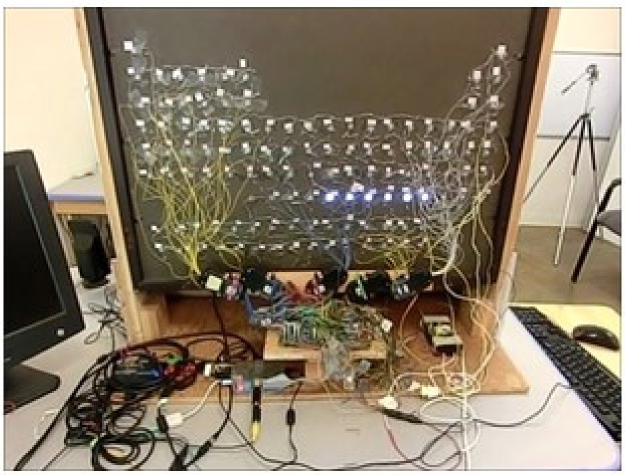
What the light-up periodic table is:

Four students, May 2014, with tools of their trades: Louis (loves programming). Arabella (great narrator), Alegra (loves hand and power tools), and Ayanna (programming and tools are her metier).

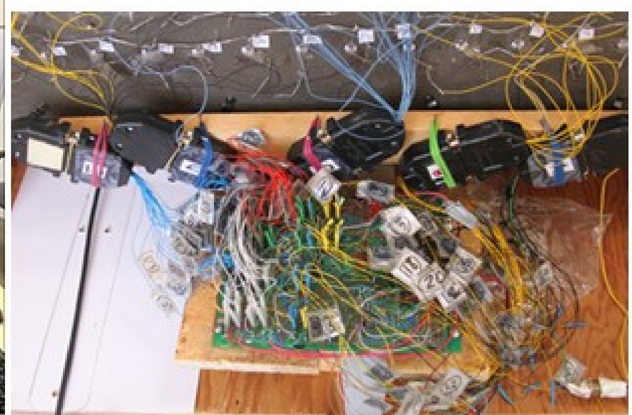
The LUPT centers on a 45 cm X 60 cm printed chart of the periodic table of the chemical elements, functioning for five different presentations about the elements, chosen by the viewer. These presentations, with LEDs and audio files, are the elements in order of atomic number, or date of discovery, or nucleosynthesis in the Big Bang and in stars, or abundance in the Earth's crust, or abundance in the human body. A viewer, prompted by concise text on a small TFT monitor, sees the options to choose any one presentation, using four simple buttons. Having chosen a presentation, the viewer can step through the sequence of the presentation – e.g., the 112 elements on our (slightly dated) version of the chart, with the option to skip forward or backward at will...or to exit and choose a new presentation. For any choice within the presentation, one (or more) LED(s) will light up behind the appropriate element(s). At the same time, a narration, 10 to 60 seconds long, will play, presenting interesting facts about the element or set or elements. Students created the narrations researching them, writing them, tuning them up for timing and content, and recording them. The most attractive feature is that the entire device was designed and built from scratch by the students, starting with 4th- and 5th-graders in 2013, finishing with four students in 7th and 8th grades. They did aesthetic design, design of the user experience. They used hand and power tools, did wiring, soldering, electronic design for current paths and loads and with logic gates (addressable latches), programming of a tiny full-function Raspberry Pi computer, testing, and debugging. They learned project management, careful documentation, and public speaking. The project stretched out over three full years as the students worked in teams during our school's twice-a-week technology class led by teacher Dr. Vince Gutschick. (We also did some post-school-day and weekend work.) An 8-minute video summarizes the story visually, at https://youtu.be/urcIdu2K_WU. We have more details below, if you wish.

