2. inside three very different factories

It's hard to understand how a computer works without opening it and looking around inside. Likewise, it's hard to understand how products are made without going into a factory and touring the line. Although we often think of manufacturing as the necessary but boring step after innovation, in reality, the two are tightly coupled. An inventor thinks about a product once; a factory thinks about the same product day in and day out, sometimes for years on end.

The importance of factories as an innovation node is only growing in today's connected global economy. The reality is that there is no "Apple factory" or "Nike factory." Rather, there is a series of facilities that are domain experts in processes (such as PCB fabrication or zipper manufacturing) that are curated by the familiar brands. Thus, it's not uncommon to see two competitors' products running side by side down similar lines in a single facility. This concentration of domain-specific expertise means that the best place to learn how to make an aspect of your product better is often the same place that makes a similar aspect in everybody else's products.

Some of the greatest insights I've had into improving a product have come from observing technicians at work on a line and seeing the clever optimization tricks they've developed after doing the same thing over and over for so long.

This chapter takes you on a tour of three factories that make everyday things: PCBs (in particular, the ones used in the Arduino), USB memory sticks, and zippers. By peeling back the curtain, you'll get some insight into the design trade-offs behind the products, and how they can be made better. In the PCB factory, I discovered the secret of how they print a high-resolution map of Italy on the back of every Arduino; in the USB memory stick factory, I witnessed a strange marriage of high- and low-tech manufacturing techniques; and in the zipper factory, I found out how even the humblest of products can bear valuable lessons for product designers.

WHERE ARDUINOS ARE BORN

It was July 2012, and it had been about six months since my previous startup, Chumby, ceased operations. I had decided to take a year off to figure things out and cross a few items off the bucket list, one of which was a trip to Italy. My girlfriend had the bright idea of reaching out to the Arduino team to see if I could visit their factory in Scarmagno (this was years before the Arduino/Genuino split) as part of our itinerary. Members of Officine Arduino (particularly managing director Davide Gomba) kindly took time out of their busy schedules to show me around their factory. They patiently waited as I expressed my inner shutterbug and general love for all things hardware, and I definitely came away with a lot of great photos.

A small town in northern Italy, Scarmagno is about an hour and a half west of Milan by car, near the Olivetti factories on the outskirts of Torino. The town handles all the circuit board fabrication, board stuffing, and distribution for officially branded Arduinos. I was really excited to see the factories, and the highlight of my tour was seeing System Elettronica, the PCB factory that made the Arduino PCBs.

One charming aspect of System Elettronica is that the owner painted the factory green, white, and red to match the colors of the Italian flag. On the factory floor, I saw some of that spirit in the red and green posts that ran the length of the facility.

A wide view of the factory floor at System Elettronica in August 2012

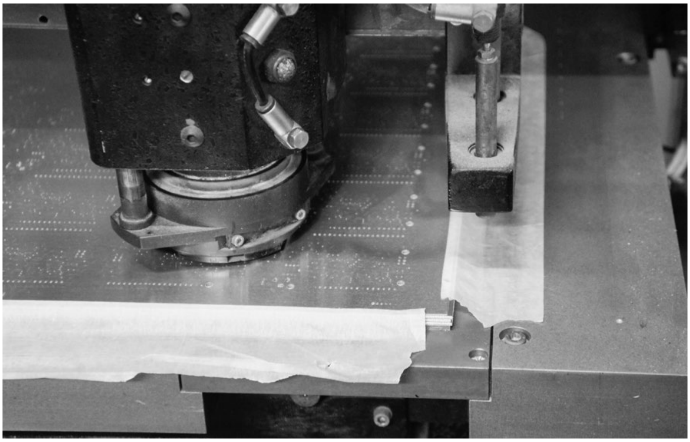
But I soon stopped paying much attention to the décor, as that factory floor was also where I got to follow a fresh batch of Arduino Leonardos through the entire manufacturing process. Here's how those boards were made.

Starting with a Sheet of Copper

Arduino Leonardo boards start as huge sheets of virgin copper-clad FR-4, a material made of fiberglass and epoxy that most PCBs use for a substrate, an insulating and structural layer between the copper layers. The sheets were 1.6mm thick (the most common thickness for a PCB, which corresponds to 1/16 inch), probably a meter wide, and about a meter and a half long.

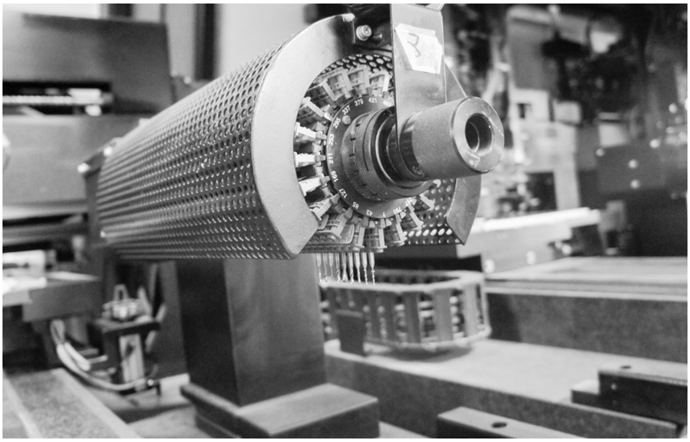
A stack of copper sheets waiting to become Arduino boards

The first step in processing PCBs is to drill all the holes—pads, vias (the small holes that connect different layers of the PCB), mounting holes, plated slots, and so forth. When a PCB is manufactured, the holes are drilled before *patterning*, the stage where a masking chemical is photographically defined on the sheet everywhere the final boards need to have copper, including locations of traces, solder pads, and so on. Some of the drilled holes are used to align the masks that pattern the traces later in the process. Drilling is also a dirty and messy process that could damage circuit patterns if they were in place beforehand.



