeed it. —Edsger Dijkstra[Q13]

It's cheaper to replace software than to change it. —Phil Neches[Q37]

Often the customer's needs are unclear, and successful systems live for a long time, during which needs change. Just thinking hard is usually not enough to make unclear needs clear, because you aren't smart enough and don't know enough about the customer. It's better to follow the agile model: build a prototype, try it out, improve it.[R25]

A successful system must do more—it must adapt and evolve, because needs change as people see ways to make it do more, as the number of users grows, as the underlying technology changes, and as it works with other systems that perhaps didn't even exist originally. Evolution requires modularity, so that you can change parts of the system without having to rebuild it completely. Interfaces allow clients and code to evolve independently. These are aspects of divide and conquer.

Evolution is easier with *extensibility*, a well-defined way to add certain kinds of functionality. This is a special form of modularity, and it needs a lot of care to keep from exposing secrets of the code that you might want to change. Examples:

- You can add new tags to HTML, even complicated ones, and old code will just ignore them.
- Most operating systems can incorporate any number of I/O drivers that know about the details of a particular scanner, printer, disk, or network.
- Inheritance in programming languages like Smalltalk and Python makes it convenient (if dangerous) to add functionality to an existing abstraction.

Another way to extend a component is to let the client pass in a (suitably constrained) program as an argument; for example, a search engine can take a parser for an unfamiliar format. You can do this without pre-planning by patching, but it's tricky to maintain all the code's invariants.

Policy ↔ mechanism [A] —Change your mind.

When the facts change, I change my mind. What do you do, sir? —Paul Samuelson[Q48]

The mechanism is what the system *can* do, determined by its specs and code, and the policy is what the system *should* do: the control system for the mechanism. Policy is different for each installation and typically changes much faster than the code. Administrators, rather than engineers, set policy, and they think of it as part of the spec. It should give them as much control over the mechanism as possible.

The most elaborate example of the distinction is in security, where the mechanism is access control and the policy is what principals should have access to what resources. Other examples: policy establishes quotas, says how much replication there should be, or decides what software updates should be applied. Policy is an aspect of system configuration, which also includes the hardware and software elements that make up the system and the way they are interconnected. Historically all these things were managed by hand, but cloud computing has forced automation.

Consistent ↔ available ↔ partition-tolerant [D] —Safety first. Always ready. Good enough.

If you want a system to be *consistent* (that is, all the parts of it see the same state; not the same as ACID consistency) and highly *available* (very unlikely to fail, because it's replicated in different places), then the replicas need to communicate. But if the replicas are *partitioned* then they can't communicate. So you can't have all three; this is the CAP "theorem". The way to get around it in practice is to make partitioning very unlikely. A partial mitigation is *leases*, which are locks that time out, using the passage of real time for uninterruptible communication.

Generate ↔ check [D] —Trust but verify.

A problem is in complexity class NP if finding a solution is hard (takes work $O(2^n)$), but checking it is easy (work $O(n^k)$). In code most checks are in an `assert`—the code has done something complicated, and the check confirms that it hasn't gone too far off the rails. But other examples are closer to the NP paradigm, such as randomized algorithms or proof-carrying code. The general idea, however, is much broader: keep a hint that might be wrong, but is easy to check. This is a narrower meaning of "hints" than in the title of this paper. The end-to-end principle is closely related.

Being ↔ becoming [I] —How did we get here? Don't copy, share.

There are two ways to represent the state of a system:

- *Being*: the values of the variables—a *map* $v \to x$
- *Becoming*: a sequence of actions that gets the state to where it is—a *log* of actions.

Different operations are efficient in different representations. If you're only interested in a single point in time, you want the map. If you care about several different versions (to recover the current state from a checkpoint, undo some actions, or merge several versions), you want the log. There are ways to convert one representation into the other, and points between the extremes: applying the actions gets you the values, a `diff` produces a *delta* (a sequence of actions that gets you from one state to another), *checkpoints* shorten the log. Ordinary programs use being; fault-tolerant programs use both. More on this in § 3.8.1.

Iterative ↔ recursive, array ↔ tree [I] — Keep doing it. A part is like the whole.

To iterate is human, to recurse divine. —Peter Deutsch[Q11]

The basic principle of recursive design is to make the parts have the same power as the whole. —Bob Barton[Q3]

Iteration and recursion are both Turing-complete. You can write an iteration recursively using tail-recursion (which is easy: the last step in the loop is the only recursive call), and you can write a recursion iteratively using a data structure to simulate a call stack (which is a pain).But iteration is more natural when there's a list or array of unstructured items to process, and recursion is more natural when the items have subparts, especially when the parts can be as general as the whole.

Thus recursion is what you want to process a tree or a graph where the description of the structure is itself recursive. You don't need recursion to treat a sequence of different items differently, though, because you can make them into objects that carry their own methods. Here are examples that illustrate both points:

- A hierarchical file system can have different code at each directory node. Some nodes can be local, others on the Internet, yet others the result of a search: `bwl/docs/?author=smith`.[R27]
- Internet routing is hierarchical, using BGP at the top level, other protocols locally in an AS.

These examples also show how a *path name* (a sequence of simple names) identifies a path in a graph with labeled edges and provides decentralized naming. Just as any tree node can be the root of an entire subtree, a path name can grow longer without conflicting with any other names.

