How to Make User Interfaces More Accessible and Easier to Use for People who Are Different from Us: Breaking the Spell of the Curse of Knowledge

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Abstract: When we are young most things are reasonably easy to use and we rarely think much about them — we just get on and do things. As we get older, though, what used to be simple things become harder and harder. Since people who are successful designers tend to be younger (and certainly not so old that things are getting difficult to use!), they may unintentionally make things harder for older people. They also unintentionally make things harder for busy people, such as nurses, firefighters and others with demanding jobs that leave less cognitive resources for dealing with poor design. This article gives some examples, and makes suggestions so we can recognize, avoid and fix or mitigate the problems.

"**True ignorance is not the absence of knowledge, but the refusal to acquire it**." Karl Popper

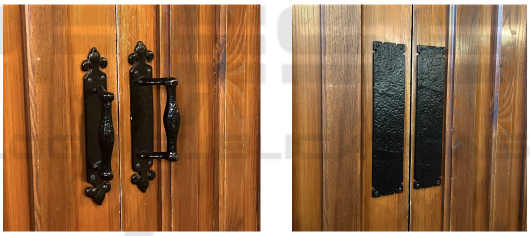
1 INTRODUCTION

I was in a church meeting and somebody got up, went to the door, but the door was stuck, so she came back and sat down. A few minutes later, somebody else got up, pushed the door and walked out.

This is a standard story of doors. The door's handles had the affordance to pull (figure 1.a), so the first person pulled the door, but it wouldn't open. The second person completely ignored the door handles, and just pushed the door directly. It opened.

The first person did not know which way the door opened, and they were stuck because the door handle was designed for pulling but the door did not open that way. The second person already knew how the door worked, and they didn't even bother trying to use the handles.

- A little knowledge makes things easier to use. In this case, if you know the door is a 'push door' then the door is very easy to open *for you*. If you don't know this (that is, being deceived by the door handle's affordance to pull) makes the door impossible *for you* to open.
- The learning point is this: a little knowledge makes it very hard to design things for other people. The person who designed the door or who put the door handles on the door *knew* how the door worked. So the door was easy to use as far as they were concerned — their knowledge of the obvious way the door worked made them ignore the issue of door handle affordance. Yet if they had done some user studies (or had previously learned about affordance so they had a word to talk about what they knew) they would have (re)designed the door much better.
- In general, then, our knowledge biases our opinions about accessibility, usability, safety, and effectiveness. If we are not very careful, the more we know the worse designers or developers we become. Sadly, it even becomes easy to dismiss



a *b*

Figure 1: Door handles, (*a*) seen as triggering a poor user experience, where a user got stuck trying to pull the door (which doesn't work), and (*b*) as seen after my fixing them with flat plates, where the doors can now only be pushed (when they open).

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users' problems as faults of their own making.

This basic door handle story illustrates a lot about the problems of building usable, accessible, and dependable (safe and reliable) interactive systems. Doors are, as things go, very simple interactive systems. We used the door problem as an example to start this paper, because it makes clear important design points without being distracted by any of the power, fancy features and exciting innovation of fancy digital systems.

Our examples throughout this article will make similar points by highlighting details of the ubiquitous problematic design issues in digital systems. You will note that none of the examples we discuss have nice design names or concepts like 'affordance.' Inevitably, designers fail to talk or think about problems they cannot name, and hence the problems get little attention. Worse, when there are principles and names like 'accessibility' skilled designers may not realize why these things are so important — their own experience of accessibility is different from their users and it is hard to recognize and give these ideas proper weight and attention.

2 THE CURSE OF KNOWLEDGE

Steven Pinker used the *curse of knowledge* to explain why many people's writing is very often unnecessarily hard to understand.

When you are writing (for instance, like me writing this article) you know what you mean, and you type or write down a sentence. The sentence makes sense *because you already know what it means*!

However, for anyone else *before* they know what you are trying to say, they have to read your writing. They have to parse your sentences into their structures of meaning. If there is any ambiguity in how any sentence is structured, understanding it becomes very difficult. If the structure of the sentence lends itself to multiple meanings, the reader can't work out the meaning until *after* they have parsed it and read it successfully. But they can't parse it reliably until they know what it means. Bad writing creates a mess for the reader.

Here's a simple example to illustrate the point:

"Let's eat Grandma!"

The person who wrote this knows Grandma has cooked a meal, and the children are telling Grandma they want to start eating the meal now. The sentence makes perfect sense. But without that knowledge, which isn't in the sentence itself, somebody new to the sentence might think it is a said by ghastly children who want to eat their Grandma. Other people don't know what the sentence means, because they can see both meanings.

The problem can be solved in various ways, like writing "Let's eat, Grandma!" or better, "Grandma! Let's eat!" — but thinking of ways to fix the sentence misses Pinker's point. The person writing the sentence knows what they mean, so they don't think the awkward sentence needs improving. They are not short of solutions (like commas) *if they realize they need solutions*. The problem is they think the sentence is clear, so that's the end of their thinking.

If you are bored with the familiar Grandma example, how about a news headline I read in January this year:

Amber snow warning across country

I thought this was a warning we were going to have amber snow (perhaps colored with dust blown in from the Sahara?), but on reading the article below the headline it became clear that the UK has yellow, amber and red *warnings* for bad weather.

Once you know that bit of knowledge, the headline is easy to parse as intended by the writer. The curse of knowledge for the headline writer is they knew they meant an amber warning, so when they read "amber snow warning" they couldn't see it could mean anything else.

Since not everyone has the curse of knowledge in this specialist area of weather warnings, a better news headline would have been "Amber warning for snow across country!" or, better I think, "Warning for snow across country!" (that's for people who don't know what amber warnings are).

The curse of knowledge is that the person who writes a sentence knows what it means, so they only see that meaning, but in truth sentences often have two or more meanings. The reader doesn't know which, so may choose the wrong meaning, or they will be slowed down until they've made a decision on what it means.

Exactly the same happens in user interface design — which is a lot more complicated than writing and parsing natural language (English in the Grandma and snow examples). The curse of knowledge, then, is that the designer knows what everything means and does, so it is *obvious* how to use and understand their design. They then accidentally under-estimate the difficulties users may have, even, and often, to the extent of not bothering with user trials because the user interface is so obvious to them it doesn't need testing.