The CNC drilling head used to drill the Arduino boards

The blank copper panels were stacked three high, and a CNC drill took a single pass for all three, allowing it to drill three substrates at a time.

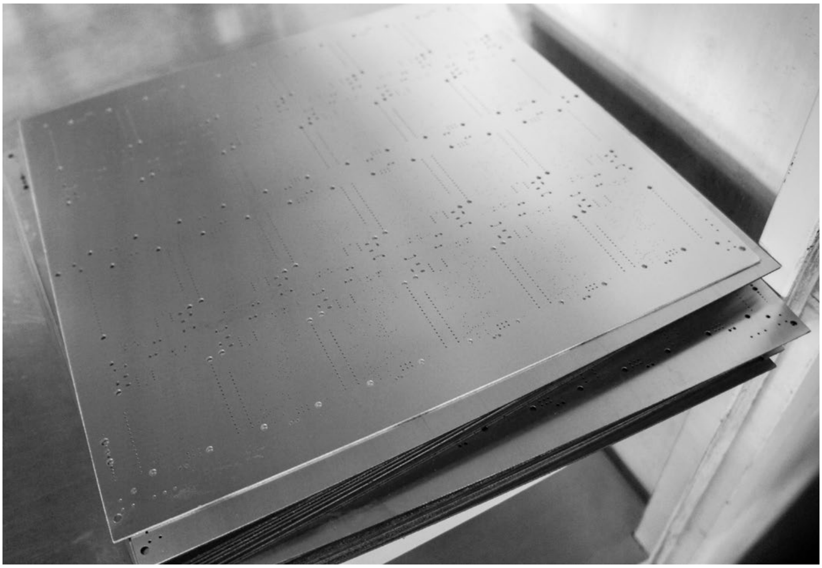


The drill rack used by the CNC drilling machine.
If you've ever had to create NC-drill files, this is that "drill rack."

Every hole in the Arduino board was mechanically drilled, including vias. The same is true of any PCB with through-holes, which is why the via count is such an important parameter in calculating the cost of a PCB.

Note that the particular drill I saw at System Elettronica was relatively small. I've seen massive drill decks in China that gang (mechanically attach) four or six drill heads together in a truck-size machine, processing dozens of panels at the same time as opposed to the three panels this drill could handle. The reasoning behind this approach is that the precise, robotic positioning assembly is the expensive part of a drilling machine. The drill itself is cheap—just a spinning motor to drive the bit. So, one way to increase throughput is to gang several drills together on one large assembly and move them in concert. Each individual drill still goes through its own stack of panels, but for the price of one X-Y positioner, you get four to six times the throughput as the drill I saw on my trip to Italy. Those bigger machines drill so fast and hard that the ground shakes with every via drilled, even from several meters away.

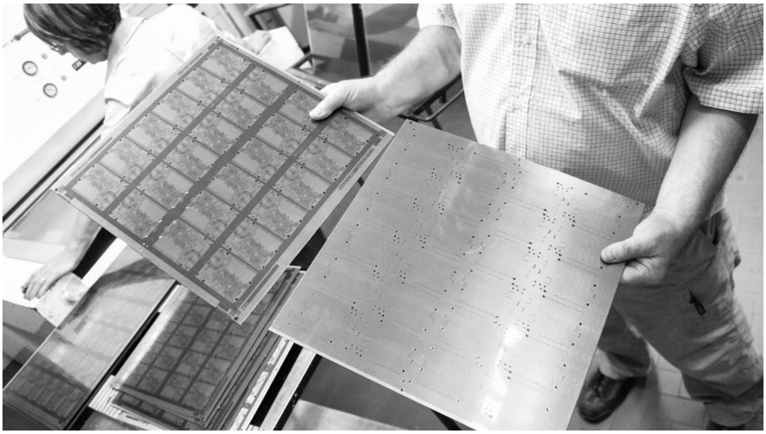
Once the panels are drilled, cleaned, and deburred, they are ready for the next step in the manufacturing process.



A stack of finished, drilled panels of Arduino Leonardo boards

Applying the PCB Pattern to the Copper

The next step is to apply a *photoresist*, a light-sensitive chemical, to the panel and expose a pattern. At System Elettronica, this process used a light box and a high-contrast film. I've also seen direct laser imaging—in the form of a raster-scanning laser—used to apply a pattern to a PCB. Direct laser scanners are more common in quick-turn prototype houses, and film imaging is more common in mass-production houses.

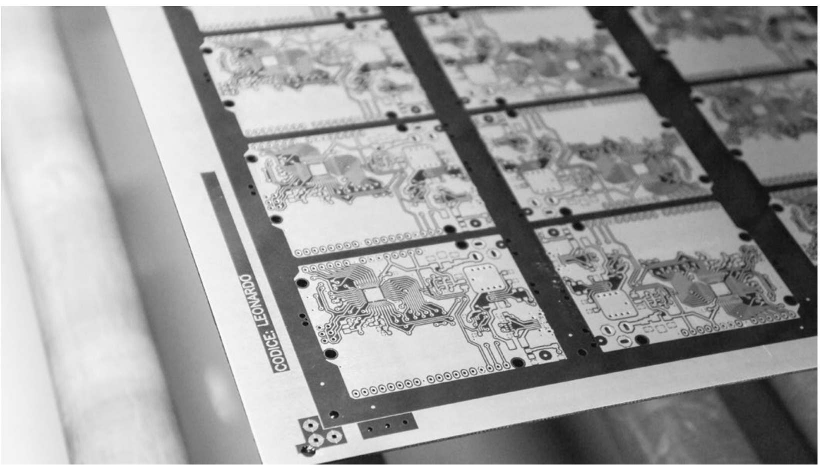


Before and after: the right panel shows photoresist prior to exposure, and the left panel after.