The TFT monitor displays selections

Arabella selects oxygen for its abundance in the human body



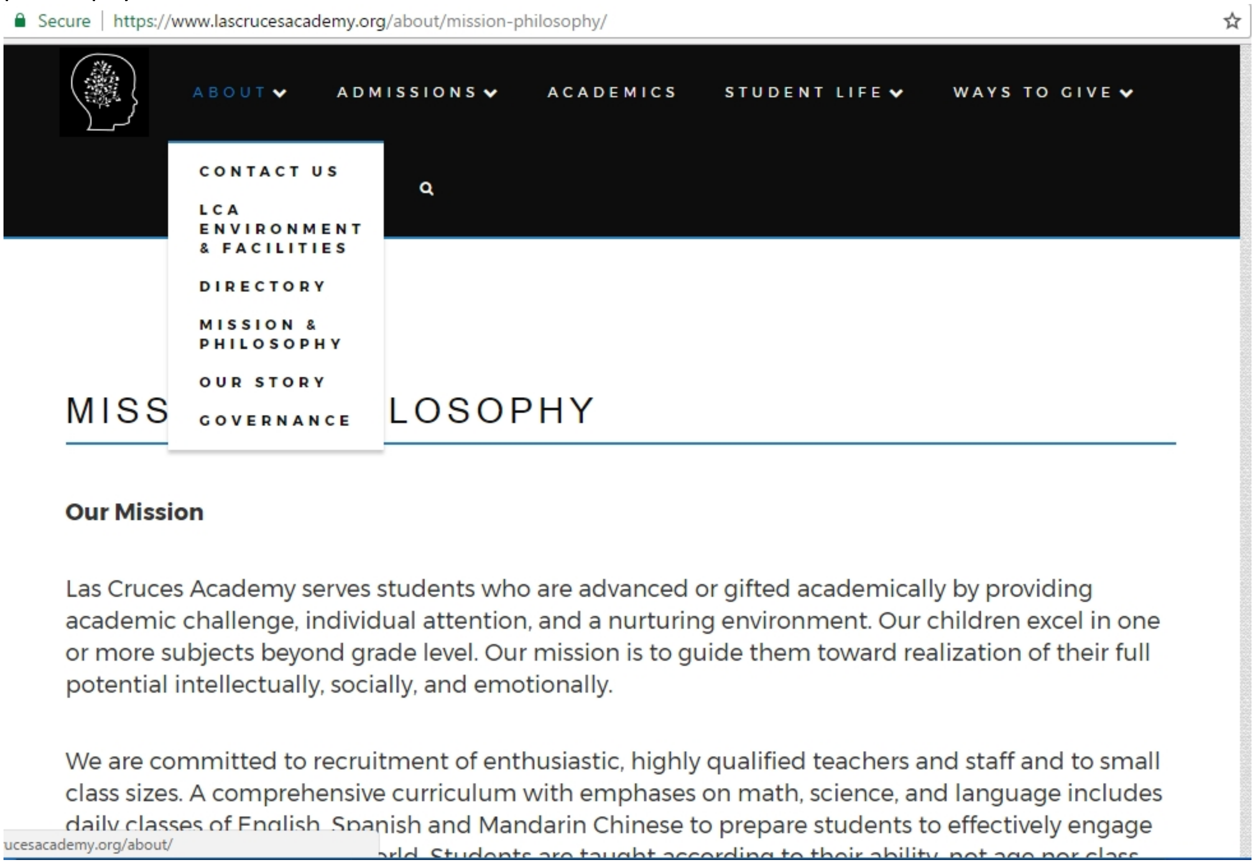
The back shows the LED wiring, the Raspberry Pi (toward the left), the logic board (low, at center), and other electronics + audio system



A detail of the logic board shows 112 wires from LEDs going to 14 addressable latches (mounted on bottom)

Motivation: Our students are talented and ready for project-based learning from the early grades. We also share with them our culture of science and technology and our experiences (Vince and Lou Ellen, school founders) around the world. One of those experiences was in July, 2013, at the Arecibo Radio Observatory in Puerto Rico (alas, on the chopping block at the National Science Foundation). In the observatory's museum was a periodic table of the chemical elements with 4 buttons to push to light up any of 4 sets of elements: those formed in the Big Bang, those formed in the Sun at its present age, those to be formed by the end of the Sun's life, and those formed in a supernova. We figured we could make a similar periodic table...and, rapidly, we realized that, with Vince's electronics experience, we could make one with much greater capabilities. It would have presentations that would single out individual elements or groups of elements, and it would have student-recorded narrations to play for any selection. We would involve the students in grades 4-6 in every aspect: designing the user experience, learning about the elements to make the narrations, constructing the physical box, drilling holes to place LEDs, wiring, soldering, learning the logic of control of the LEDs, learning Python programming to create the physical controls, and a great deal of basic electronics. The device and our experiences in presentations are also viewed as great tools for outreach to the public and to students in other schools or in homeschooling.

Why it happened at the LCA: We had the motivation we needed. Underpinning all of it is our philosophy of education. You can read about this on our website in some detail.



We are a non-profit private school, founded in 2007 by Lou Ellen Kay (Ph. D., Biology, CUNY) as the most important thing she could do with the rest of her life. Having learned science and public issues, and having taught for decades, she was alarmed at environmental and political conditions. Starting a school to educate talented students to become wise and compassionate leaders is a clear contribution to resolving the problems. We incorporated in 2007, found board members, teachers, students, helpers, and a location to rent, enabling us to open in August, 2009 with 14 bright kids of parents who trusted in a new school and a new approach. We have small classes, student placement by ability rather than age in each class level, foci on science, math, and languages (English, Spanish, Chinese), devoted teachers chosen for knowledge and passion than simple credentials, world experience (having visited or lived in 38 nations on 6 continents), and great resources amassed over long careers, and, notably, freedom from excessive testing and the highly constraining mandates of our public schools. We also wrote outreach as a core activity into our Articles of Incorporation, following that up with activities, charitable and educational, outside our school.

Why we're sending this around to people and institutions: Our reasons are several. We are honoring our students for their accomplishments. More to the interests to the broader public and outside organizations is our wish that projects such as this can be evaluated as a model for primary education. We are all aware of the frustrating and perplexing low performance and false starts in public education in the US. We see many reasons for the problems, which we need not detail. Many of the problems are structural, a glaring one being the model we borrowed from Prussia in the late 1800's, of lock-step education, all students of a given chronological age getting the same academic content, with minor exceptions. This model produces cogs in an industrial machine, not engaged and innovative citizens. Co-founder Vince Gutschick (Ph. D., chemistry, Caltech) contrasted the old ideas and the new ideas (mostly yet to be implemented) in a TEDxElPaso talk. We are following through in our Academy and offer our experience to all who have an interest, with this story as a recent element. We invited comments and inquiries. Our contact points are email (director@lascrucesacademy.org, vince@lascrucesacademy.org), phone (575-521-9384 for Lou Ellen, 575-571-2269 for Vince), and, soon, curated comments on our website, https://lascrucesacademy.org.