The curse of knowledge explains the problems with doors. The person who originally screwed the door handles on knew how the door worked. The person I watched confidently going through the door knew how the door worked. The person who got stuck hadn't been in thrall to the curse of knowledge. Anyone with the curse of knowledge knows how to 'parse' the door.

The curse of knowledge explains one of my own writing habits. I sit down and write an article like this one, and I usually focus on the writing. Writing is hard, and I am pleased I can concentrate and get it done. But when I am writing, I can easily remember what I mean so I am unavoidably susceptible to the curse of knowledge. What I do, then, is do something else for a week or so, *then* read my article with a view to making it clearer. When I read and edit a week later, I hope I have forgotten lots of the minor bits of knowledge that made my writing seem simpler than it was when I first wrote it. Now, rereading a week or so later, I find lots of details to improve because now they aren't even clear to me!

We should do the same when building systems. Build and debug them. Then try and use them next week or next month, and fix the confusing or weak features. Effectively, we become another person and do user centered design a little better.

The curse of knowledge explains the next example in this article. In the example the On key causes confusion for a user, but the designer *knows* what On does, so — for the designer — it's obvious that pressing On twice is counter-productive. Since the designer knows what it does, and from that point of view it is so simple, why bother testing it? Why would anyone press On twice? The designer, cursed by knowing what On does, thinks it's so easy it doesn't even merit a test, so they never find out that it does need some serious user centered design . . .

3 BREAKING THE CURSE

The curse of knowledge is not knowing, in some way that you do not have the same knowledge or skills as the user. You don't realize you know something the user doesn't; or, conversely, you don't realize you *don't* know something the user does know (whether the user can articulate that or not). User centered design, UCD, helps sort out knowing things you should know, but it doesn't sort out the serious curse of knowledge: knowing or assuming things the user does not know.

Here are some important solutions:

- Involve users in design
- Diversity in the design team
- Experiment with prototypes — use iterative design cycles
- Use mathematics to help you think more clearly
- **Deliberately** work out how to extend this list for your application.

Figure 2: A Sony TV remote control, with 48 buttons including a confusing on button.

4 SIMPLE TELEVISIONS?

Televisions are established, mass-market devices, so we would expect them to be reasonably well designed and easy to use.

My father tried to turn on his new Sony TV using his remote control (figure 2). Nothing happened, so he pressed the On button again. Still nothing happened. He told me it never worked and he was very frustrated.

I could understand his problem. Pressing On turns the TV on, but the TV doesn't appear to be on for a few seconds, so Dad pressed the On button again to make sure.

Unfortunately, On isn't an On button as such but an On/Off button (but it doesn't say so). Pressing On when the TV is already on (as it was) makes it turn *off*.

The obvious solution to me was to buy a simplified remote control, as widely advertised for elderly people.

Figure 3 shows an example. Note that the ON on the simplified remote control really says ON — I had simplified a bit when I talked about the original remote control, as it actually used a green technical symbol, ⏻, rather than the self-explanatory word ON that the simplified remote more helpfully uses.

When you get one, the new remote control of course doesn't know how to operate your TV since it is a generic remote control, so you first have to train it from your existing remote control. This is a very complex process — a TV remote control uses infra red signals to control the TV, so you have to point the two remote controls at each other and press corresponding buttons to train the new remote control what the TV's infra red commands are. There is absolutely no feedback whether you are being successful.

An interesting side-effect of having to train each buttons is that you can decide *not* to train the little

Figure 3: The Doro simplified remote control. Compare with figure 2.

Figure 4: Apple's different "few buttons" philosophy is a contrast to Sony's "one button for each function" philosophy (see figure 2).

AV button. On my father's TV this would normally have meant "change the audiovisual (AV) input" — for instance to watch a DVD rather than a TV program — but he had no other AV sources, so having a button to change sources would have created another problem. So I left it not doing anything at all.

When you've finished, you have (hopefully) a trained remote control that can control your TV, and with far fewer buttons it must surely be easier to use?

In fact, it is worse!

You now have a remote control with two nice large buttons labelled ON and OFF. Each button uses the correct infra red signal learned from the old remote control that has a single On button. So what you have done is train the new buttons to do the *same* thing — now ON and OFF *both* switch the TV on *and* off! Pressing the button ON will now turn the TV on, then off, then on … and so on. The TV is now even more confusing!

Apple have a different approach. Instead of a remote control with lots of buttons (including some you never use), it has a smaller remote control with six buttons and a small trackpad (figure 4). Interestingly, explaining *why* this remote control is better and more usable is quite hard to explain. However, what is much harder to explain is how a different corporate culture leads one company to put effort into making user interfaces simpler, rather than taking the easy route Sony took of providing one button for each function they can think of. Sony's approach just makes the remote control more and more complex — but is no challenge to the designers. Apple's, in contrast, clearly required not just some thought but some determination to make a simpler user interface.

The lesson is, what is easier to design is not necessarily easier to use. Just because designers find something easy does not mean users will find it easy.

Let us imagine a TV manufacturer going through a standard design process: defining tasks, personas and scenarios, then prototyping, evaluation and iterative design — much as the standard ISO 9241-110 Principles of the Human-Centered Approach recommends. Such a process explores the design space, raises basic questions, and follows a cycle of evaluation-improvement until the design performs well.

Thinking like this: we need to be able to turn the TV on. So the remote control needs an On button. Do some evaluations. And then the crucial insight from such user-centered design would be that the On button should *always* turn the TV on.

It seems plausible that Sony designers are so used to how their On button works on their own TVs they never bothered to put their design ideas through a design process involving a representative sample of real users and tasks. They never asked the design questions that Apple evidently did. Put crudely, they probably thought their TV was simple, so it did not require — and did not get — much design effort. The result was a TV that was completely unusable for some people, such as my "impatient" father.

5 PROBLEMS EVERYWHERE

An old man's problems with a TV user interface might seem like a niggle. But if this problem was fixed, it would improve everyone's user experience.

TVs (and remote controls) have been made for years, so the use case we described above is not news — it's something that could have been fixed on the second TV ever made, if anyone did user studies. Modern TVs are actually computers and keep upgrading their software all the time. Continual user evaluations could (if the manufacturers wished) ensure that TVs continue to improve and become easier and more pleasurable for everyone.

