The Science of Computers

A Novel Approach

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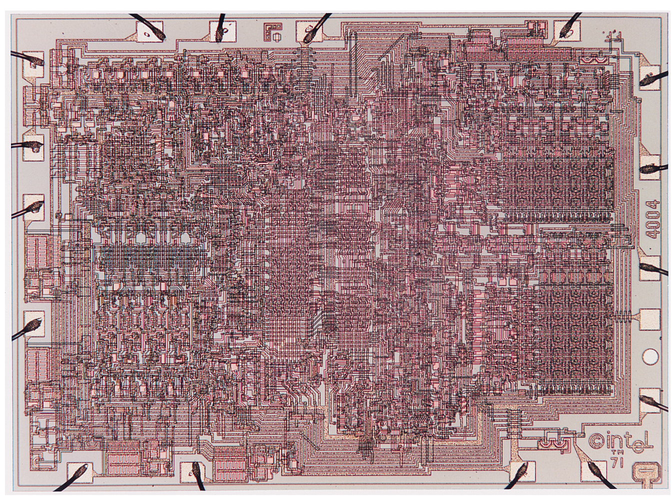

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Preface

For almost two decades, I taught a course titled *Computer Architecture and Machine Language*. The course was offered to second year college students intending to become computer scientists. This course was by far my favorite one, since it let me take students on an exciting journey of discovery.

When I first was offered this course, the basic material covered assembly language programming for the Intel 8086 processor. Architecture took a back seat to learning another programming language. I found that odd that the course focused on a 16-bit processor since most computers at the time were using 32-bit Pentium processors. Upgrading the course required new development tools, and I decided to make the course vendor neutral. That meant getting rid of the Microsoft bias present in many courses at my school. I started off by deciding to introduce my students to tools commonly found in open-source projects. Those tools included programmer's editors, build tools, source code control tools, and standards compliant compilers capable of building projects on any platform. Many of my students were shocked to learn that they could build software without using some magical *Integrated Development Environment*. My theory was simple. Choosing an IDE is something best left to that first job the student will land. That job will have an development process and tool chain that the new employee will need to learn.

As the course evolved, I added more emphasis on the inner workings of the machine the students were learning to program. At first the focus was still on Intel chips since they power most of the computers students are familiar with. However, the world is changing, and more and more work is being done on systems that use other processors. The most common chips in mobile platforms today are variants of the *ARM* processor.

The *ARM* processors are complex chips, maybe too complex for beginners in my course to study. There was a simple alternative available though. The *Microchip AVR* processor found on the new —emphArduino development boards was available very inexpensively. I decided to buy enough of these boards to set up lab kits for my classes so students could do hands-on development work on real hardware.

The course became very popular. It was challenging, but prepared students well for their future jobs.

I continues to add material focusing on what was going on inside the processors they were learning to control. Then in 2017 something interesting happened. The Texas body charged with setting standards for college courses changed the course requirements for my course in an interesting way. The new guidelines asked students to write a simulator for a real processor as part of the course. They also added a focus on embedded processors intending to get students ready for those mobile platforms found everywhere. I was already doing most of what they asked. I only needed to add the simulator to my course to meet these new guidelines.

This book is designed for this course. Although I have now retired, I decided to write this book based on my lecture notes but with a new twist.

Instead of producing yet another dry textbook, I decided to write a book along the lines of one of my favorite books: *Godel, Escher, Bach* by Douglas Hofstadter Hofstadter (1999). The result is not so much a textbook, but more of a novel. I want the student to want to read this text, not just scan it looking for answers to exercises they are given. I hope the result is interesting enough to show them why they are learning all this new material. I also hope to produce more professional candidates for that job market waiting for them in their near future.

I hope you enjoy reading this book as much as I enjoyed producing it.

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Chapter 1

Blue Flames

In a quitet basement somewhere in Dayton, Ohio, two young students are working into the night on a computer. No, this is not a fancy desktop or laptop computer. It is a simple machine designed to help one of the students learn how to program in assembly language.