The pieces that came together:

The students: in November, 2013, we had 8 students in grades 3-5 and we were engaging them in project-based learning. Arabella, Alegra, Ayanna, Andres, Frankie, and Louis became regular workers out of class time, with Ben, Adrienne, and Syan participating at times. As students move on over the years with changes in family situations (Arabella and Frankie staying the whole time), others came in – Kira and Xitlali joining in 2015.

The time: We made technology a regular class in the fall of 2015, meeting twice weekly. Students also worked in some periods after regular classes ended and on some weekends. Vince as the teacher also worked these times and at home.

The background of the students and of Vince: Among the students, Louis had, and has, an abiding interest in all things digital; we got the others engaged and enthusiastic. Vince has an extensive background, holding a PhD in chemistry from Caltech and having much experience in building research equipment in chemistry, field sensors and dataloggers, and lab and field equipment for plant physiological ecology. His teaching experience extends from co-teaching a graduate course in scattering theory at Caltech to chemistry, physics, many fields of biology, and photography, at levels from elementary school on up, and outreach via public presentations.

Equipment and supplies: We had major hand and power tools, electronic parts, test equipment, solder-ready project boards, construction parts (wood, Masonite, Plexiglas, fasteners), a power strip and power cords, and computer apps on hand from Vince and Lou Ellen's careers in science and in crafts. We had donations: the chart from Perkin-Elmer, the Raspberry Pi kit from Board member David Gutschick, jigs with magnifiers and lights from Lou Ellen, a table top from . We bought supplies and devices: a shadow box, LEDs, resistors, solder, a soldering station, wire, more wire-wrap tools, a USB hub, a TFT monitor, three books on the Raspberry Pi and Python programming, RPi breakout boards and cables, a sound card, pin connectors, button switches, logic and op amp chips, chip sockets, D-sub connectors, an HDMI-VGA converter, dedicated speakers, and additional wood for table legs. In all, we paid out about $1200 in direct expenses.

H**ow it all developed, from November, 2013 through December, 2016:**

Initial design: Before the students got involved in the design and construction, they learned the background needed to understand the periodic chemical behavior of the elements. We covered nuclear and electronic structure and interesting chemical properties, from valence to bonding types to reactivity to practical uses. Having decided upon independent control of each LED (each element), Vince then chose the basic control structure. We'd use a *tiny* computer, showing ingenuity over raw computing power. We chose a Raspberry Pi computer, choosing it over an equally tiny Arduino or Domino for several reasons. All these small computers have a great advantage over essentially all other general purpose computers: they have external control lines, or input-output pins, that can be used to control a great range of devices. We'd also use addressable latches. These are small integrated circuits with independently controllable "drains." Drains are pins or connections that can be turned to low or high voltage with simple commands; when a pin is set to low voltage, current can flow into it, allowing current to flow through an LED and light it up. The option rejected was the use of serial registers, for which a long command string would be needed for every change. Finally, we'd use a few pushbuttons for the user to select one of the 5 presentations and to select the choices within a presentation, such as an element by its atomic number. There would be no keyboard and only a small monitor presenting concise information. It would not be a giant desktop computer or cell phone – rather, a device using fundamental electronic design. This would also let us program our own application with any functionality we want, and with the Python language in its syntax much simpler than Web programming languages (Javascript, e.g. – the older students are learning that now in our computer programming class).

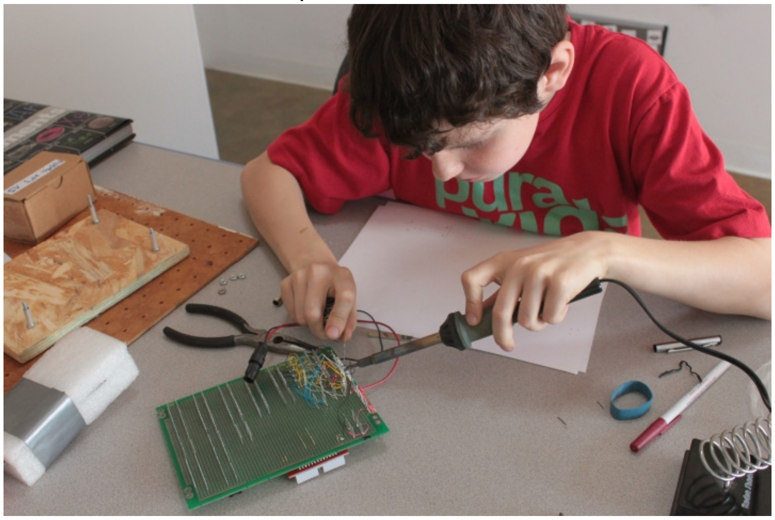
Making things: We contacted Perkin-Elmer to get a 22" x 28" chart of the elements. We bought a shadow box to fit it in, with students making careful measurement to cut and mount it. We then cut Masonite as a backing, then drilling holes that aligned with the chart's cells for each element – more careful measurement and much fun for students using power tools. Next we inserted 112 white LEDs that we'd drive at 18-20 mA each for a nice bright signal. We wired 5 bus wires to provide the +5V to all the LEDs and then 112 individual wires with current-limiting resistors to connect to the drains of the addressable latches.

At this point, we weren't concerned with the logic for controlling the LEDs; we tested that each LED did function when its wire were tied to ground potential. The wiring and the soldering were also a big hit with the students; a few had their rite of passage with a couple of solder burns.