For example, instead of just updating the software, the TV could tell you — "Did you know you never use this feature X, so in case you find it helpful, we've put it on your home screen, but you can delete it if you don't want to use it." (Or whatever.) The end result is a more usable TV, whether or not the user wants this feature.

More worryingly, such 'simple' user interface problems are everywhere, and even 'trivial' ones — like the On button confusion — can cause serious harm, such as patient fatalities in hospitals. *No user interface problem is trivial.*

In hospitals, the user is typically a nurse. They won't be old, with cognitive decline, but they will be very busy doing a complex task: the cognitive resources they have available to manage a confusing user interface are limited — and far more limited than the technically-savvy developer sitting in their com-

Figure 5: A BBraun Infusomat simulation, set up for start of the interaction sequences shown in figures 6 and 7. ('VTBI' means volume to be infused).

fortable laboratory with a powerful PC designing cute devices for nurses to use. The developer (unless they try very hard) has *no idea* what it is like to be a busy, hard-pressed user of their products.

Here is one example of the sorts of unnecessary usability problems that arise. The BBraun Infusomat is a very popular infusion pump. A nurse will select infusion details for giving a patient a drug, perhaps so-many milliliters of a drug over so-many hours. Although figure 5 is a picture of the Infusomat, in reality it will probably be one of many infusion pumps connected to the same patient — part of the design problem is which pump delivers which drug? (I must emphasize the specific example explored below isn't the only bug I've found with the BBraun Infusomat, but it's just one of the easiest to explain.)

There are four triangle-shaped arrow keys on the Infusomat that let you enter numbers. The idea is that the left and right arrows (◂ and ▸) choose a digit, and the up and down arrow keys (▴ and ▾) adjust the chosen digit.

Figure 6 is a worked example, showing how a display of zero can be increased to 2 by pressing the up arrow ▴ twice. It seems very straightforward: pressing the "up" button, ▴, increases the selected digit 0 to become 1, and pressing it again increases 1 to 2. Of course, if we carry on pressing it, 2 increases to 3, and so on, so we can easily set any digit we like.

I'll now run through how to set a drug dose of 0.01 (perhaps mL of a drug dose for a patient) as a simple example. Let's see what happens, and *how* it goes wrong.

We'll start from the display showing 0, and we'll press the ▸ key a couple of times to move the cursor to the right. The number shown automatically "expands" nicely, creating two extra 0 digits, so the displayed number becomes 0.00, with the right-most zero being selected. We now have the cursor selecting the digit we want to change. To increase the 0.00 to 0.01, the nurse should press the key ▴, expecting, of course, to increase the selected digit. The number should become 0.01.

Figure 7 shows exactly what happens. The wrong digit, not the one under the cursor, changes! The number displayed is now 0.10 not 0.01 as intended.

The infusion pump has let the user do something that it doesn't handle correctly. The dose the pump is going to give the patient is now ten times higher than what was intended, but the pump doesn't warn the user that anything unexpected has happened. It's possible that the Infusomat can't physically deliver such a small dose, so it's just made the number larger. That's a possible explanation, but it isn't an excuse for silently changing the dose by a factor of ten — it's a serious bug.

An overdose ten times out could harm the patient, and the nurse may then possibly face prosecution for the harm done to the patient — perhaps a fatality. In court, the Infusomat's log might be used as evidence. The log will show the court what the Infusomat did — namely overdose the patient. The court will conclude: that's what the nurse did. In fact, the nurse gave the correct dose, but the user interface has a bug. The Infusomat recorded what *it* did, not what the *nurse* told it to do. If the court believes the Infusomat's evidence, the nurse is guilty of negligence she did not commit. Bad user interface designs can be much worse than just hard to use.

6 GETTING THINGS RIGHT

If you read almost any book on engineering, there will be a lot of mathematics. Programming, though, despite being engineering, is very different. There is very little mathematics in most books and instructional programming material. It is as if the culture around programming is that it is easy, and it is just a matter of "learn a language, like Python, and then just start programming." Even children can program, we are told, so you'll find it easy.

I have never heard anybody say even children can do brain surgery. They can, of course, but it obviously would not be safe. The point to make from that analogy is that, of course children can program, but the programs they write will not be safe. Fun but not safe.

The Appendix makes a thorough argument that quality user interface design requires mathematics, and it also argues that needing serious maths is not surprising. Quality engineering *everywhere* needs maths, and to argue — as many do — that computer programming is a skill that doesn't need maths is unfortunate. It leads to the problems we have described. Good programming is hard, and mathematics helps.

It's the curse of knowledge again. I know how

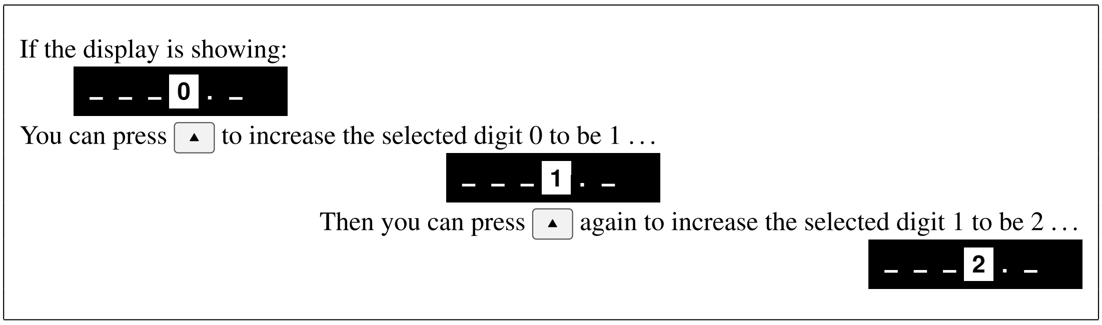

Figure 6: Increasing a selected digit, here increasing it by 2. (The whole device is shown in figure 5).