A PCB being mounted into a light box that will expose its unprocessed backside film

After the pattern is applied, each panel of boards is sent into a machine to be developed. In this case, the same machine is used to develop both the photoresist and the soldermask.

The machine that develops the photoresist



This photo of a panel with developed photoresist is one of my favorite photos from the System Elettronica factory. Also, something about "Codice: Leonardo" just sounds cool.

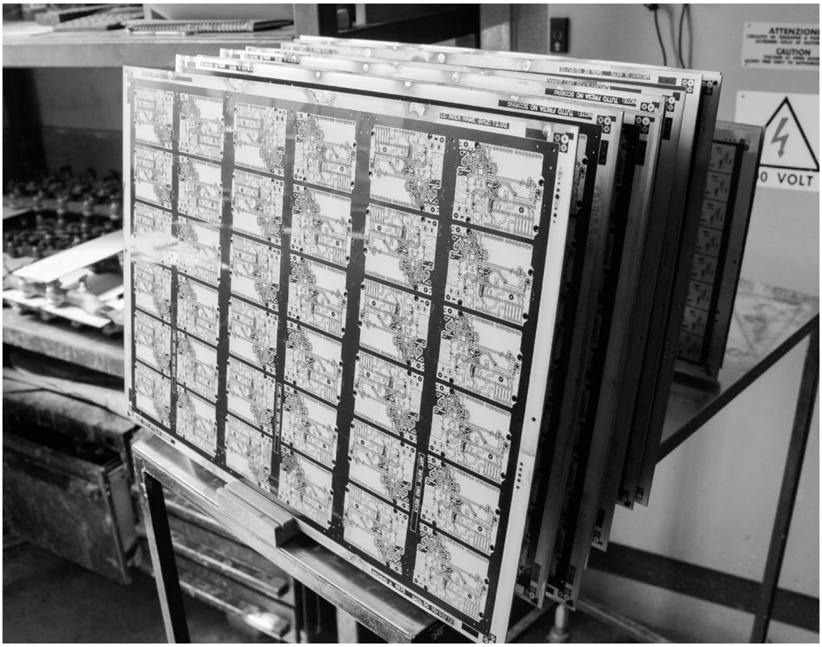
Etching the PCBs

After photo processing and development, the panels go through a series of chemical baths that etch and plate the copper.

The panels are swished gently back and forth in a chemical bath to expedite the etching process. The movement also circulates used etchant away from the panels, ensuring a more uniform etch rate regardless of the amount of copper to be removed. Moving the panels through these chemical baths was fully automated at Scarmagno. Automation is necessary because the panels must be treated with a series of caustic chemical baths with minimal exposure to oxygen. Oxygen can spoil a panel in a matter of seconds, so the transfer between the baths needs to be fast, and the amount of time a panel spends in a bath must be consistent. The baths also contain chemicals harmful to humans, so it's much safer for a robot to do this work.

A machine that moves panels around in etchant

Once the panels are processed in this series of solutions, a dull, white plating (which I'm guessing is nickel or tin) develops on all the surfaces of the panel not treated with photoresist, including the previously unplated through-hole vias and pads.



Panels of Arduino Leonardo boards after going through a series of chemical baths

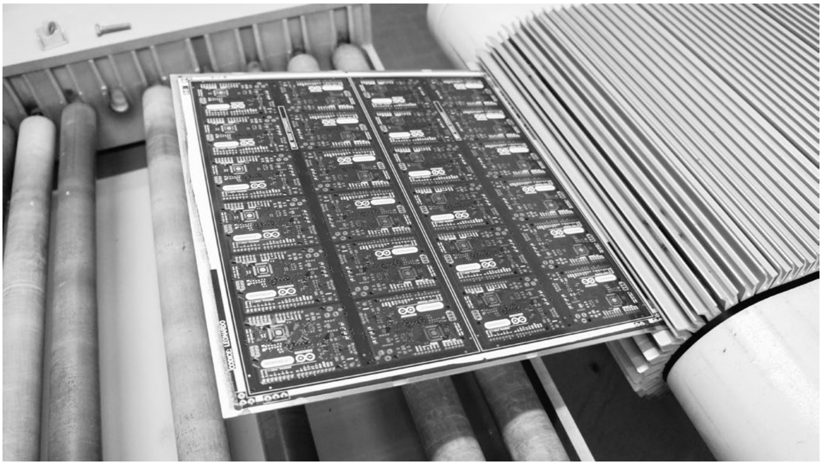
At this point, the resist and unplated copper are stripped off, leaving just the raw FR-4 and the plated copper. The final step of processing produces a bright copper finish.

A panel etched of unwanted copper

PCB panels with bright, shiny copper. This photo doesn't show an Arduino panel, as those weren't going through the machine when I photographed it.

Applying Soldermask and Silkscreen

Once the copper is polished, the panels are ready for the *soldermask* (a protective, lacquer-like layer that insulates the copper traces below and prevents solder bridging above) and *silkscreen* (the ink used to label components, draw logos, and so on). These are applied in a process very similar to that of the trace patterns, using a photomask and developer/stripper machine.