Concurrent progress on all fronts, in electronics, programming, and more:

Progress in electronics - from start to finish:

<u>Basic electronics:</u> So much depended upon directing currents and voltage signals, so the students learned Ohm's law and voltage distribution through a circuit (in essence, Kirchoff's law). Both lessons and direct measurements brought the lessons home. They practiced setting the current level through the LEDs to get a bright light that was still tolerated by the LED and within the capacity of the power supply when nearly all 112 LEDs would be on, illustrating elements created in a supernova. Wiring and soldering came early. While learning good connection techniques, students greatly enjoyed seeing their handiwork in a concrete product.



Using the Raspberry Pi computer to send and receive voltage signals brought us to a higher level of care in design and in wiring. The general purpose input-output (GPIO) pins are very easily damaged by applying incorrect voltages or short circuits; mistakes could easily have been the end of the "RPi." After reviewing all the precautions, we wired up successively more complex test circuits, operating LEDs, using simple switches, and, finally, operating addressable latches. All the testing made progress slow, but we only lost one integrated circuit, and Vince did that, inserting a replacement latch "blind" on the underside of a board.

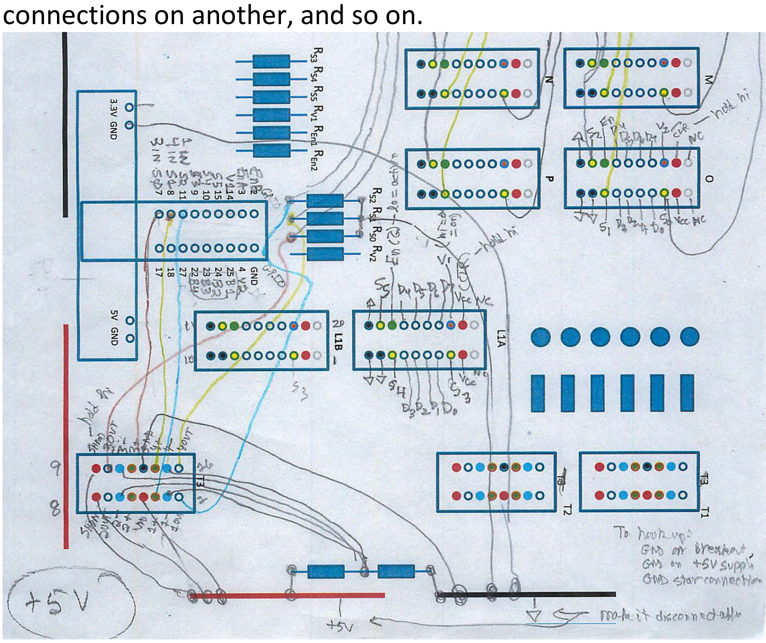
Students learned about datasheets for devices – LEDs, latches, op amps – so that we could design circuits. They learned to read codes for resistors. We figured out how to use resistors to set proper initial voltages on control lines (pull-up and pull-down resistors) with high enough resistance that a new signal sent on a control line would not need to provide much current.

The next big step in electronics was **using addressable latches**, which are described in brief a few paragraphs above. We chose TPIC6B259 latches in small plastic DIP packages; these have pin spacings large enough, 1/10 inch, to be wired by hand when mounted in a socket. Each latch has 8 drains. Voltages (from the RPi computer) on 3 selector lines set a choice of which drain is being addressed. The code is binary. Letting 1 stand for high voltage on a selector and 0 stand for low voltage, a setting of, say, 1 0 1 (*hi* on selector 2, *lo* on selector 1, *hi* on selector 0) stands for the number 5 (a 4 plus no 1's and a 1). Voltages on other pins determine what we want to happen at drain number 5. A *hi* voltage on an Enable pin lets us make a change on drain 5; a *lo* signal forbids any change to occur, protecting a previous setting. A *hi* voltage on the Data pin sets the drain voltage *lo* (current on, LED on), a *lo* turns the drain off. There is a pin to clear all settings on all 8 drains, though we chose not to use it. Of course, there are pins to supply power to the chip. Students learned binary arithmetic to control all the settings. This included some interesting functions uncommon to encounter outside deep coding, such as the bitwise AND. Consider wanting to set drain 5 again. A decimal number N, say, 5, has to be decomposed into 3 bits, a *1* for selector 2, a *0* for selector 1, and a *1* for selector 0. One writes, say, S2=(N&4)/4. The term N&4, compares the bits of N, which are 1 0 1, with the bits in the number 4, which are 1 0 0. The result is a *1* where bits in both numbers are *1* and a *0* otherwise. Clearly the result is 1 0 0 in binary, or 4 in decimal. We divide by 4 to get 1. Doing the same to compute the second bit makes the comparison of decimal number 2, which is binary 0 1 0, with decimal 5 , which is again 1 0 1 0- that is, S1=(N&2)/2. The result is 0. Finally, the result for S0 is 1. Students also learned about modulo arithmetic, noted later.

Controlling a single latch is fun; one can see one's handiwork in making connections. One can send voltage signals to the pins on the latch, using simple mechanical switches or plugging-in of wires, or, with more confidence in programming, the GPIO pins of the Raspberry Pi. Put 8 LEDs out, one connected to each drain (and a positive current source and a current-limiting resistor) and watch the LEDs turn on in any chosen pattern.