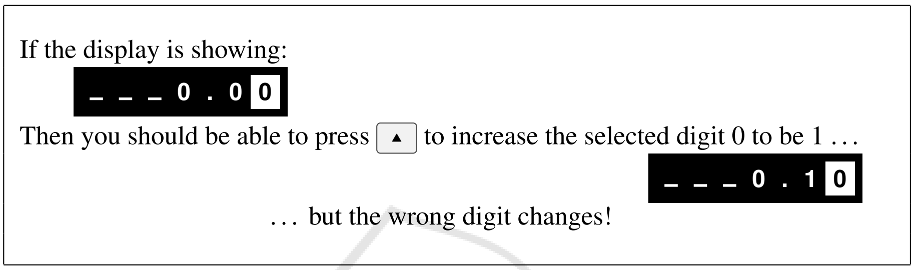

Figure 7: A critical bug, increasing the wrong digit to increase in value 10 times more than the intended one.

my program works, so why do I need to use maths to work out how it works?

The counter argument is you *think* you know how your program works, but that is the curse of knowledge. Very likely your program has bugs that you haven't noticed. The curse is you think your program is right, but you are wrong. That's why maths and code review and other techniques help!

Let's make an explicit comparison, which is elaborated in more detail in the Appendix:

1. Suppose we want a simple LED to light up. We will need to work out the value of components in a circuit. That will need maths. For more complex circuits, we would need to rely on a lot more maths, use theories like Kirchoff's Laws and more. The Appendix gives an example of the maths that's needed.

   The point is, in basic engineering like electronics *using maths is both necessary and expected*. Indeed, when you move on to designing something like a microwave cooker, the maths gets more important — and, incidentally, much harder.

2. Suppose we want a simple program to work, perhaps a user interface feature. We need to work out how to do it, and to do that we need maths too — and we are fooling ourselves if we think we can get away without maths. The Appendix gives an example.

To suppose programmers can "just tinker and things will work" is to deny the real complexity of programming, and denying the mathematical skills that are required to ensure programs work as intended *and are usable*.

I admit that the Appendix, which justifies these points, is an appendix because I didn't want mathematics to put readers off. But consider: when have you ever seen much maths in programming books or training websites for programmers? (There are some books and webpages that do get mathematical, of course, but they are relatively well hidden!)

Now consider writing the program code for a TV remote control, as discussed in section 4. The TV code will be a *lot* harder than the little bit of example code we explore in the Appendix. Chances are, though, that the programmer just wrote the remote control code without thinking it through carefully, let alone thinking it through mathematically. The result was bugs they hadn't thought about and hadn't avoided, causing the On button fiasco. The Appendix shows some maths that could have cut through these TV interaction problems and allowed the developers to think about the design issues more clearly.

7 SITUATIONAL AWARENESS

Situational awareness, SA for short, is being aware of your wider situation, being aware of more than just what you are concentrating on doing. As we grow in skill, SA becomes easier, but demanding tasks (especially emergencies) mean we have to focus on what we are trying to do — and then we probably lose sight of all the other stuff. Often losing SA does not matter, but if (when driving a car) a child runs into the road, it is really critical we see them. If we are drunk, our SA shrinks, and our awareness of the shrinking SA shrinks (our confidence grows despite us becoming less able), so we may not be aware of that child. That's why drunk driving is illegal — it undermines both SA and our awareness of SA.

In programming, a large part of what should be in our SA is the needs of users. Ironically, the nicer the code we write, and the prouder we are of it, the less likely we are to be taking account of what users need.

I once wrote a complex program that needed to display three sorts of numbers. Writing the code, it was natural for me to choose red, green, and blue colors to do this, since the program already used RGB (red, green, blue) color codes. To highlight the numbers, then, I put the colored numbers each on a different colored background. So I put R on a G background, G on a B background, and B on an R background. Of course I'd avoided the silly mistake of trying to show R on R, G on G, or B on B! For foreground color f you obviously need a background color $b \neq f$. Easy. I was pleased with the result. It worked.

I showed off my program to a friend, who asked me why I had mixed red and blue, two awkward colors that have poor contrast, particularly for red/blue color blind people. I then suddenly realized I had chosen the color mixes because I was thinking through the lens of RGB color codes as a programmer, not as a user interface designer aware of color contrasts and color blindness, and so on. In my enthusiasm for RGB tricks I had lost SA — and until my friend pointed it out — I was unaware I had even lost my SA.

8 YOUTHFUL DESIGNERS

If the complexity of design causes failures in SA, and hence often a loss of user-centered concerns, things get worse when the demographics of designers and users diverge. Inevitably, most people who design systems are younger than older users. For instance, a high proportion of older users are retired, and therefore would not be employed as designers.

It follows that most designers have not and are not personally experiencing the problems of old age. They are therefore less likely to be aware of older people's design issues (such as needing larger text), and their SA will be biased towards issues that are salient to *them*, that is younger, more healthy, more agile, better-sighted, better hearing, less arthritic, people — thus reducing the attention to these issues that become a priority to older people.

9 HAPPY PATHS

Since mistakes and errors do happen, it is important to test that our designs work correctly.

The phrase "happy paths" is a brilliant way to describe a really important problem.

When we test things, we test they work as we expect they should. We test all the things we planned for our gadget to do, and (hopefully) it does them as we expect. These, though, are the happy paths. What about the "unhappy paths?" Does the gadget handle sad and bad input sensibly?

A happy path for testing a remote control is, yes, the ⏻ button works; it switches the TV on and off as we expect.

An unhappy path question is, does the emphatic pressing ON ON switch the TV on, as a user would almost certainly expect? No, it doesn't. And, remember, there are many more unhappy paths than just this one to check! (A standard technique is to test code using random user input, probably simulated, so you don't just check the happy things you expect to work.)

10 THE DESIGN OF DESIGN

So, the user interface might be badly designed; the program code might be badly designed. Behind that, the programming language *itself* is likely to be badly designed.

An extreme, but widely used example, of a badly designed language is Microsoft Excel. Almost anything done in Excel is unreliable.[1]

Other examples of badly designed languages are C, C++, and JavaScript. Like Excel, these are wildly popular (and have done enormous good), but unfortunately that doesn't stop them having traps and defects in the ways they are designed. So the programmer may make mistakes, but the language they are using may add its own mistakes … and ensure these mistakes are much harder to spot.

[1] If you add up a column of numbers using `SUM` but mistype any number so it has two decimal points, Excel will not point out the error, but the number will be silently treated as zero with no warning, even if it looks like a million 1.000.000

11 DUNNING-KRUGER

The Dunning-Kruger effect is named after the two authors of the paper that introduced the idea; their paper has a self-explanatory title: "Unskilled and Unaware of It: How Difficulties in Recognizing One's Own Incompetence Lead to Inflated Self-Assessments." That is, people who are not very competent are not competent enough to recognize their own incompetence, so they generally think they are better than they actually are.