Ada is the student who is building the computer, and her friend, Alan, is helping her get the critter running. Ada has managed to come up with a nice case for her machine. The sides of the case are cherry wood which she will finish off later to make things look nice. The actual case is a bent piece of aluminum sheet metal she convinced a local automotive body shop to fabricate for her.

The goal this evening is to power the gadget up. Alan is working on wiring a power supply for the machine that will be bolted inside the case. A switch will be attached to the sheet metal cabinet along with a keypad and an LED display.

Ada is bolting a small printed circuit board to the bottom of the case. This board comprises a complete 8-bit computer system. It is not fancy, nor is it very powerful, but it will be sufficient for Ada's goal. Alan is wiring up the power supply and the switch. Both of them work together to get everything installed in the case, ready for the first power-up!

The evening wears on, and things are getting close to ready. Another student, Nick, wanders down the stairs into the basement.

"Hey Ada, have you got the thing powered up yet?"

"Just about. Alan is almost finished with the power supply."

Alan puts a screwdriver down on the table.

"Ready for the first test. Ada, you do the honors!"

Ada reaches a nervous hand toward the switch. All three of them hold their breath. Ada flips the switch.

A brief flash of light is seen inside the case, and the lights go out!

In the darkness, Nick mutters "I guess you flunked the Blue Flame test!"

Chapter 2

Electricity

Where did you first see a 'Blue Flame? For most humans it was probably seeing or hearing lightning. If you saw lightning you saw a flash of light coming in the form of jagged streaks seemingly moving at random from the sky toward the ground.

Humans have pondered that flash of light since it was first noticed back in prehistoric times. Only recently have scientists been able to explain what was going on in that flash. Their studies brought us to the point where we have a basic understanding of the most elementary particles that make up everything in our known world. Before we can understand how electricity behaves, we need to take a quick look at the structure of a single atom.

2.1 What is an atom?

If we take anything physical in our world, and start tearing it down into smaller and smaller chunks, eventually we end up looking at a structure we call an "atom". For a long time, humans resisted the idea that there was such a gadget, today, we put a lot of energy into researching what happens if we tear and atom apart to see what it is made up of. We even want to go a bit further and see what those atomic parts are made up of.

Welcome to the world of high-tech physics!

We will not dive smaller than the basic atom. (Real, serious physicists are trying to go much farther!) That will let us look at its most basic parts.

Some of this, you should have learned in your high school chemistry class!

2.1.1 Basic Atom Structure

An atom is sort of like a tiny solar system. There is something big in the center of this system, and a bunch of smaller things flying around that center in tiny orbits.

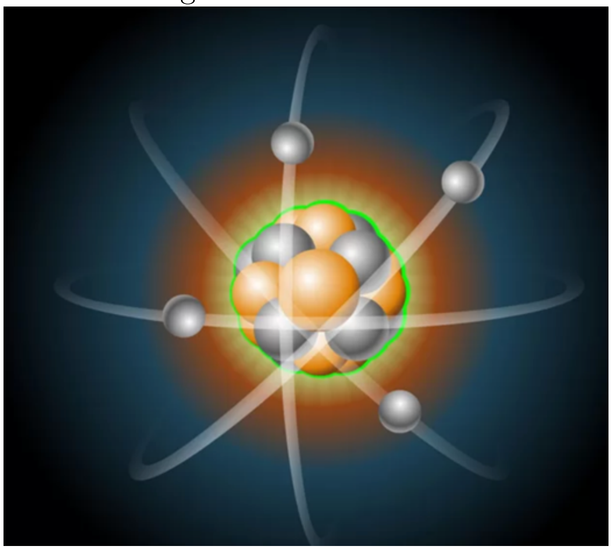
Atoms are pretty small. Estimates as to their size depends on the material, but a single atom is as small as $10^{-8}cm$ in size. That is pretty small. But, amazing as it might seem, we can build machines that can move single atoms. Take a look at this image, created by IBM engineers in 1989. The image was taken using a scanning electronic microscope!