A panel of Arduino boards with both soldermask and silkscreen developed

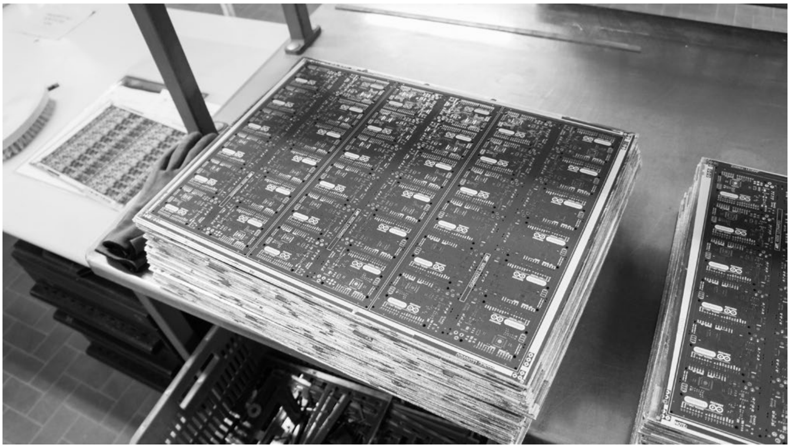
In the case of Arduinos, the silkscreen is actually a second layer of soldermask. A very specific formulation of dry-film white soldermask was procured for the Arduino team to create a sharp, good-looking layer that resolved the intricate artwork you see on Arduino boards—particularly the map of Italy on the backside. Other techniques I've seen for producing silkscreen layers include high-resolution inkjet printing, which is better suited for quick-turn board houses, and of course, the namesake squeegee-and-paint silkscreen process.

Testing and Finishing the Boards

After all that chemical processing, the panels receive a protective plating of solder from a hot-air solder leveling machine.

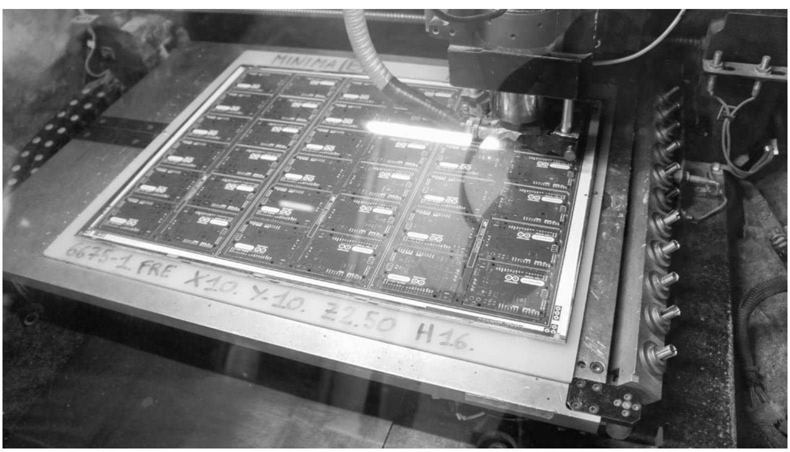
With the solder plating in place, every board is 100 percent tested. Every trace has its continuity and resistance measured with a pair of flying probes. The process I saw is called *flying head testing* (also referred to as *flying probe testing*), and in that sort of setup, several pairs of arms with needlelike probes test continuity between pairs of traces in a swift tapping motion. Considering all the traces on an Arduino Leonardo, that's a lot of probing! Fortunately the robot's arms move like a blur, as it can probe hundreds of points per minute.

NOTE *An alternative to flying head testing is clamshell testing, where a set of pogo pins is put into a fixture that can test the entire board with a single mechanical operation. However, clamshell fixtures are very labor-intensive to assemble and maintain, and require physical rewiring every time the Gerber files describing the PCB images are updated. So, in lower volumes, flying probe testing is more cost-effective and flexible than clamshell testing.*

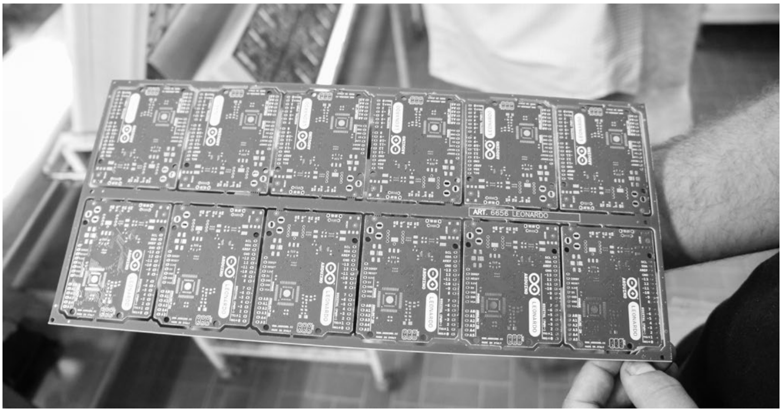


A stack of near-finished PCB panels,
ready for a final step of routing out the individual boards

This particular facility only created the panels; a different factory actually populated the components. In situations like that, before the panels can be sent to the next factory, the individual PCBs need to be routed so they'll fit inside *surface mount technology (SMT)* machines to have the components placed. The panels are once again stacked up and batch-processed through a machine that uses a router bit to cut and release the boards. After that, the boards are finally ready to ship to the SMT facility.



Several Arduino panels, stacked for routing



Smaller 2×6 panels make SMT processing more efficient.

A veritable stack of about 25,000 bare Arduino PCBs, ready to leave the PCB factory. From there, they were stuffed, shipped, and sold to makers around the world!

I'm glad I made the side trip to visit the Arduino PCB factory. I've visited several PCB factories, and every one has a different character and its own set of tricks to improve yield, as well as unique limitations that designers need to compensate for. It was also interesting to see the little trick about using an extra layer of soldermask instead of silkscreen for achieving high cosmetic quality. While the resolution of a silkscreen is limited by the mesh of the silk barrier to hold the paint, soldermask is limited by the quality of the optics and chemical developing, giving over an order of magnitude improvement in resolution and ultimately a higher perceived quality. Normally the lower quality of silkscreen is acceptable because end users don't see the circuit boards inside computers, but for Arduino, the end product *is* the circuit board.