6. Conclusion

I don't know how to sum up this paper briefly, but here are the most important points:

- Keep it simple. Complexity kills.
- Write a spec. At least, write down the abstract state.
- Build with modules, parts of the system that people can work on independently
- Exploit the ABCs of efficiency: algorithms, approximate, batch, cache, concurrency.
- Treat the state as both being and becoming: map vs. log, pieces, checkpoints, indexes.
- Use eventual consistency to keep data available locally.

In addition to the papers I've referenced, there are some good books about building systems: Lamport[R36,R37] and Ousterhout[R53] on how to write specs, Hennessy and Patterson[R30] on hardware architecture, Cormen, Leiserson, Rivest and Stein[R19] on algorithms, Bentley[R8] on efficiency, Hellerstein, Stonebraker and Hamilton[R29] on databases, Tanenbaum and Wetherall[R66] on networking, and Anderson[R6] and Schneier[R60] on security.

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Quotations

I've tried to find attributions for all the quotations; some were unexpected, and it's disappointing that some of the best ones lack citations and may even be apocryphal. References of the form [Author99] are to PDF files that might not be at any link I've given; you'll find them here.

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Q14. Edsger Dijkstra, The humble programmer, *Comm. ACM* **15**, 10, Oct. 1972, pp 859-866; p 864, col 2. Link

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Q17. Bob Frankston, in Martha Baer, Immortal code, *Wired*, February 1, 2003. Link [Wired03; p 3, ¶ 2]

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is about three a day.' BOSWELL. 'How your statement lessens the idea.' JOHNSON. 'That, Sir, is the good of counting. It brings every thing to a certainty, which before floated in the mind indefinitely.' BOSWELL. 'But Omne ignotum pro magnifico est: one is sorry to have this diminished.' JOHNSON. 'Sir, you should not allow yourself to be delighted with errour.' BOSWELL. 'Three a day seem but few.' JOHNSON. 'Nay, Sir, he who entertains three a day, does very liberally.'" [Boswell1783]

Q24. Juvenal, Satire 6, ll 346-348. "Quis custodiet ipsos custodes? Qui nunc lasciuae furta puellae hac mercede silent." Link

Q25. Alan Kay, quoted by Andy Hertzfeld in *Creative Think*, 1982. This is the best citation I could find, but surely it's much older. The original words: "Point of view is worth 80 IQ points." Link [Hertzfeld82; p 3, slogan 4]

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Q33. Somerset Maugham, quoted without citation in Ralph Daigh, *Maybe You Should Write a Book*, Prentice-Hall, 1977, p 7. Link [Daigh77, p 9]

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Q35. Don Mitchell, Brainstorming—Its application to creative advertising, *Proc. 13th Annual Advertising and Sales Promotion Executive Conference*, Ohio State University, October 26, 1956, p 19. Misattributed to Walt Kelly in the form, "We are faced with an insurmountable opportunity." Link

Q36. Joni Mitchell, Both sides now, on *Clouds*, Reprise Records, May 1969. Link [Mitchell67]

Q37. Phil Neches, who told me in August 2019 that he did say this, but didn't know where it was published. I have not been able to find a citation either. I saw it in a list of four such quotes attributed to Neches, which I now can't find either. The others are: "It's cheaper to process, store, or communicate than to display," "It's cheaper to be networked than standalone," and "Public transactions are cheaper than anonymous ones, because of accountability."

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Q42. Blaise Pascal, *Lettres provinciales*, letter 16, 1657. « Je n'ai fait celle-ci plus longue que parce que je n'ai pas eu le loisir de la faire plus courte. » Misattributed to Mark Twain. Link for the history. Link for the original.

Q43. Henri Poincaré, *Science et Méthode*, Flammarion, 1908, p 29 (ch. 2, L'avenir des Mathématiques). The context is: «… la mathématique est l'art de donner le même nom à des choses différentes. Il convient que ces choses, différentes par la matière, soient semblables par la forme, qu'elles puissent pour ainsi dire se couler dans le même moule. Quand le langage a été bien choisi, on est tout étonné de voir que toutes les démonstrations, faites pour un objet connu, s'appliquent immédiatement à beaucoup d'objets nouveaux ; on n'a rien à y changer, pas même les mots, puisque les noms sont devenus les mêmes. » Translation by Maitland: "… mathematics is the art of giving the same name to different things. It is enough that these things, though differing in matter, should be similar in form, to permit of their being, so to speak, run in the same mold. When language has been well chosen, one is astonished to find that all demonstrations made for a known object apply immediately to many new objects: nothing requires to be changed, not even the terms, since the names have become the same." Link [Poincaré1908; p 16, ¶ 2; p 47, ¶ 2; p 62, ¶ 1]

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Q50. Seward, *Biographiana*, footnote to entry for Abbé Marolles. Apparently there is no direct citation. Link, Link [Seward1799]

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Q55. Alan Turing, Lecture on the automatic computing engine, Feb 20, 1947, in *The Essential Turing*, Oxford, 2004, p 392. Link. [Turing47; p 12]

Q56. Voltaire, 'La Bégueule', *Contes*, 1772, l 2. Link. « Dans ses écrit un sage Italien / Dit que le mieux est l'ennemi du bien. » He credits the Italian proverb in *Dictionnaire philosophique*, 1764, Art dramatique, Du récitatif de Lulli. Link. For the Italian, see Pescetti, *Proverbi Italiani*, 1603, p 30: "Il meglio è nemico del bene." Link

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Q63. From "'Twas the night before release date," in many places on the Internet.

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