The Information Train

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Abstract

The increased application of software-controlled digital electronics hinders the understanding of how things work. The information train is a scientific experiment exhibit that physically demonstrates how computers communicate. It comprises a network in which a model Lego train acts as a physical carrier transferring a picture's pixels from one computer to the other. The sending end computer scans a simple picture, and directs a model train to send that pixel to the receiving end computer. This is done by sensing the approaching train and switching a rail junction depending on whether a pixel is on or off. The train carries on its top a piece that rotates depending on the train's route, thus carrying the data between the two computers. At the receiving end, two sensors detect the shape's orientation allowing the receiving-end computer to reassemble the picture bit-by-bit, pixel-by-pixel. The receiving-end computer is a One Laptop per Child (OLPC) XO-1 machine, programmed using EToys. This provides further opportunities for motivated adventurous children to interact with the experiment's implementation.

When I was a kid I had a pretty good idea of how most appliances in our home worked. The phone was a circuit that physically connected the microphone at each end with the speaker at the other end. The record player's needle picked up the sound from the grooves of a rotating disc and converted it to current through a magnetic coil. Even the TV was a relatively simple affair: two electromagnets had a ray scan the picture while it was modulated to turn parts of the screen white.

How things change… Nowadays to give a similarly realistic picture to our generation's children I have to talk about analog to digital conversion, CPUs, flash memory, compression, psychoacoustic coding, packet routing, pixels, color perception, and liquid crystal displays. Or lie.

Yet, there is still value in understanding the basic principles of modern communication technologies, even at the cost of brave simplifications, for this will seed in our children the interest in the world surrounding them, the willingness to explore it, and, maybe, the ambition to pursue a personally and socially rewarding career in science and engineering.

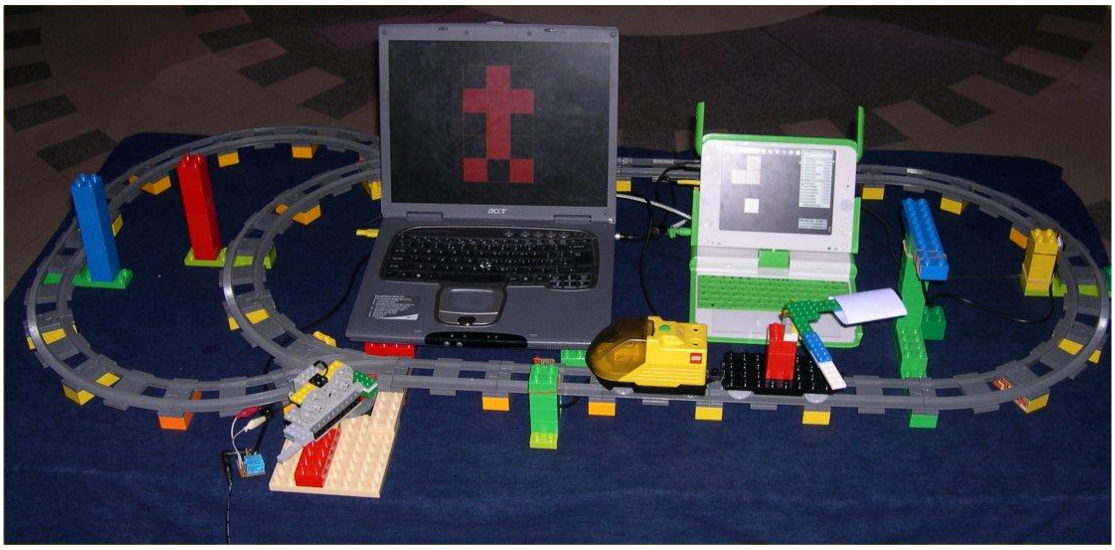


Figure 1 Experimental setup

In response to this goal, I created a scientific experiment exhibit that physically demonstrates how computers communicate with each other by setting up a network in which a model Lego train transfers a picture's pixels from one computer to the other (Figure 1). In brief, the sending end computer (on the figure's left) scans a simple picture from left to right and from top to bottom, and directs a model train (on the front) to send that pixel to the receiving end computer (on the right). This is done by sensing the approaching train and switching a rail junction (front-left) depending on whether a pixel is on or off. The train carries on its top a horizontally-mounted L-shaped piece, hinged in a way that allows it to rotate so that it protrudes from the train's left or right side. This part carries the data between the two computers. Depending on the track to which the junction sends the train, the train will pass close to a column on its left (red) or right hand side (blue), thereby rotating the L-piece to the corresponding direction. At the receiving end, a sensor (yellow, on the right) detects the train's passing, and a second one (green-blue, on the front right) checks to see the shape's orientation. Based on that input the receiving-end computer reassembles the picture bit-by-bit, pixel-by-pixel.