Those bumps are actually single atoms, nudged into place to create this logo. Amazing!

Electrons

The particles flying around the center are electrons. These particles are tiny! Linus Pauling, a Chemist who won the Nobel Prize for Chemistry in 1954, thought they were on the order of $< 10^{-18}cm$ in size. That is pretty small.

Figure 2.1: The Atom.



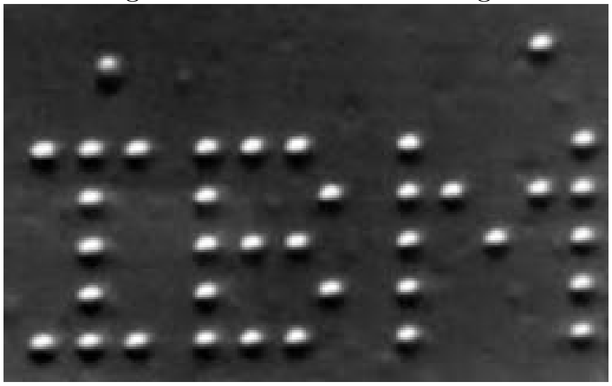
These electrons carry a charge (actually a negative charge).

.. note::

Contrary to popular thinking, if something is positively charged, that means it has fewer electrons than it wants to have. If something is negatively charged it has too many electrons than it wants to have. Electrons are attracted to positively charged things, and repelled by other negatively charged things.

So, two electrons hate each other, and want to keep away from each other.

Figure 2.2: IBM's atomic logo.



Protons

At the center of our tiny solar system sits a clump called the core. This core is made up of two more tiny elementary particles. One is the proton.

Protons are about 10^{-13} cm in size. That is (1000 times bigger than an electron!)

Protons carry a positive charge. In a single atom, there should be as many protons as there are electrons flying around this atomic core.

As long as this is true, the atom is happy, and the electrons sit there, flying around the core with its pile of protons.

Neutrons

The second particle in the core is called a neutron, which carries no charge. Neutrons are about the same size as protons. Neutrons are not attracted to either electrons or protons. They just sit there, stuck to the protons in that core. What they do is give the atom addition mass (think weight).

2.2 Atomic Numbers

We like to classify things. At the level of atoms, we assign an atomic number to each kind of atom we discover. Those protons and neutrons in the core both act in a similar way. So we lump them together and call then neucleons. The “atomic number is the number of neucleons in the atom. (Where do you think the term nuclear physics came from?)

Ions

Since electrons are always flying around, and the core just sits there, there is the possibility that an electron will get close enough to another atom that it will fly off of the first atom, and join in the mess of electrons flying around the second atom. The atom that the electron left is now left with more protons than electrons and has a net positive charge. It is not happy in this state, but there is not much it can do. The second atom is also ”unbalanced”. It has more electrons than protons and has a net negative charge. That second atom is also unhappy. We call these ”unhappy” atoms ions.

.. note::

We have names for each kind of ion. A positively charged ion is called an cation, and a negatively charged ion is called an anion. Cations are also called ”metals”, and an anion‘ is called a ”non-metal”. The terms anode and cathode refer to points in a device where the charge is more positive, or more negative. Makes sense, right?

We can create ions by heating atoms up and firing a stream of electrons at them. Those electrons can knock off other electrons from each atom, setting up this ionized state. The mess at the middle of this action is called a plasma, and it has interesting properties, but we will not explore them here. Plasmas might be interesting if you need to wipe out space aliens!

Stable Ions

Some ions are content with being "unbalanced", but only up to some limit.

For example Sodium is an element with 11 protons in the core, and 11 electrons spinning around. It is happy in this normal state. But, Sodium will tolerate losing an electron, becoming a Sodium ion. The chemical symbol for Sodium is Na and the term for the Sodium ion is Na^+. This ion is positively charged).

Chlorine is another element, this one with 17 protons, and 17 electrons. Chlorine is happy to accept another electron, becoming a Chloride ion. The chemical symbol for Chlorine is Cl. The Chloride ion is

$$Cl^-$$

. It is negatively charged.