It is likely if we confronted designers of TVs or infusion pumps, they — or most of them — would think they are more competent at their job than we do. In other words, trying to help improve the quality of user interfaces by talking to existing practitioners is likely to fail — bad designers and developers think they are better than they really are.

Dunning and Kruger's suggestion to get out of the dilemma is to educate. When you get qualifications (or fail to get them!), you get a more objective assessment of your own skills. Furthermore, your interviewers and employers also get a better idea because there are facts on your application. In a word, education *calibrates* us.

The implication is that we need qualifications in user interface design, and in design for safety.

While the implication of Dunning-Kruger is that people who are unskilled often don't recognize their limitations, the opposite problem, which afflicts us all designers and developers regardless of our skill, is the curse of knowledge (which we introduced in section 2).

12 SOLUTIONS

This paper has, I hope, demonstrated that designers and developers could learn and do things that would improve the usability of their products. Basic knowledge can be used to improve user interfaces, and applying it would make a huge difference to busy people (like nurses) and people with cognitive or physical decline (like some of the elderly).

Behind the lack of knowledge is a systemic problem. Our current qualifications (like degrees in computer science, psychology, design, or HCI) do not establish or prove competence.

For example, I have a degree in physics, so I have a qualification that shows I understand electricity (check out my electronics example in the Appendix!). But understanding electricity is very different from being a *competent* electrician. Indeed, in the UK, I do not have the legally-required qualifications and certificates to prove I am competent to wire up a house. From a graduate physicist's point of view, wiring up a house is completely trivial. From a professional electrician's point of view, however, it is very complex and requires professional skills, specialist tools, insurance, up to date certificates, and lots more. Knowing the principles of how a multifunction tester works (as I do) is very different from being able to use one safely and competently. My degree qualification does not make me into a safe electrician; for instance, my qualifications in physics covered none of the laws, regulations, and standards electricians are legally required to know and to follow to be safe.

It is the same with programming, HCI and the other disciplines that are needed for designing and building quality, easy to use interactive products. The fact that people understand something (even if they have the qualifications) does not mean they are any good doing it. Nor does it mean their competence is up to date — for instance, laws on electrical wiring standards have changed since I got a degree in physics, so even if my degree had covered professional wiring, my knowledge would not be legal today.

If electricians are required to have professional certificates to work, tell me why programmers or user interface designers who build tools electricians rely on for safety testing need no electrical qualifications or supervision? When an electrician presses a button, who knows what will happen if an incompetent designer or programmer built it.

Similarly, why don't designers of infusion pumps need professional competence qualifications — their programs are doing medical activities (like giving patients drugs) that doctors and nurses legally require years to learn how to do safely. It is crazy that a nurse needs to be registered and qualified before they can press a button on an infusion pump, but what that button does to the patient is anyone's guess because it can be implemented by an unqualified programmer!

13 BIGGER SOLUTIONS

This article has focused on 'little' interaction problems, because they are easier to explain and clearly introduce the principles. Bigger problems are generally more intricate and harder to understand, let alone avoid. Unfortunately explaining and understanding the bigger problems compromises our SA and we are less likely to see the good design processes.

When a fire truck goes to an emergency, like a car accident, everyone gets heavily involved. The rescue may be complicated and urgent, and if so people will lose SA. It is therefore standard practice that a designated person — often the driver — has the job of *only* checking SA for everyone else. Is there any traffic coming? Is there fuel running across the road? If you are busy getting a casualty out of a car, you may not notice these critical factors.

Likewise, when building complex systems assign a designated person whose only job is to ensure nobody loses sight of user interface design, nobody loses sight of the needs of users. And that is all that designated person should do. The designated person's SA is precious, and should not be cursed by getting too involved in the technicalities of the design.

14 WHAT DOES THE USER WANT?

UCD, User Centred Design is supposed to be user-centered. What does the user want? What are the user's tasks? What empowers the user? What engages users into flow? What does the user enjoy?

Often, these questions are most important but hardest to answer when the user does not have the capacity to explain them. For example, my father did not complain about the TV, he simply felt cross, and cross with himself. It takes a detailed non-user centered analysis to trace the frustration back to technical design decisions, though of course my analysis was motivated by being user-centered.

Or a nurse using a badly-designed infusion pump. The problem is, the user is generally unaware of (or unable to explain) the design errors that cause their problems. In fact, if one performed a user centered analysis of nurses and infusion pumps, a significant bias would be the "impossible error" problem. The nurses who have had direct experience of errors have lost their jobs, and can no longer be present for focus groups or other user studies.

Often we design for users in organizations. Who wants to admit their own problems in a competitive environment, or where promotions are not guaranteed and jobs are not secure? Many users adopt work-arounds to help make their work more efficient, and often these work-arounds cannot be seen by the computer systems. Soon there is a vicious cycle of providing what the computer wants, because the computer feeds management with the fruits of work-arounds rather than honest information.

Many computer systems are specified by managers and people 'at the top.' But these people with the money and power to specify new computer systems don't know how their workers work — ironically, the worse the existing systems are the more work-arounds are needed just to get things done, and the more disconnected the managers become from what is actually done.

15 CONCLUSIONS

It is time to professionalize user interface design and construction. Employers and users need to know that the people who design, build and maintain the systems they want to buy and use are competent.

This paper gave examples of how and why today's designers, interface developers, and engineers are often not competent, do not built easy to user systems (especially for people unlike themselves, like the elderly) and, certainly, are not safe to build critical systems that people depend on.

Steven Pinker's curse of knowledge is a core idea, the significance of which has been belabored in this article. But Steven Pinker did not think of all the ways of being cursed by knowledge:

- If the designer knows *too much* then they know 'secrets' about how the design works, so they under-estimate its difficulty for the user who may not know these secrets. In particular, if the designer knows too much relative to the user, for instance if the user has disabilities or impairments not shared by the designer, then the curse of knowledge is a given.
- Conversely, if the designer knows *too little* then they will under-estimate the difficulty and problems of the design for the user. We often think maths is difficult, but it is difficult because it helps us do difficult things. If we avoid maths, we enforce our own ignorance, and do not see or analyze difficult problems that may make problems for users. We are unable to fix problems we do not know about.
- Thirdly, the knowledge cursing us may be wrong. For example in the TV example, calling the button $\boxed{\text{On}}$ gave us the incorrect knowledge that the $\boxed{\text{On}}$ button turned the TV on. It doesn't; this is wrong knowledge.