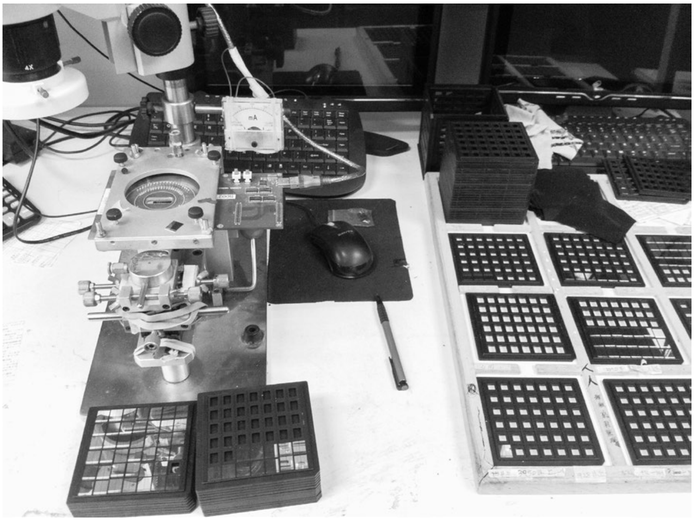
WHERE USB MEMORY STICKS ARE BORN

Several months after my tour of the Arduino factory, I had the good fortune of being a keynote speaker at Linux Conference Australia (LCA) 2013. In my talk, "Linux in the Flesh: Adventures Embedding Linux in Hardware," I discussed how Linux is in all kinds of devices we see every day. This story isn't about Linux, but it does connect me and, tangentially, LCA to a factory.

One of the tchotchkes I received from the LCA organizers was a little USB memory stick with Tux the penguin, the Linux mascot, on the outside. When I saw the device, I thought it was a neat coincidence that about a week before the conference, I had been in a factory that manufactured USB memory sticks exactly like it. I saw the USB stick board assembly process from start to finish, and it surprisingly involved a lot less automation than the Arduino manufacturing process did.

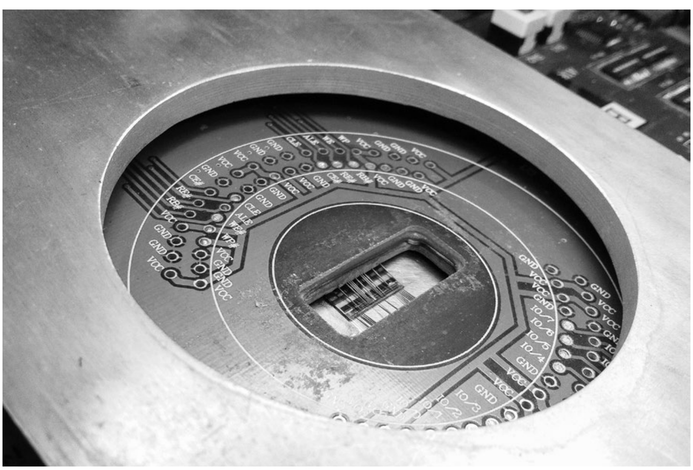
The Beginning of a USB Stick

USB sticks start life as bare flash memory chips. Prior to being mounted on PCBs, these chips are screened for memory capacity and functionality.

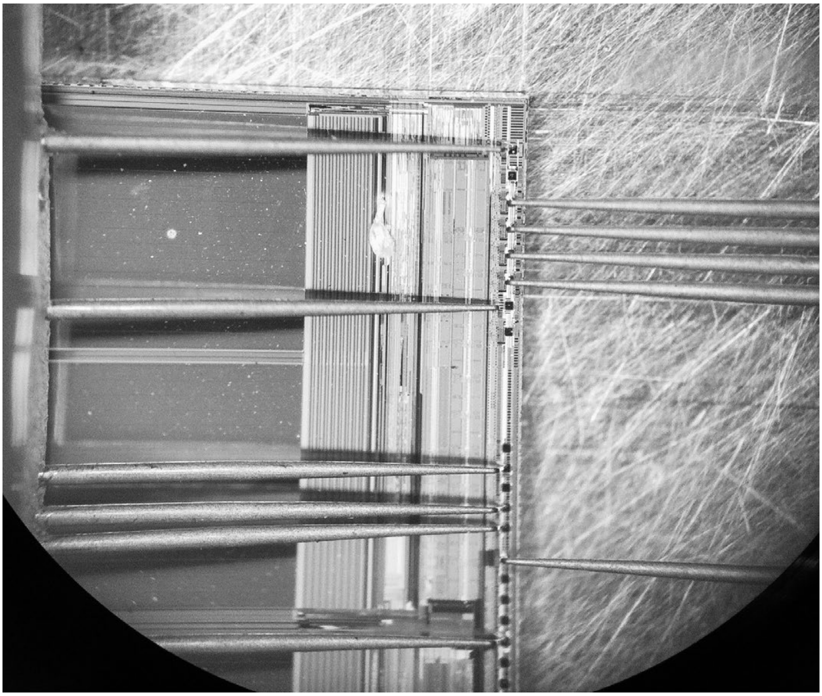


A workstation where flash memory chips are screened.
The metal rectangle on the left with the circular cutaway is the probe card.

At a workstation in this factory, stacks of bare-die flash chips awaited testing and binning with a *probe card*, which has tiny, very accurately positioned pins used to touch down on pads only a little bit wider than a human hair on a silicon wafer's surface. (I love how the worker at this particular station used rubber bands to hold an analog current meter to the probe card.)



The probe card, up close



Looking through the microscope on the microprobing station. Notice the needles touching the square pads at the edge of the flash chip's surface. Each pad is perhaps 100 microns on a side—a human hair is about 70 microns in diameter.