When these two ions get near each other, they "bond". The electron does not move from one to the other, but the attractive force causes them to move close together. This "bond" is pretty strong, and the result is a lattice of atoms we call a crystal. This one is known as "salt"! The chemical symbol for this is

$$NaCl$$

. The original ions are still ions, but they are quite happy being close together.

Metals

We already mentioned the term metal. That term describes an element with a strong willingness to lose an electron, becoming a cation. When many of these atoms get together in a material like copper, they collectively let electrons fly off, forming a sea of electrons that fly around, seemingly at random, surrounding the entire collection of atoms. These electrons are called free-electrons because they have no real home on any single atom. This sea of electrons produces something called conductivity, a willingness of a material to let electrons move easily. New electrons can join into this sea, others can be pulled off.

2.3 Electric Fields

An electric field is a region around an charged particle. The charge at any point in that area around the charge is measured in something we call volts. Voltage is a measure of the electrostatic potential energy available at that point. Near a positive charge, the voltage is high, near a negatively charged particle it is low.

It takes energy to move a point from one voltage to another one. It takes a lot of energy to move a voltage higher, just as it takes energy to lift an object to a higher position above the ground. Once at the high point there is a potential to release that energy by moving the object (or the charge) to a lower point.

The strength of this electric field is measured in something we call volts.

When electrons move, they generate a magnetic field around them, often called an electromagnetic field, since there is a magnetic field and an electric field at work at the same time. All of this is described by Maxwell's Equations, which are the foundation of many technical disciplines, especially radio. Those waves propagate through space, interact with other metals, and induce electrons to move in those metals. (Hey, that is how radio works!)

2.3.1 Electricity

We now have enough background to explain how electricity works (well at least in a (very) simple way!)

I have a cool book called *There are no Electrons, Electronics for Earthlings* Amdahl (1991). In that book the author describes electrons as "party animals" who need to party. The parties are all at positively charged points. The electrons are attracted to those parties, and work tirelessly to find their way to them! However, they must travel over "conductive" paths. Something like a copper wire will do nicely!

Batteries

There has to be a source of both positive and negative charges in any electrical system. That source is often called a "battery". The battery is a device that can hold both positive and negatively charged particles, but it separates them with a wall, preventing them from getting together. Instead, the battery has two terminals, One will let electrons loose, the other is where the party is.

Now, if we provide a path from the electrons to the party, those electrons will fly. Actually a stream of electrons will join the sea of free electrons in the mtal, and that will cause many of them to seem to move toward the other end. The path is called a "circuit".

.. warning::

It is vitally important that we not allow all the electrons to the party at once. That can cause very harmful side effects, like smoke! That is called a "Short Circuit". Batteries have been known to explode if this happens!

Usually, we put some gadget in the circuit that slows things down. A light bulb will do. The bulb is designed so that it slows the electrons down. They want to move, so they get hot. The heat produces light. Cool! (Well, actually, HOT!)

2.4 Who Cares?

This is a computer architecture text, What does this have to do with Computers?

Well, think about this simple C++ code fragment:

```
int main(void) {
    int x, y=5;
    x = y;
}
```

What needs to happen to make this statement work? How do you think the computer is going to make this actually happen? The answer is simple. It will launch some of those party animals, and cause them to travel from the place called ”y” to the party at the place called x”. We design a machine that causes the electrons to carry ”data” along as they move to the party!

Wow!

Now, don't panic. You do not need to understand all of the physics in this discussion. It will not appear on a test.

I, on the other hand, and one of those crazy folks who keeps digging, as far down as I can go. It gets more fascinating as you dig deeper.

.. warning::

You can kill a lot of time Googling all of this! You have been warned!

Chapter 3

Nick's Lab

Nestled near a fence behind Nick's home sits a small wood frame building. The building is old enough that it must have been there before the nearby home was even built. Inside of this building are several wooden workbenches filled with equipment used to study electricity. The test gear is surrounded by a sea of wires.