Controlling all 112 LEDs requires a hierarchy of latches, in one of several possible connections. There have to be 14 "final" latches connected to the LEDs lighting up behind each element on the chart, of course. Consider wanting to light up element 60, neodymium or Nd. LEDs for the first 8 elements, H through Ne, are connected to what we'll call latch 2A; elements 9-16 are on latch 2B, and so on; elements 55-64 are on the 8th such final latch, latch 2H. Number 60 is the 6th number in the series 55-64, so we want to control the 6th drain...which is denoted as drain 5, because the number in our binary control scheme always starts with 0, not 1. Ah, we want to set selectors on this drain as 1 0 1, as in the example earlier. How do we choose the 8th latch and not all the others? We have to send the same signals, S2, S1, S0, to all these 14 final latches (we don't have 112 control lines from the RPi); we need to selectively enable only the 8th latch, 2H. We can do this by using the voltage on another latch used only for signaling to 8 final latches. This is straightforward to work out. We send 3 voltage signals to the selectors on this latch – call it 1A- in order to set its drains *hi* or *lo*. In the case in question, we set a *hi* on the final drain, D7, and a *lo* on all the others. The voltages on the drains are sent to the Enable pins on latches 2A through 2H; only latch 2H gets enabled, and we only reset the connection to element 60 on or off. One last item is that there has to be another primary latch, 1B, to control latches that work elements 61 and higher.

Wiring all these connections could be a nightmare, with connections to so many drains and control pins and power pins, not to mention pull-up or pull-down resistors (and some more devices, described shortly). We also used star connections from any power or signal connections that had to branch out from one source to many latches; you can read about these to see how a star connection prevents different devices from seeing slightly different voltages. Much work was expended in drawing, first, a master wiring diagram with approximately 400 wires and then, more sanely, partial wiring diagrams that a worker can follow – all the positive power connections on one diagram, all the Enable connections on another, and so on.

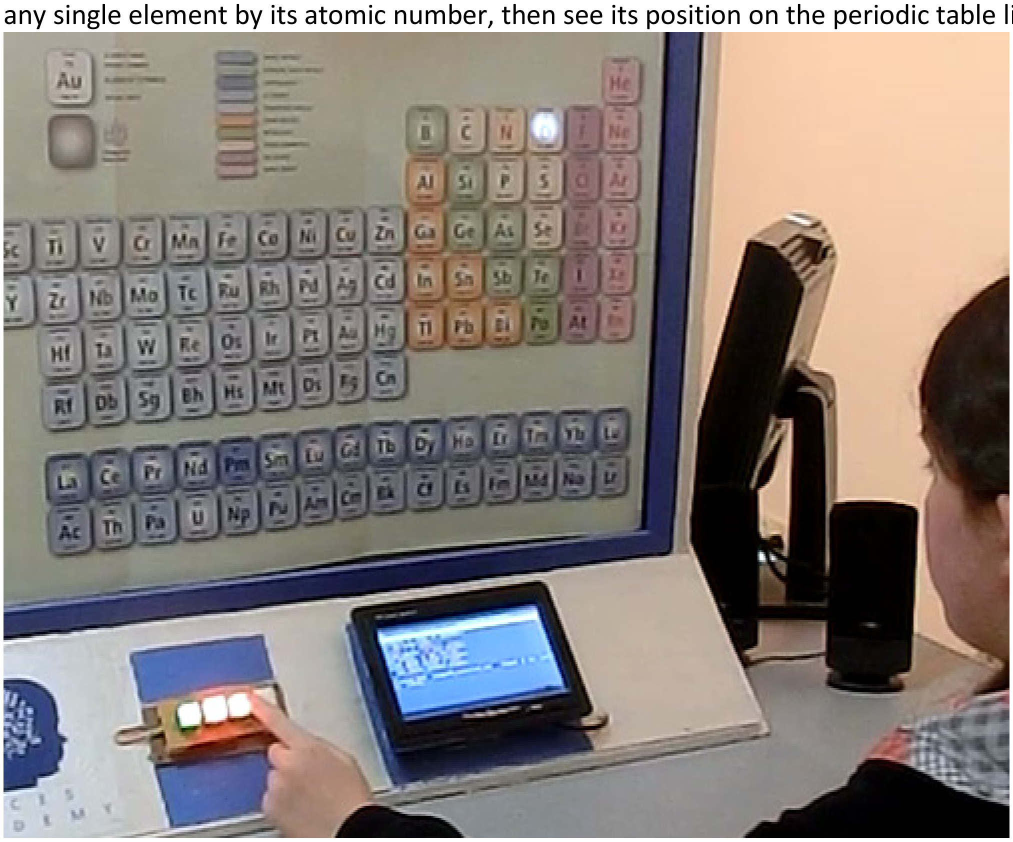


Students began the wiring and Vince completed it. We only had one missed wiring. Almost all the wiring was done as wire-wrap, using 30-gauge plastic insulated wire. Students learned to handle the very fine wire well. Wire-wrapping allowed us to make quick (relatively quick) connections and to undo/redo connections if necessary – rarely necessary, fortunately. Students learned meticulous tracing of wires visually and with an ohmmeter to verify that the connections went exactly where they had to be. After all the checks, we soldered the wires in place. Again fortunately, we had only a few cases of wires needing desoldering and new placement.