Interestingly, the chips I saw were absolutely not tested in a clean-room environment. Workers handled chips with tweezers and hand suction vises and mounted the probe cards into their jigs by hand.

Hand-Placing Chips on a PCB

Once the chips were screened for functionality, they were placed *by hand* onto the USB stick PCBs. This is not an unusual practice; every value-oriented wire-bonding facility I've visited relies on the manual placement of bare die.

A controller IC being placed on a panel of USB-stick PCBs. The tiny bare dies are on the right, sitting in a waffle pack.

A zoomed-out view of the die-placing workstation

The lady I watched placing the bare die was using a chopstick-like tool made of hand-cut bamboo. I still haven't figured out exactly how the process works, but my best guess is that the bamboo sticks have just the right surface energy to adhere to the silicon die, such that silicon sticks to the tip of the bamboo rod. A dot of glue is preapplied to the bare boards, so when the operator touches the die down onto the glue, the surface tension of the glue pulls the die off of the bamboo stick.

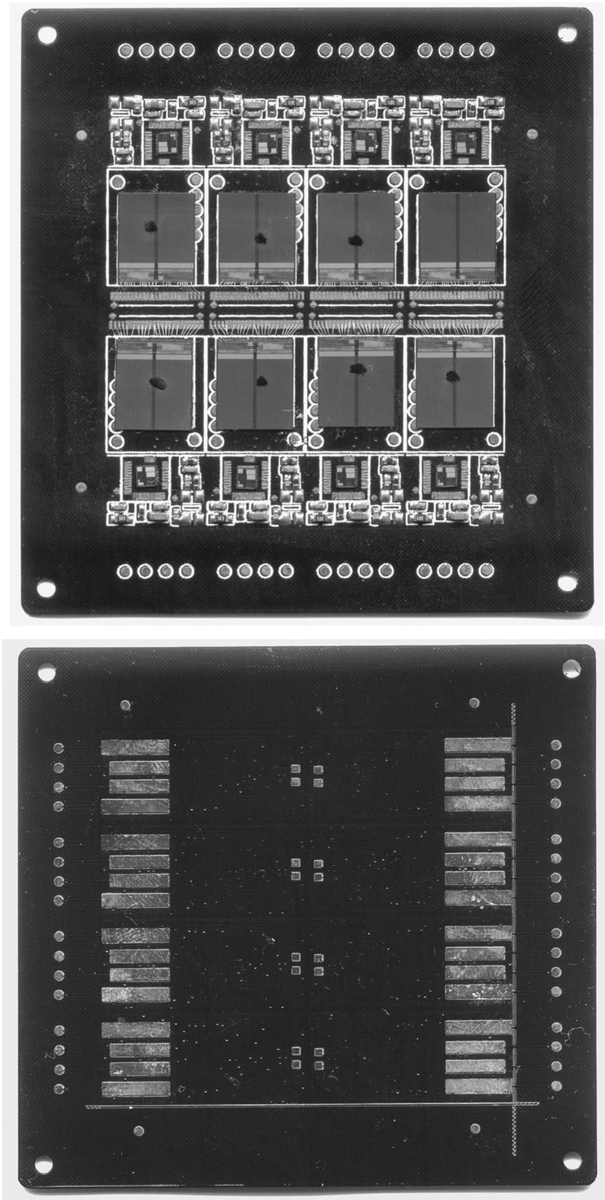
It's trippy to think that the chips inside my USB stick were handled using modified chopsticks.

Bonding the Chips to the PCB

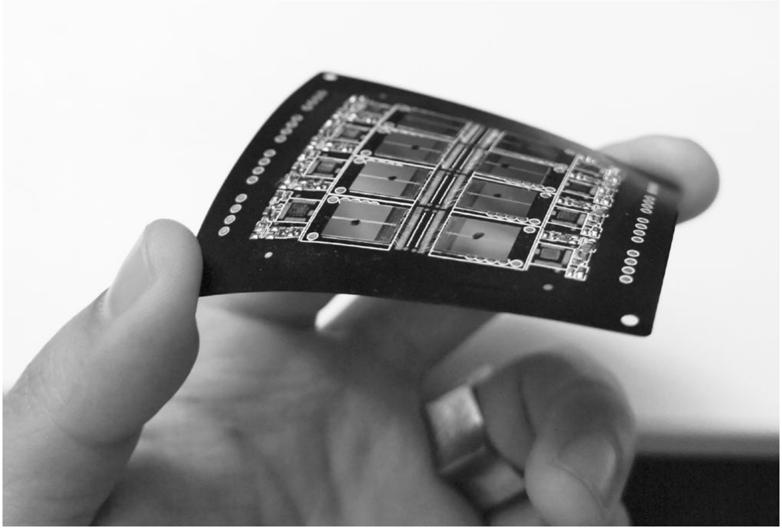
Once the chips were placed on the PCB, they were *wire bonded* to the board with an automated bonding machine, which uses computer-assisted image recognition to find the location of the bond pads (this is part of the reason the factories can get away with manual die placement). Wire bonding is the process that connects an integrated circuit to its packaging, and the automated bonding machine connected wires to the IC at an insane speed, rotating the circuit board all the while. As I watched this process, the operator had to pull off and replace a misbonded wire by hand and then refeed the wire into the machine. Given that these wires are thinner than a strand of hair and that the bonding pads on the packaging and the IC are microscopic, that was no mean feat of manual dexterity.