On the back wall of the building is a small window that opens up to the pasture on the other side of the fence. Several Arabian horses spend their days in that pasture, and occasionally wander up to see what is goin on inside of the building.

This is Nick's lab. When he is not studying for school, Nick spends a lot of time in this lab playing with electricity and trying to figure out what it can do. Nick keeps a supply of carrots handy when he works, and when a horse sticks its head in the window, a carrot is usually delivered to keep him happy.

Nick has run electrcity to this building from his home so he can work on his experements. Nick has always been fascinated by Eelectricity. When he was a kid, he took some wire, a light buld and a battery and built a simple flashlight. That silly gadget was used to read magazines under the covers in his room when he was supposed to be sleeping.

Seated in Nick's lab is the last member of our gang of students. Leo is tearing apart an old radio to see what makes it work. The radio dates back to the 1940s and Leo's grandfather told him he used it to listen to the BBC during World War II. The radio was sitting unused in an upstairs room in his grandfather's house. Two wires were running from the back of the radio out a nearby window. One of the wires extended up into a tree some distance from the house. The other wire ran down the side of the house and was connected to a water pipe that went into the ground. Leo had to disconnect those wires before he took the radio to Nick's lab for proper study.

Leo is one of those strange people who loves to take things apart. Sometimes he even manages to put them back together again. The back of the radio is made os some kind of wood his grandfather called bakelite. Leo removed the five screws holding the bakelite panel in place so he could see what was inside. Then he plugged the radio into the wall socket and turned the knob on the front of the radio. That knob was supposed to power up the radio and adjust the volume according to his grandfather.

Leo was not quite sure what to expect, but looking inside he saw a set of seven glass gadgets all of which were glowing and giving off quite a bit of heat. "This is crazy" Leo muttered to himself!

There was nothing coming out of the radio. That might be because Leo had not hooked up those two wires. Maybe those were needed to make it really work properly.

The rest of the gang arrived as Leo was pondering the glow inside of his radio. Alan piped up first.

"Hey Leo, I see you have managed to light up some old vacuum tubes! Those were common when dinosaurs roamed the Earth."

"Funny, Alan. I just want to understand how this old thing manages to produce sound."

"You really need to attach an antenna to that thing" was Nick's comment.

Leo was still puzzled. "But how does a wire sitting up in the sky manage to make the radio work?".

"Electromagnetic waves induce a current in the wire which the radio processes into sound."

Ada chimes in. "Leave it to Alan to speak in tounges that mean nothing to the rest of us! I guess we all have tome studying to do"

Nick has other ideas in mind.

"I thought we were here to see some real sparks fly."

"Fine, as long as we do not get burned by anything." Ada was just being a bit cautious. All these folks knew they were immortal, at least until they reached 35 years old! Still, it never hurts to be careful, especially in Nick's lab!

Nick walks over to another workbench. Sitting in the middle of this bench is a cardboad tube about a foot long with thin wire wound around it from top to bottom. At the bottom of this tube is another coil of wire attached to some electronic gadgets and finally attached to a power supply plugged into the wall. At the top of the long tube is a silver donut made out of aluminum.

"Leo, hit the lights!"

Nick flips the switch and sparks several inches lone shoot out of the donut, dancing in the air. The smel of ozone fills the room.

"That is definitely way cooler than Alan's miswired switch!" says Ada.

Leo is intrigued. "It looks like electricity zooming through those wires managed to generate something that made lightning fly away from that donut. Did the coil make that happen?"

Alan contributes more of his vast wisdom. "When you make electricity move around in circles like that, an electromagnetic wave is produced that moves away from the coil. What is really cool is what happens if you hold a flourescent light near this coil. It lights up with no connections. Somehow that electromagnetic wave gets turned back inot enough electricity to light the bulb."

Aha! That is the basis of radio!" Leo has figured out why the antenna wire is needed to produce any sound. "But what is the other wire all about? The one connected to the water pipe."