PS please read the Appendix and *its* conclusions.

APPENDIX

Why We Need Maths

Maths in Electronics

Let's design a very simple electronic circuit, like a circuit to light up a LED. That is about as simple as you can get and still do something useful. It could be a child's flashlight or torch, for instance.

In this circuit (figure 8), we have got the right components, nicely connected. But what values do they need to be?

If we start with a 9 volt battery, and look up the voltage and current of our LED, we can start to work things out. Then we will need to work out what the value of the resistor is before anything is going to work.

We can use Ohm's Law: $R = V/I$ to work out the resistance R.

The voltage V across the resistor will be $V = V_b - V_d = 9 - 2.1$ which is 6.9. So $R = 6.9/0.01$, which is 690, or more precisely 690 Ω. It turns out that 690 Ω is not an off-the-shelf resistor value, so we pick 680 Ω, which is readily available (it's an E6 value, so also in the common E12 and E24 series of values). Now we need to work out the power dissipation of the resistor, $W = I^2R$, so we can calculate the wattage is $0.01^2 \times 690 = 0.069$. We can safely use a standard 0.125 W resistor for 0.069 watts. Job done.

This is about the simplest interesting electronic circuit you can build, just a little LED that lights up. **And we needed to do some maths to get it right.**

And, of course, we still need the practical skills of being able to wire it up and solder it all together. If we got the LED or battery the wrong way round, for instance, it won't work (notice that we turned the battery around to be correct in the second circuit). While batteries come with little + and – signs on them, LEDs don't so we need to know the lead out pattern of the LED we are using. Details matter.

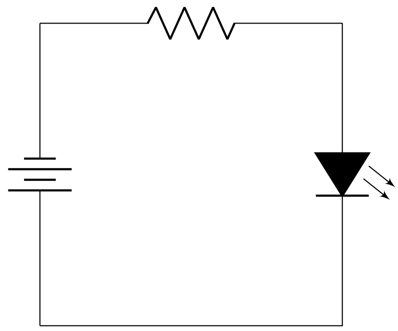

Figure 8: A simple circuit to light a LED.

Maths in Programming

Now compare that basic electronics experience with programming.

To get programs right we also need to do some maths. But most of the time programmers get away with doing no maths, so "most" of the time their programs work by chance, and some of the time their programs fail. Bugs, in other words.

Another thing good programmers need to do is called code review. If I've made a mistake in my maths above, did you notice? Did I notice? The idea of code review is that as we don't notice our own mistakes (I wouldn't make mistakes if I noticed them!), then we need other people to review our work, and ask us questions. "Are you *sure*? … *Why* are you sure?" they'll ask. Without code review, we cannot be sure we are right.

As we did with the LED electronics example, let's write down a very simple program and then show how to check the details are right. Let's say we want to be able to add up the numbers in an array of numbers A in the programming language Python. In normal programming, we would usually want to do something far more complicated — this example is trying to show that doing even 'simple' programming requires mathematics, in exactly the same way that doing even simple electronics does. The difference is that electronic engineers expect maths, but programmers don't — and therefore many programs are more buggy than they need be.

Here's how we start. Most programmers can just write this down (like most electronics enthusiasts can just draw the LED circuit).

```
def sum(A):
    total = 0
    for i in range(len(A)):
        total = total + A[i]
    return total
```

My first job as a programmer was working at the Hammersmith Hospital cyclotron unit. Staff wore dosimeters, to record how much radiation they had been exposed to working around the cyclotron. My job was to make some modifications to the program that added up daily doses of radiation, to check that the staff member had not had too much radiation over the day, the week, the month or the year. It also identified staff who had had a low dose, and might therefore be able to do more work safely. So the program had several loops that added up numbers, much like the Python above, although (given this was the 1970s) the code was written in FORTRAN.

What I noticed was that the original code was incorrect. It added up the weekly radiation dose for 52

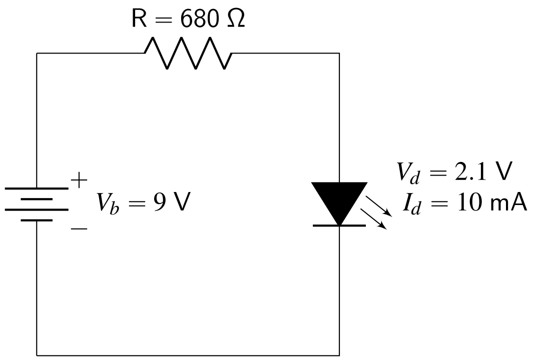

Figure 9: More details are needed for a simple circuit to light a LED. (There are still many missing details, such as whether the wiring is insulated, and how the components are connected — soldered? twisted?)

weeks, to get a yearly dose. Unfortunately, weeks are 7 days, and 52 weeks of 7 days each adds up to 364 days, so that leaves one or two days unaccounted for (depending on whether it's a leap year). Where does the program put those extra one or two days — adding to this year's total, or next year's total? Are the regulations per year or per 52 weeks?

These are the sorts of question that have to be asked, and they arise because being really clear *mathematically* about what code is doing is critical to the code being safe (and in this case, legal).

Most people, programmers anyway, would just write that down Python code to add up some numbers without much thought — they've done this sort of thing lots of times before. Well, not all loops are the same (as the dosimeter example showed), so here in this article we will go through the process as if we are doing it properly.

First off, we ought to check that `sum()` works for a few cases; so we check (showing just one example) `print( sum([1,2,3]) )` certainly prints 6, which is $1+2+3$, which is correct. But will the code be correct for *all* sorts of numbers in `A`? What about special cases like `A=[]`?

For anyone not too familiar with Python, the expression `range(a)` means the integers $0,1,2,3,\ldots,a-1$. The `for` loop starts at 0, and takes `i` successively through 1, 2, 3, …, to the length of the array `A` minus one. The first element of the array is `A[0]` and the last element is `A[len(A)-1]`. Somewhat confusingly, when an array starts at zero, if it has `len` elements, then its last element will be `len-1`.