A Close Look at the USB Stick Boards

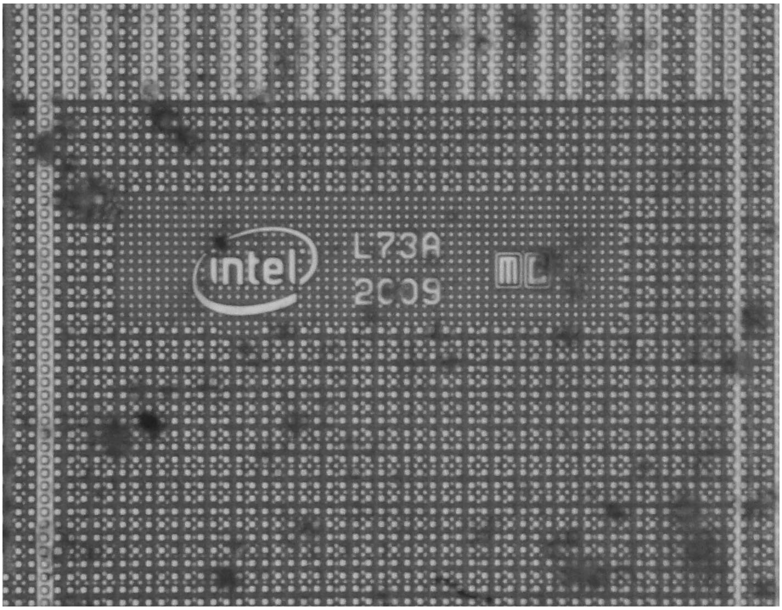
Just as the Arduino factory used panels containing multiple Leonardo boards, the USB memory stick factory used panels of eight USB sticks each. Each stick in the panel consisted of a flash memory chip and a controller IC that handled the bridging between USB and raw flash, a nontrivial task that includes managing bad block maps and error correction, among other things. The controller was probably an 8051-class CPU running at a few dozen MHz.



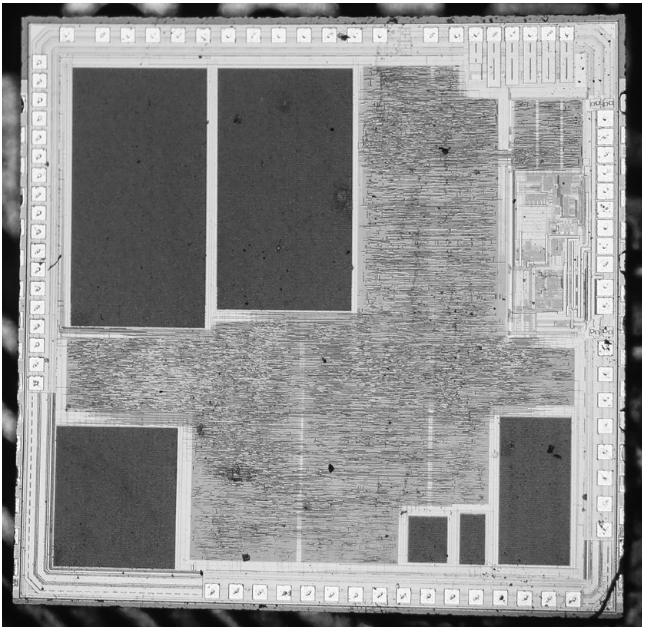
The partially bonded but fully die-mounted PCB that the factory owner gave me as a memento from my visit. Some of the wire bonds were crushed in transit.



Interestingly, the entire USB stick assembly is flexible prior to encapsulation.



The die marking from the flash chip. Apparently, it's made by Intel.



A die shot of the controller chip that went inside the USB sticks

Once the panels were bonded and tested, they were overmolded with epoxy and then cut into individual pieces, ready for sale.

But that's enough about electronics manufacturing; next, I want to show you a different kind of factory floor.

A TALE OF TWO ZIPPERS

My friend Chris "Akiba" Wang has a similar background to mine, except in his younger years he was way hipper: he was a dancer for acts like LL Cool J and Run DMC in the '90s. After going through a phase working for big semiconductor companies, he eventually quit and followed his passion to design and manufacture his own hardware projects. An expert in short-range, low-power wireless networking (he's co-authored a book on Bluetooth low energy and sells an Arduino + 802.15.4 variant called the "Freakduino"), he now consults for organizations like the United Nations and Keio University, runs FreakLabs, and collaborates with various dance acts, such as the Wrecking Crew, to provide unique and compelling lighting solutions for stage shows.

I had the good fortune of introducing Akiba to the greater Shenzhen area on a trip with MIT Media Lab students in 2013—the same trip where we toured the USB memory stick factory. Since then, he's been exploring deeper and deeper into the area. As his work spans the disciplines of performance art, wearables, and electronics, his network of factories is quite different from mine, so I always relish the opportunity to learn more about his world.

In January 2015, Akiba took me to visit his friend's zipper factory. I was very excited for the tour: no matter how humble the product, I always learn something new by visiting its factory. This factory was very different from both the Arduino and the USB stick facilities. There were far fewer employees, and it was a highly automated, vertically integrated manufacturer. To give you an idea of what that means, this facility turned metal ingots, sawdust, and rice into zipper parts.

Approximately 1 ton of ingots, composed of 93 percent zinc and 7 percent aluminum alloy

Compressed sawdust pellets, used to fuel the ingot smelter

Rice, used to feed the workers

Finished zipper puller and slider assemblies

Let's look at one side of how that process actually works.

A Fully Automated Process

Between the three input materials and the output product was a fully automated die-casting line to create the zipper pullers and sliders, a set of tumblers and vibrating pots (or, as I like to call them, "vibrapots") to release and polish the zippers, and a set of machines to deburr and join each puller to its slider. I think I counted fewer than a dozen employees in the facility, and I'm guessing their capacity well exceeds a million zippers a month.