<u>An intervening adjustment, a major one:</u> translating voltage levels. We played with the TPIC6B259 chips, thoroughly examining their performance. Alas, these work on 5V power and 5V signals, while the Raspberry Pi provides and accepts only 3.3V signals. Vince found latches working on 3.3V and made a 3-latch hierarchy, but discovered that they could not handle the total current of 160 mA with all drains active, as occurs in displaying the elements created in a supernova. We had to return to the 5V chips. We added a circuit layer that accepted 3.3V signals and translated them to 5V. In brief, we used quadruple (quad) operational amplifiers (op amps),each op amp comparing a signal that is either 0V or 3.3V to a reference voltage and then flipping either full off (0v) or full on (5V). The extra complexity made the wiring gnarlier but manageable.

Progress in designing and refining the user experience - from start to finish:

<u>What to present:</u> the original motivation was to make a simple presentation with 3 choices: the elements formed in the Big Bang (H, He, Li), the elements created in the Sun currently in significant amounts (He, C, N, O), and the elements created in a supernova (everybody, omitting H). Our design gives us full control over all the elements, so we developed four other presentations. The first is elements in order of atomic number. With simple controls to describe shortly, a user can navigate to any single element by its atomic number, then see its position on the periodic table light up



and hear a short narration, 10-20 seconds, with interesting facts about the element. Here is one of our scripts ready for reading and color-coded by author:

Sometimes people hear lutetium metal described as the most expensive rare-earth element. That information is out of date. It is more common naturally than silver. It is used in petroleum engineering.

Thallium is a soft, gray, post-transition metal not found uncombined in nature. It resembles tin but discolors quickly when exposed to air. It is a very poisonous element that has no smell or taste.

Plutonium, a radioactive element mostly made in nuclear reactors, is lots of times called the most poisonous element. Nearly all of America's plutonium is kept in Los Alamos. The only allowed private possession of plutonium is in pacemaker batteries.

Einsteinium, a silvery, radioactive, man-made element, was first detected in 1952 during a hydrogen bomb test. It has a half-life of 471 days and it is named after Albert Einstein.

Another is elements in their order of discovery, allowing for 13 of them being known to the ancients, having no named discoverer. A fourth is elements in order of abundance in the Earth's crust, and a fifth is elements in order of abundance in the (average) human body.

Creating the narrations was a huge exercise in gaining knowledge about the elements, public speaking, critiquing content, and recording quality audio. We set ourselves a huge task, creating about 320 different narrations: 112 for elements in order of atomic number, another 112 for elements in order of discovery, 3 for groups of elements in order of nucleosynthesis, 68 for elements in order of abundance in the Earth's crust (the last 44 are too rare to have been measured accurately or were made artificially), and 20 for elements in order of abundance in the human body (we got a little tired by this time). All students were given the task of researching information about a set of elements, then writing a concise, informative, and entertaining text about each element that would be recorded. We sat in our technology class many times listening to students read a proposed narration while checking it for accuracy, fluidity of delivery, and length. We'd reach consensus and proceed to recording. Student Arabella wrote about 85% of the narrations, being highly motivated and taking her spare time out of class. Students learned to use a microphone and the Audacity application for recording the narration into a WAV-formatted file on a PC, which then was transferred to the RPi. Some recordings went simply, while others required several or even many takes. Students became quite performance-conscious and adept.

Navigating to choose a presentation and to any one part of a chosen presentation: Student Arabella developed ideas of using various areas of a small monitor to show users how to select presentations. We then simplified it some, to use a quite small TFT monitor, 4" x 6", allowing 10 lines of 32 characters in 14-point text. To make it more engaging, we imported the colorama module in Python programming to distinguish features by color; that was fun. We went through several iterations of proposed arrangements to buttons for the user to make choices, with the buttons activating momentary-contact switches. The final choice was using 4 buttons with re-used functions. The buttons are square in shape and of a size suited to small-to-adult hands, being squares 15 mm on a side, mounted about 20 mm apart. Three of the buttons have lighted LEDs, one green, one red, one with both red and green making amber. The last is white, unlit. At the start, the green and red buttons allow the user to step forward and backward among the 5 presentations, each described by a line of text that gets highlighted as it is ready for selection. The selection wraps around, or, we may say, obeys arithmetic modulo 5, going either past the end or the beginning. Pushing the amber button causes the program to enter the selected presentation. The buttons now have a new, if similar, function. The green and red buttons move the selection forward and backward. If the user is in the presentation by atomic number and is currently seeing element 5, boron, highlighted on the screen, he or she can push the green button to advance to element 6, carbon, or the red button to go to element 4, beryllium. Pushing the amber button causes the appropriate element's cell on the chart to be light from behind by its LED. It also starts the playing of an audio file, or narration, about the element.