Instead of Python, we'll use the standard mathematical notation, where $[a..b]$ means the set of integers i where $a \leqslant i \leqslant b$, so it is inclusive of both a and b (assuming a and b are integers). Hence Python's `range(n)` means $[0..n-1]$, and the reason Python seems idiosyncratic is because, defined like this, `range` better suits array subscripts that start at 0 rather than 1.

Hence, using this notation, the Python `for i in range(len(A))` used above means take the values in sequence from $i = [0 : len(A)-1]$.

It's convenient to generalize the standard [..] notation to allow `A[0..i-1]` to mean the ordered set of values of the array `A`, at indices 0 to $i-1$ inclusive. Note that the sum of `A[0..-1]` is zero, because the set $[0..-1]$ is empty, as there is no i such that $0 \leqslant i \leqslant -1$.

Rather than Ohm's Law, we need to use a law called the *loop invariant*. We took Ohm's Law as a bit of magic and didn't explain it, but the invariant that's needed here is straight forward.

When the loop terminates, we want $\texttt{total} = \sum A[0..\texttt{len(A)-1}]$ so the function returns the sum of all elements in `A`, and this equation will inspire the exact form of loop invariant we need.

The Python `for` loop takes `i` over the values 0 to $\texttt{len(A)} - 1$, so on the last iteration we want to finish with $\texttt{total} = \sum A[0..\texttt{i}]$. For each iteration, then, if we ensure $\texttt{total} = \sum A[0..\texttt{i}]$ is true at the end of the loop body, we will finish with the correct total sum. Since this equation is (supposed to be) true every time through the loop, it is called an *invariant*.

$$\texttt{total} = \sum A[0..\texttt{i}]$$

In Python, the loop variable (here, `i`) remains defined *after* the loop has terminated, so the invariant will (or should!) be true all way from the loop to the return statement, where the truth of the invariant is relied on so that the function returns the correct value, namely the sum of the elements of `A`.

Each iteration of the loop starts with the *previous* value of `total`, so the assignment `total = total + A[i]` inside the loop ensures the invariant is made true just before the end of each iteration of the loop.

All we need to do now is ensure the invariant is true the first time around the loop, when $\texttt{i} = 0$. To do that, we simply set `total = 0`. You can think of that as establishing the invariant $\texttt{total} = \sum A[0..\texttt{i}]$ for $\texttt{i} = -1$, since $A[0..-1]$ is empty, so $\sum A[0..\texttt{i}] = 0$.

Therefore the code is correct, at least if the invariant is correct — and assuming our reasoning is correct.

The maths showed our Python code was correct, and correctly added up the values in the array as we wanted.

But we know that when you do something complicated, there is a danger of losing SA. Furthermore by using maths (or even just by using programming) you now know more details than the user — there is a real danger of the curse of knowledge.

So we, or our SA helper, must check what the user wants and needs, and ensure we are also taking steps to design for the user and *their* task — however satisfying may be just to use our nice correct code!

Loss of SA or otherwise, thinking about all that mathematics might have distracted us from an arguably better, certainly neater, solution to the problem. Indeed, as you read the stuff about invariants, did you ask yourself whether this was the best way to solve the problem?

Specifically, we focused on i, the index of `A[i]` rather than the value of elements of `A`, so we missed considering this (potentially) better solution:

```
def sum(A):
    total = 0
    for ai in A:
        total += ai
    return total
```

This solution doesn't have subscripts (like `A[i]`) nor does it need to have an explicit expression `len(A)` for the length of the array. The invariant, by the way, is identical to the previous one we used, with the proviso that (thanks to renaming the loop variable) we just need to assert

$$\texttt{ai}_{\textit{this code}} = \texttt{A[i]}_{\textit{previous code}}$$

Sharp-eyed readers may notice that the font used for Python was `a fixed width font` but the font used for maths was *Times italic* (mostly). What does this mean? The point is mathematical variables have one value and they mean just one thing, namely their value. If you see i in an equation and you know $i = 0$, you can replace i with 0 and the equation will still be correct, or at least as correct as it was before.

Not so with programming variables. For example, what is the value of `total`? It changes all the time; in fact, that was the point of `total`, to keep a running total. *Programming does not work like maths*, so we tried to help by using different fonts. So, `this is programming` and *this is maths*.

It was hard to get all the font details right, and I skipped the standard way of doing it correctly. Ideally, you would use a notation called emphatic brackets to indicate the transition from code to maths. For example, $[\![\texttt{total}]\!]p$ is the mathematical value of the program variable `total` at point p in the program.

Unfortunately to define the environment and state p would take us too far beyond the scope of this paper (and too far into the inner details of Python). **But it shows, again, that to get things right, details matter**. And, conversely, if you don't get these 'little' details right, the user interfaces will have 'little' user interface bugs.

Maths in UIs

Mathematics in user interfaces is typically associated with Fitts Law (and other ways to compare timings of different designs), but maths can also do a lot with the meaning of interaction.

How would we analyze the TV's confusing $\boxed{\text{On}}$ key example from section 4, say?

One of the problems with user interfaces is that they are usually side-effects of running programs. So the sort of analysis we did for the Python `sum` tells you what the program does, but it doesn't tell you about the things the program does interacting with the user (it printed the sum of some numbers). In fact, the problem is as tricky as the distinction between mathematics and programming we briefly discussed above.

In the short space we have here, we will take the $\boxed{\text{On}}$ button and some variations and show how we can reason about them. How this reasoning is connected to program code and might help us improve the code is "an exercise left for the reader." (It's easy, especially if we use formal methods tools, but it is a bit tedious to explain.)

First, let's say all that the user is interested in is that the TV is on, or that the TV is off, and for the sake of argument that is all we need to be interested in here. The TV cannot be both on and off, and it cannot be neither on nor off.

Everything of interest in this TV can thus be represented by two states, on and off, both of which can be represented in a state vector which has values we can name, $\mathbf{on} = \begin{pmatrix}1 & 0\end{pmatrix}$ and $\mathbf{off} = \begin{pmatrix}0 & 1\end{pmatrix}$.