Chapter 4

Boolean Algebra

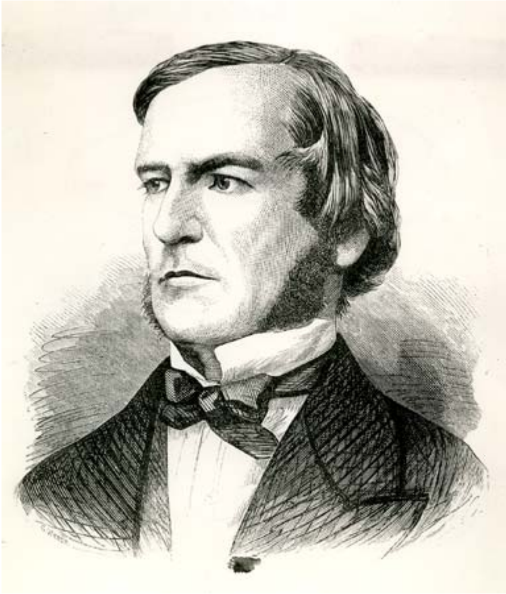
Math can be a lot of fun. (OK, many folks cannot believe math can ever be called fun, but over the course of history, it sure has gotten a lot of attention.)

Way back in 1854 George Boole published a book Boole where he studied the mathematics of a number system with only two symbols: ”0” and ”1”. We can also call those two values *true* or *false* if we wish, but let's stick with our familiar numbers.

> By the way, one of George's famous papers is part of ”God Invented the Integers”, a collection of famous math works edited by Stephen Hawking. Hawking. This book is tough to read, but worth the effort!

George wanted to understand how a system of mathemetics would work if restricted to just those two values. His theories have became known as *Boolean algebra* and are important to us computer folks. His work

Figure 4.1: George Boole



was recognized as a foundation for computer systems that also work with just two states: *on* and *off*. (For some reason, computer folks still insist on saying machines work with "ones" and "zeros", but it really is not so.)

4.1 Arithmetic

The basic arithmetic operations we are all familiar with are the first place we run into something interesting. A few results work just fine. Let's start off by considering *addition*:

$$0 + 0 = 0 \tag{4.1}$$

$$1 + 0 = 1 \tag{4.2}$$

$$0 + 1 = 1 \tag{4.3}$$

But what about this next one?

$$1 + 1 =? \tag{4.4}$$

Instinctively, you want to write down "2", but there is no such number in this system. In binary the result should be "10", which is also illegal in this system. The only result that makes sense (at least to George) is "1", since it surely cannot be "0" (the only other possibility)!

So:

$$1 + 1 = 1 \tag{4.5}$$

In fact, using this philosophy, the following is also true:

$$1 + 1 + 1 + 1 = 1 \tag{4.6}$$

Now that seems just plain silly, and hardly useful. But it really leads to something very useful!

4.1.1 Subtraction

Subtraction does not really make much sense, since, by definition, subtraction is identical to addition of negative numbers, which do not exist in George's boolean world. So we will ignore that operation.

4.1.2 Multiplication

Multiplication still seems reasonable:

$$0 * 0 = 0 \tag{4.7}$$

$$0 * 1 = 0 \tag{4.8}$$

$$1 * 0 = 0 \tag{4.9}$$

$$1 * 1 = 1 \tag{4.10}$$

No problems there!

4.1.3 Division

Once again, we run into another problem, just as with subtraction. Division is repeated subtraction, and we eliminated that operation. So, division goes out as well!

That is all we need for now. But exactly why this form of math is useful needs to be explored.

/section[Truth Tables]

Remember back when you were learning about "logical expressions"? You should have been introduced to *truth tables*, which showed exactly how the logical operators worked. Here is a refresher:

Op	**in1**	**in2**	**out**
AND	0	0	0
	0	1	0
	1	0	0
	1	1	1
OR	0	0	0
	0	1	1
	1	0	1
	1	1	1

Table 4.1: Simple Boolean Truth Table

Do you see a pattern here? The truth table for the *AND* operator follows George's math rules for multiplication, and the table for the *OR* operator follows George's math rules for the addition opeator! Interesting!