I was mesmerized by the vibrapots* that put the zippers together. There were two vibrapots: one with pullers and one with sliders. Both sliders and pullers were deposited onto a moving rail, and as I watched these miracles at work, it looked as if the sliders and pullers were lining themselves up in the right orientation by magic. Each fell into its rail, and at the end of the line, they were pressed together into a familiar zipper form, all in a single, fully automated machine.

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* I honestly don't what they're called, so yes, I'm going to keep calling them that.

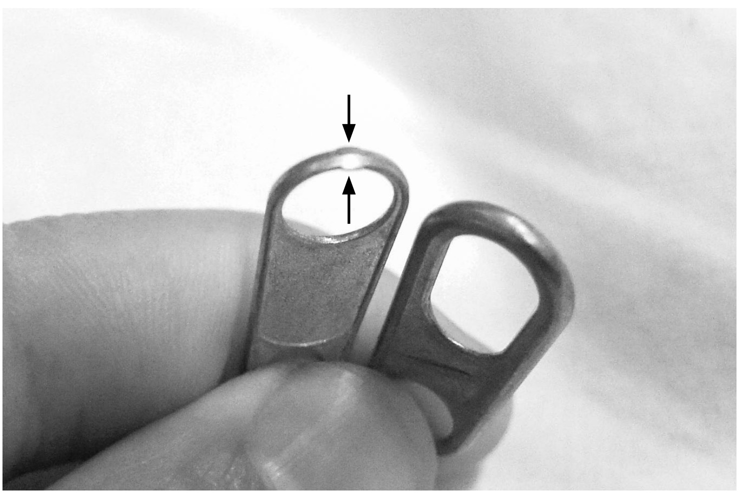
When I put my hand in the pot, I found there was no stirrer to cause the motion; I just felt a strong vibration. I relaxed my hand, and found it started to move along with all the other items in the pot. The entire pot was vibrating in a biased fashion, such that the items inside tended to move in a circular motion. This pushed the pullers and sliders onto the set of rails, which were shaped to take advantage of asymmetries in the objects to allow only the pieces that jumped on the rail in the correct orientation to continue to the next stage.

A Semiautomated Process

Despite the high level of automation in this factory, many of the workers I saw were performing one operation. They fed the pullers for a different kind of zipper into a device connected to another vibrapot containing sliders, while the device put the sliders and pullers together.

Of course, I asked, "Why do some zippers have fully automated assembly processes, whereas others are semiautomatic?"

The answer, it turns out, is very subtle, and it boils down to shape.



Note the difference in these two pullers, indicated by the arrows.

One tiny tab, barely visible, was the difference between full automation and needing a human to join millions of sliders and pullers together. To understand why, let's review one critical step in the vibrapot operation. A worker kindly paused the vibrapot responsible for sorting the pullers into the correct orientation for the fully automatic process so I could take a photo of the key step.

Pullers coming through the vibrapot

When the pullers came around the rail, their orientation was random: some faced right, some left. But the joining operation must only insert the slider into the smaller of the two holes. That tiny tab allowed gravity to cause all the pullers to hang in the same direction as they fell into a rail toward the left.

The semiautomated zipper design doesn't have this tab; as a result, the design is too symmetric for a vibrapot to align the puller. I asked the factory owner if adding the tiny tab would save this labor, and he said absolutely.

At this point, it seemed blindingly obvious to me that all zippers should have this tiny tab, but the zipper's designer wouldn't have it. Even though such a tab is very small, consumers can feel the subtle bumps, and some perceive it as a defect in the design. As a result, the designer insisted upon a perfectly smooth tab, which accordingly had no feature to easily and reliably allow for automatic orientation.

The Irony of Scarcity and Demand

I'd like to imagine that most people, after watching a person join pullers to sliders for a couple of minutes, would be quite content to suffer a tiny bump on the tip of their zipper to save another human the fate of manually aligning pullers into sliders for eight hours a day. Alternatively, I suppose an engineer could spend countless hours trying to design a more complex method for aligning the pullers and sliders, but there are two problems with that:

- The zipper's customer probably wouldn't pay for that effort.
- It's probably net cheaper to pay unskilled labor to manually perform the sorting.

This zipper factory owner had already automated everything else in the facility, so I figure they've thought long and hard about this problem, too. My guess is that robots are expensive to build and maintain; people are self-replicating and largely self-maintaining. Remember that third input to the factory—rice? Any robot's spare parts have to be cheaper than rice for the robot to earn a place on this factory's floor.

In reality, however, it's too much effort to explain this concept to end customers; in fact, quite the opposite happens in the market. Putting the smooth zippers together involves extra labor, so the zippers cost more; therefore, they tend to end up in high-end products. This further enforces the notion that really smooth zippers with no tiny tab on them must be the result of quality control and attention to detail.

My world is full of small frustrations like this. For example, most customers perceive plastics with a mirror finish to be of a higher quality than those with a satin finish. There is no functional difference between the two plastics' structural performance, but making something with a mirror finish takes a lot more effort. The injection-molding tools must be painstakingly and meticulously polished, and at every step in the factory, workers must wear white gloves. Mountains of plastic are scrapped for hairline defects, and extra films of plastic are placed over mirror surfaces to protect them during shipping.

For all that effort, for all that waste, what's the first thing users do? They put their dirty fingerprints all over the mirror finish. Within a minute of a product coming out of the box, all that effort is undone. Or worse yet, the user leaves the protective film on, resulting in a net worse cosmetic effect than a satin finish.

Contrast this to satin-finished plastic. Satin finishes don't require protective films, are easier for workers and users to handle, last longer, and have much better yields. In the user's hands, they hide small scratches, fingerprints, and bits of dust. Arguably, the satin finish offers a better long-term customer experience than the mirror finish.

But that mirror finish sure does look pretty in photographs and showroom displays!