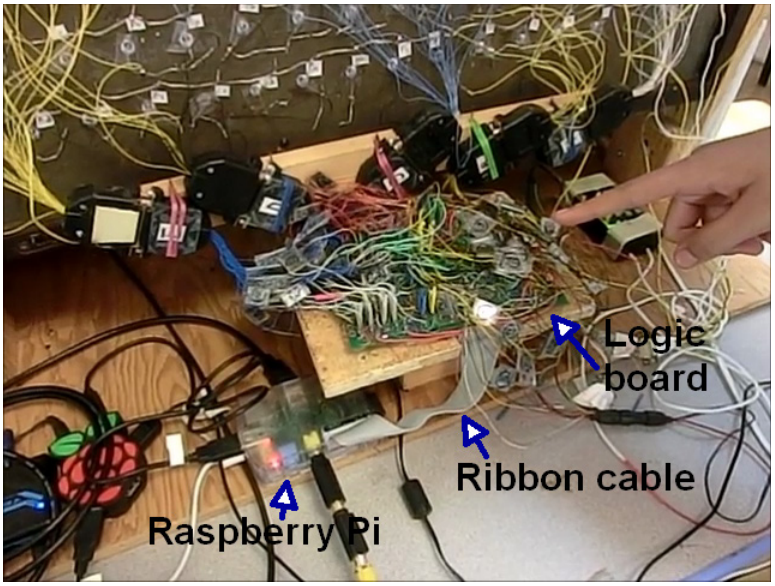
The control program, written in the Python 2.7 language on the RPi, has to respond appropriately to the button pushes. This is fairly straightforward. We wired leads from the ground or 3.3V potentials to the button, which then connects to an input pin to the RPi. A current-limiting resistor is in line, to protect the RPi. Constructing the small unit holding the buttons and wiring was somewhat tedious, so Vince did this.

More progress in physical design and construction - from start to finish:

Deciding on connectors. We had to connect 112 LEDs behind the elements' cells to the addressable latch drains. With a view to easy disassembly and reassembly in case of problems, we chose to connect the wires from the LEDs to D-subminiature (D-sub) connectors, with D-subs of the opposite gender getting wires that ran to the latch drains. This involved very careful wire-stripping, positioning, and soldering. It also involved a lot of careful bookkeeping to record which pin on which D-sub connected to which element. While it would have been convenient for, say, pin 1 on D-sub 1 to go to element 1 (hydrogen), pin 2 to element 2 (helium), ... pin 1 on D-sub 2 to go to element 26 (iron), and so on, that would have made many wires criss-cross the periodic table; H and He are on opposite ends. Thus, we grouped wires handily and kept records (which sometimes needed correction). Similarly, the wires running from the D-sub mated to the D-sub from the LEDs had to be kept track of. We had to pass the information to the Python control program in an array, so that the program could look up which latch and drain connected to a chosen element – say, element 26, iron, is connected to drain 34, which is drain 2 on the 5th latch, L2E. The complexity came back to bite us when we switched from a small demonstration logic board connected to the first 16 elements – in exact order, element 1 to drain 0, element 2 to drain 1, .. element 16 to drain 15 - to the full board connected to all 112 elements. Vince overlooked that "disordered ordering" for some time, so that testing the final program gave strange results for awhile. Students helped with a great deal of debugging of the Python program and of physical connections – a most valuable skill and commitment to quality.

More connectors. From the D-subs to the latch drains is the "last mile." Each wire from a D-sub had to attach to a latch drain, that is, to a specific pin on a latch. We decided to solder the bared ends of the wire-wrap wire into small Molex-style connectors, which are thin metal tubes that fit snugly over equally small metal pins. Now, each latch is mounted into a DIP socket (*D*ual *I*nline *P*in). The socket has long metal pins that pass through the perforated board on which everything is mounted, emerging on the other side. We trimmed off excess length of the pins and slipped the Molex connectors onto these pins. The Molex connectors are long, about 20 mm, and could short out to each other, so we applied heat-shrink tubing around them. Heat-shrinking was a task students vied to do; we had plenty of it. Student Xitlali, also an artist, did the fine wiring avidly, with her great fine-motor control.

The physical logic board, the shadow box, and their supports. For quite awhile, the shadow box with the chart and all its wires running off it sat on its face and we worked on connections in that position. About 2/3 of the way through the project, we built a substantial wooden frame with hand and power tools, another task students enjoyed finishing after Vince cut the lumber on a table saw. The logic board has to be kept in a rather tight position so that the many wires don't pull loose. Vince built a wooden platform, cutting places for cables to run. One major cable is a ribbon cable that carries signals from a header (26 pins in an array) on the Raspberry Pi to another header ("breakout board") mounted on the logic board. It makes a tight fit.



Progress in programming and editing - from start to finish:

<u>Learning programming in Python and the Linux operating system</u> was an engaging task from the very start. Two students, Ayanna and especially Louis, were drawn to this and did most of the work through the first 2/3 of the project. Vince encouraged the others to put in productive time. Task number one was learning to use line commands in the shell and some point-and-click commands. They could then navigate in the filesystem, create and modify files, run executable files such as Python programs, learn to import new packaged programs, print over the network, and more. Only a couple of errors caused significant loss of work, which is par for learning computers.

<u>Creating the whole control program in the Python 2.7 language</u> proceeded in a long series of stages, with much amusement. We imported Python 2.7 to the Raspberry Pi, later adding some other packages such as colorama for color printing to the monitor. Our program was built up in about 100 steps, starting with writing the classic "Hello, world" program, learning basic syntax, including the novel indentation demanded in Python. We added the use of control blocks (if-blocks), loops over indices, the use of arrays, subroutines, breaks, and more. Students learned how to test and debug programs as they ran them in different initial conditions and different inputs. We used the *vi* editor, though in the final 1.5 years the older students had also learned the more powerful *emacs* editor. Students became adept far beyond cut-and-paste, learning powerful commands for multi-line substitutions and other editorial functions.