4.2 Boolean Variables

Let's add variable names to our system. Convention says these are single capital letter names. (I capitalize things to yell at myself. This is to remind me that the variables only have two possible values!)

Assume a variable "A" has some boolean value. The *compliment* (opposite) of that value is denoted using a bar over the variable name. Like this: $\overline{A}$

The rules for this notation look like this:

$$if\ A == 1\ then\ \overline{A} == 0 \tag{4.11}$$

$$if\ A == 0\ then\ \overline{A} == 1 \tag{4.12}$$

4.3 Boolean Algebra

With these definitions in place, we can define a few rules for *boolean algebra*. Most of these should be obviously true.

.. note::

In the formulas presented below, we will follow standard conventions and use the standard math operator "+" to denote **OR** and the standard math operator "*" to denote **AND**. (Personally, I really wanted addition to use that **AND** operator, because it seemd to make sense. But not to George. I finally got over that urge!)

$$A + 0 \equiv A \tag{4.13}$$

$$A + 1 \equiv 1 \tag{4.14}$$

$$A + A \equiv A \tag{4.15}$$

(Boy, that last one probably makes your head hurt! Remember, this is *Boolean* Math)

$$A + \overline{A} \equiv 1 \tag{4.16}$$

$$0 * A \equiv 0 \tag{4.17}$$

$$1 * A \equiv A \tag{4.18}$$

$$A * A \equiv A \tag{4.19}$$

$$A * \overline{A} \equiv 0 \tag{4.20}$$

$$\overline{\overline{A}} \equiv A \tag{4.21}$$

That last one works for any even number of compliments!

There are a few other rules that are useful.

$$A + B \equiv B + A \tag{4.22}$$

$$A * B \equiv B * A \tag{4.23}$$

$$A + (B + C) \equiv (A + B) + C \tag{4.24}$$

$$A * (B * C) \equiv (A * B) * C \tag{4.25}$$

$$A * (B + C) \equiv A * B + A * C \tag{4.26}$$

These formulas are useful because there is an equivalence between boolean algebraic formulas and digital circuits involving the fundamental components (aka gates) we use to build them. We can actually set up digital circuits as boolean expressions, then simplify those expressions and produce a simpler circuit that operates the same way. This is a key concept in designing digital systems.

As an example of simplifying a *boolean expression*, let's prove the following:

$$A + A * B \equiv A \tag{4.27}$$

See if you can follow this sequence of operations:

$$A * (1 + B) \equiv A \tag{4.28}$$

$$A * 1 \equiv A \tag{4.29}$$

$$A \equiv A \tag{4.30}$$

This sequence can be produced by applying the rules shown above using familiar algebraic operations. *

4.3.1 De Morgan's Theorems

There are a few more rules that are very useful in simplifying *boolean expressions* (circuits) They were developed by Augustus De Morgan, and named after him.

$$\overline{A * B} \equiv \overline{A} + \overline{B} \tag{4.31}$$

$$\overline{A + B} \equiv \overline{A} * \overline{B} \tag{4.32}$$

Op	in1	in2	out
**XOR	0	0	0
	0	1	1
	1	0	1
	1	1	0

Table 4.2: Exclusive OR Truth Table

Again, these are very handy when we need to simplify an expression. Simpler expressions lead to fewer components and lower cost. They might also lead to more speed, and we like that!

4.3.2 Exclusive OR

There is one more logical operator that is very useful in digital design: The **XOR** operator. This operator has the following truth table:

The operator produce a "1" if and only if one of the two inputs is a "1". It produces a zero otherwise.

This operator often appears in *Boolean Algebra* as a funny symbol in some texts, but we can do better. Since we have eliminated subtraction from our system, let's use the minus sign as the operator. This has unexpected consequences, but *Boolean Algebra* seems to have lots of those:

$$X - 0 \equiv X \tag{4.33}$$

$$X - 1 \equiv \overline{X} \tag{4.34}$$

$$X - X \equiv 0 \tag{4.35}$$

$$X - \overline{X} \equiv 1 \tag{4.36}$$

We will develop a couple of additional rules involving this operator later.