State machines (e.g., finite state machines, FSMs) can be turned into mathematics by using state transition matrices, and in fact they are often taught this way. To understand our TV, we will treat each button on the remote control like a little state machine, each with its own transition matrix.[2]

The TV's original $\boxed{\text{On}}$ button behaves like a finite state machine defined by the state transition matrix $\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}$; in fact if we wanted to be pedantic, we would write

$$[\![\,\boxed{\text{On}}\,]\!] = \begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}$$

(This is using the same $[\![\ ]\!]$ notation we introduced when discussing Python above.)

Here, I'm just stating this as a fact, but it can be worked out from scratch. For example, if somebody

[2] If we now worked out the matrices for all the other buttons, they would all be I, the identity matrix — because all the other buttons leave the TV on, or leave it off if it is already off.

had already built the TV, the matrix can be worked out by simply running a program on the TV — we can either use the matrix to describe what a TV already does, or we could have used the matrix to specify what the TV should do.

However we choose to do it, given that button matrix for $\boxed{\text{On}}$, we can work out what it does in arbitrary situations. For instance, consider this example:

$$\begin{aligned}
\textbf{off}\ \boxed{\text{On}} &= \textbf{off} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \\
&= \begin{pmatrix} 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 \end{pmatrix} \\
&= \textbf{on}
\end{aligned}$$

This is just doing matrix multiplication; that is, given a state and a matrix representing a button, then $\mathit{state} \times \mathit{matrix}$ will be the next state after the button is pressed.

Let's now work out what $\boxed{\text{On}}$ does when the TV is already on:

$$\begin{aligned}
\textbf{on}\ \boxed{\text{On}} &= \textbf{on} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \\
&= \begin{pmatrix} 0 & 1 \end{pmatrix} \\
&= \textbf{off}
\end{aligned}$$

So when we press $\boxed{\text{On}}$, if the TV is on, it is switched off, and if it is off, it is switched on. Sounds like we should have called the button $\boxed{\text{On/Off}}$ so the user isn't confused.

So what does $\boxed{\text{On}}\,\boxed{\text{On}}$ do, that is when it's pressed twice in succession?

We could work out what $\boxed{\text{On}}\,\boxed{\text{On}}$ does for all possible states, as we demonstrated testing $\boxed{\text{On}}$ pressed once for each of the two cases on and off above. In general it would be tedious to do this for all possible states (for a more realistic example); instead, lets use maths to work out what $\boxed{\text{On}}\,\boxed{\text{On}}$ does for *any* state regardless of the number of states we are dealing with, thus:

$$\boxed{\text{On}}\,\boxed{\text{On}} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

We may recognize this matrix as I, the identity matrix; in other words $\boxed{\text{On}}\,\boxed{\text{On}} = I$.

Since pressing $\boxed{\text{On}}$ twice gets the identity matrix I, it does nothing (that is the definition of identity).

It is now easy to see that pressing $\boxed{\text{On}}$ three times is the same as pressing it once:

we worked out above that:

$$\boxed{\text{On}}\,\boxed{\text{On}} = I$$

so post-multiplying[3] both sides by $\boxed{\text{On}}$ we get

$$\boxed{\text{On}}\,\boxed{\text{On}}\,\boxed{\text{On}} = I\,\boxed{\text{On}}$$

but I times any matrix is the same value, and here that matrix is $\boxed{\text{On}}$, so finally we have

$$\boxed{\text{On}}\,\boxed{\text{On}}\,\boxed{\text{On}} = \boxed{\text{On}}$$

We conclude that pressing $\boxed{\text{On}}$ three times in a row is equal to pressing it once. In general, it is easy to prove that pressing $\boxed{\text{On}}$ an even number of times does nothing (is equivalent to I), and pressing it an odd number of times is the same as pressing it exactly once.

You could summarize our findings elegantly:

$$\boxed{\text{On}}^{2n} = I$$

and (although it is a trivial consequence of that)

$$\boxed{\text{On}}^{2n+1} = \boxed{\text{On}}$$

If doing the mathematics hasn't been too distracting, what we have discovered, for a key $\boxed{\text{On}}$ as defined for this the TV case study, then pressing it twice in succession doesn't make the TV more likely to be on. As my father discovered, pressing the button twice, four times, six times ... does nothing; on the other hand, pressing it once, three times, five times ... *does* switch the TV on.

In other words if you press the button enthusiastically, pressing it numerous times, there is only a 50% chance you will switch the TV on. But it gets worse: if you have switched the TV on but you really want it to come on, you have to wait. If you don't wait long enough (however long that is) and you press $\boxed{\text{On}}$ again thinking you will finally switch the TV on, you will definitely switch the TV off. Sigh.

A 2×2 matrix is trivial, and almost all user interfaces are obviously going to be much more complex. The question is: do matrices scale up?

There are two answers: we can use block matrices, and anyway (if we use computers to do the sums) we don't need to see the matrices themselves.

Suppose the device can do all sorts of things when it is on; perhaps a 100 things. We could represent all the on possibilities with a state vector like this

$$\begin{pmatrix} S & 0 \end{pmatrix}$$

where S is a block (here, with 100 elements) inside the vector. It turns out the matrix algebra will work out as before, but hiding all the details. Previously we said $\begin{pmatrix} 1 & 0 \end{pmatrix}$ was 'on' because 1 was how we represented on in the state vector; now we are saying $\begin{pmatrix} S & 0 \end{pmatrix}$ is on and, more specifically, on in some state represented inside S. Note that we will also have to change the

[3]Since all the matrices here are the same, post-multiplying is the same as multiplying in any order, but I emphasized post-multiplying to remind us that the last key pressed should be on the right, ensuring the order of multiplication is the same as the order of pressing.

matrix for On since we have to decide (inside that matrix) what specific state the TV will come on in.

Or we could just use other methods of course — there are many in the formal methods area to choose from.

Appendix Conclusions

The LED circuit, the Python program and the On button maths were all absolutely trivial as things go. Yet we showed that to understand these designs, and get them right we needed to use mathematics.

While engineers take it for granted that electronics requires maths, for some reason programmers and UI designers hardly ever use mathematics. That dislike of mathematics and careful reasoning goes a long way to explain all the bugs and user interface fiascos we all experience with poorly designed programs.

It's worth emphasizing maths has many more benefits. For example, with a bit of routine work (sadly beyond the scope of this article) we can explore and prove *and understand* why Apple's simple TV remote (figure 4) control was much harder to design than Sony's huge remote control (figure 2). Once we understand that, we can start using the insights elsewhere to help improve other user interface designs.