There were several major areas to master, over and above internal program logic. One was getting the audio files, the narrations, to play on command. Suggested ways taken from the Web led at first to some often hilarious malfunctions, with choppy chipmunk voices as the bit rates got tangled in elaborate lines of code that never really worked well. We stumbled upon a notably simple system call, *aplay*, that worked like a charm. Students learned patience and good humor. Another area to master was creating control sequences sent over the GPIO pins to the latches. The final program shows, with ample imbedded comments, the complexity of making a series of commands over 11 different control lines that turns any chosen LED on or off. A third area to master was simpler, using math, time, and other modules. The time functions allowed us to set comfortable delay times for the user to respond as well as to add short delays between commands to the latches to allow for differences among individual gates in the latches to respond properly. The math functions allowed us to compute settings on latch selectors using bitwise AND, as noted earlier, as well as to allow scrolling across the end of a list to the beginning.

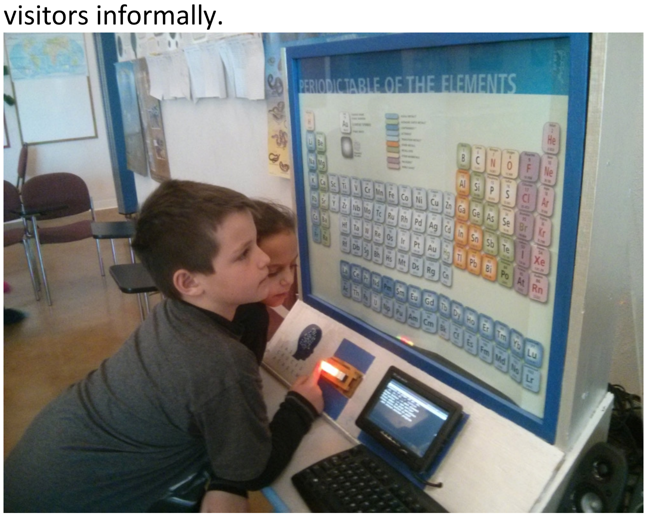
The final program, *elements.py*, has 744 lines of code, with about 300 being comments. About 150 of the executable lines have comments appended to them. Students learned how critical it is to document code in great detail. Otherwise, one can leave code for 3 weeks and spend a day remembering why the code in a subroutine was written as it was.

Progress in project management, including fixing mistakes - from start to finish: Students came to appreciate how very important it is to keep detailed records in any technical effort, especially a group effort with a group whose members may come and go. We have about 500 pages of printed records – narrative text, integrate circuited datasheets, so-called pin-out diagrams, wiring diagrams, logic sketches, etc., arranged in a number of folders by topic. These records record our decisions, our failures, our retrenchments, our successes, and simple easy-to-forget technical details. There are hundreds more pages in electronic form as Word, Excel, PDF, and JPEG files, plus Python program text files. Not to forget are the video files, most of them recorded for publicity.

The project was a success beyond creating the physical product, the novel light-up periodic table with its narrations. We created teamwork, enthusiasm, persistence in the face of multiple failures, attention to detail, and the habits of quality control. The students, and Vince, too, came away with a great feeling of accomplishment.

Progress in learning about the elements and presenting that knowledge - from start to finish: The final stage, with preparations all along the way, is **presentation to the larger world** – the other students in the school, parents, and people well outside our school, including you, dear reader. Publicity is one aspect, getting people to see what students can accomplish. Outreach is another aspect, sharing the useful product, the LUPT, and the methods by which students can learn and can teach each other. In our school, the Las Cruces Academy, our Articles of Incorporation demand that we reach out to the widest range of people, in our school, our community, and the wider world of adults and students. Our project illustrates how all our resources can be used to good end – physical resources of tools and materials, and intellectual resources of students and teachers. This is storytelling, one of the ageless human traditions. As science correspondent Robert Krulwich expressed at Caltech's 2008 commencement, there are many competing stories out there; scientists have many stories to tell; we have to make our stories heard and valued.

The LUPT is in use. We showed a 6-minute video on it to the 120 attendees at the school's end-of-term performances on December 17, 2016. We've shown it to younger students, parents, and visitors informally.



On Wednesday, January 25th, the middle-schoolers were the teachers for the science class of the 3rd- through 5th-graders, engaging half the class in exploring the chemical elements... and the same of the other half of the class on Friday, the 27th. They used samples of 18 solid chemical elements (the gallium hadn't melted yet in our winter room temperature) and let the students operate the LUPT extensively. Then they and Vince made samples of 3 gaseous elements – outdoors! – oxygen, hydrogen (ignited), and chlorine (which bleached a cloth strip).

Videos, DVDs, press releases. We are working to reach people who can use our experience to improve education and add to the appreciation of science and technology. We're reaching out to educators, educational organizations, scientific organizations, legislators, colleagues, and friends. We've put our story in brief on our webpage and Facebook page, and now we've been generating press releases that lead to an expansive set of deeper information – this write-up and an 8-minute video.

The video is already on YouTube, at https://youtu.be/urcIdu2K_WU, and is also on this DVD. Creating it was a joint effort of the students and Vince, proving to be quite a learning exercise. We had a number of still images and videos from the process over 3 years. A year ago the students tried editing video clips and images together into a coherent video with a program that proved clumsy in the extreme, so that failed. We also needed new images and video, so we planned photo shoots and a script for segments to add to a final video. Students, who had learned some acting in earlier classes as well as public speaking, put their skills to work. Vince learned the tricks to use Windows Movie Maker. In December, 2016 it all came together. The 6-minute video for presentation at the end-of-term performances took shape. An 8-minute version with more detail followed shortly. Our long effort and our success is now documented!