Cast of Characters

I want my text to be something you want to read. In today's hurry-up world, students actually do not read as much as they did in the past. That is sad, because you can learn a lot from reading a well-written text.

Yes, there are badly written textbooks around, maybe even mine!

Probably, my most favorite book is *Godel, Escher, Bach*, by Douglas Hofstader Hofstadter (1999). I first read this, shortly after it came out. In this book a set of characters lay out an interesting concept in one short chapter, then the next chapter presents that concept in terms that are now fun to read. The normally dry text, suddenly comes to life. Douglas won a Pulitzer Prize for this book, As a Computer Science student, you should read it! I am currently on my seventh pass through it!

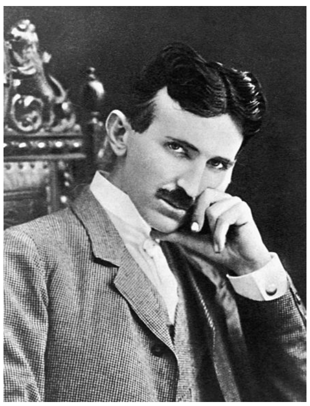
I am stealing Douglas' idea, I have my own characters, and I use them in these lecture notes on occasion.

We will follow four characters through our journey into computers and programming. These four are good friends, but have very different goals in life. That affects how they approach problems they encounter.

Like all teams, they have to work through their differences and come up with an approach to getting some job done that works for everyone.

Here are our characters:

.1 Nick: The "Doer"



Nick has a few interesting characteristics:

- Tank - impervious to harm.
- Gets blown up a lot, but survives.
- Hates to wait for anything.
- Needs lots of documentation.
- Can fix anything.
- Mechanical genius.
- Drives a Ford Mustang (GT)
- Uses Windows 10 Pro.
- named after: Nikola Tesla

.2 Ada: Curious about everything!

Ada is going to learn as much as she can about everything. She has a burning desire to know something about everything!

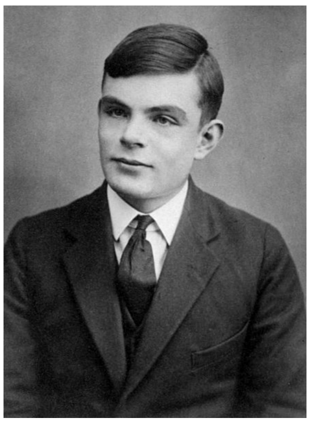
- Questions things a lot.
- Never quit asking "why" when told how something works.
- Tends to stop working on a problem when she sees the answer.
- Seems interested in everything, especially technical stuff.
- She is a peace maker, trying to calm things down when they get tense.
- Drives a Prius.
- Uses a Macbook Pro.
- Named after Ada Lovelace.

.3 Leo: the mechanic.

Leo is the mechanic of the bunch. He is constantly taking things apart so he can figure out how they work. He is also an artist. As he disassembles things, he makes drawings of the gadgets he is studying. Leo can take a box of junk and come up with a Ferrari!

- He can see how things move, because he understands how they are put together.
- Likes to concoct new machines.
- Rube Goldberg is his idol!
- Drives a 1964 Alfa Romeo Giulia Spider sports car.
- He does not own a stinking computer!
- Named after Leonardo da Vinci.

.4 Alan: the wizard



Alan is the genius of the group. He does know a lot about everything. In fact, tripping him up is a game the other two like to play. How he got this way is a puzzle, but he has been caught, late at night, scouring the Internet with his iPad!

- Comes across al very knowledgeable, even if he is not really that up on the topic.
- Has a photographic memory, seldom forgets anything.
- Wants to guide the action because he knows the "right way".
- Something of a space cadet, he wanders off track at times.
- Drives a Mercedes (he got it used)
- Uses Linux on an Alienware Laptop.
- Named after Alan Turing.

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