The exhibit is based on readily available components. The use of a large-scale (Duplo) Lego train provides a robust, accessible, and configurable platform to which children can easily relate to. The sending and receiving computers are laptops. In contrast to desktop computers, these are self-contained, and can therefore easily communicate their sending or receiving function by placing them near the positions of the track related to it. One of the laptops is a One Laptop Per Child (Lee 2006) XO-1 model, thus demonstrating the machine's educational potential. The interfacing parts are bespoke circuits based on cheap electronic components. Although the same functionality could have been achieved using Lego-provided black-box components, like WeDo or Mindstorms, the chosen alternative is more open and affordable. Most modern PCs lack simple general purpose input output ports. In particular, USB ports require complex interfacing hardware and device drivers. I therefore repurposed ports provided for other purposes. Nevertheless, the USB ports proved useful for providing a relatively clean 5V supply needed to power the sensors.

Sender implementation

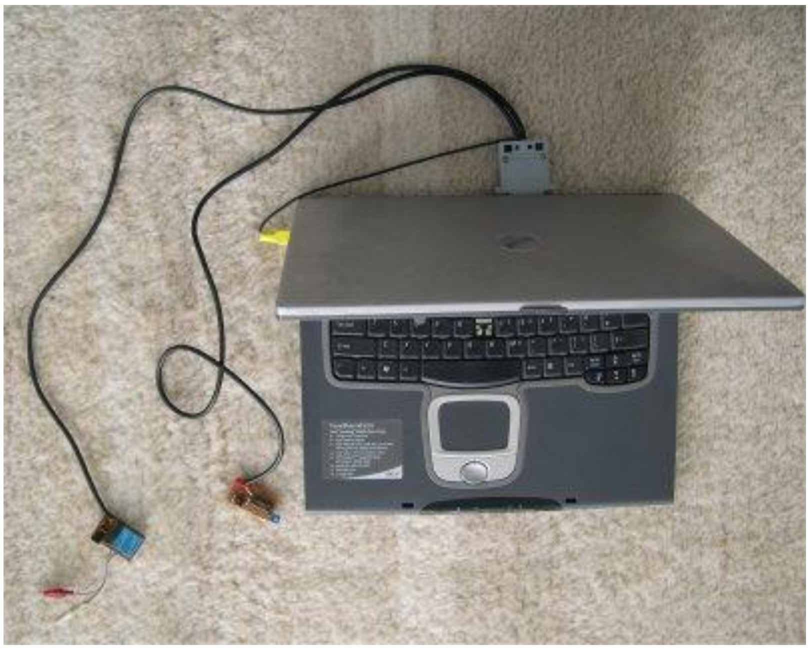


Figure 2 The sending computer

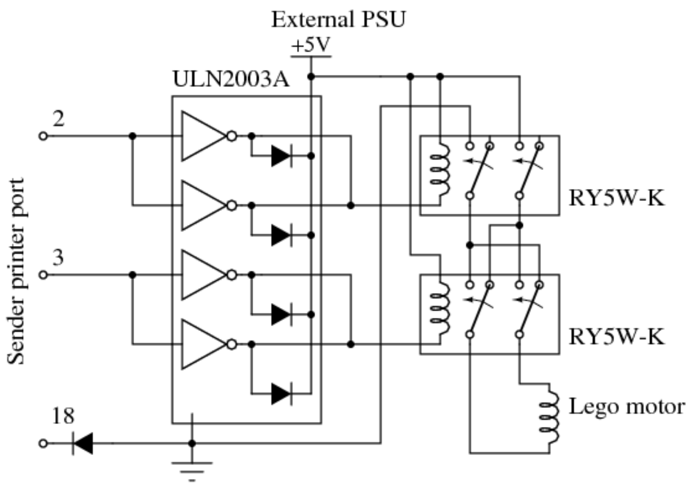


Figure 3 Sender motor control circuit

On the sender side (Figure 2), interfacing takes place through the laptop’s parallel printer port. This supports eight output bits and five input bits used for signaling conditions like “printer busy” or “out of paper”. A motor is used to control the rail junction’s position through a rack and pinion assembly. The motor control circuit (Figure 3) uses two of the printer port’s output bits to control the junction’s motor, according to the following table.

Bit A	Bit B	Motor
0	0	Stopped
0	1	Forward
1	0	Reverse
1	1	Not allowed

This is done by using a Darlington transistor array integrated circuit (Texas Instruments 1976) to control the windings of two relays, which in turn switch externally-supplied current to the motor. One of the relays controls the motor's power and the other its rotational direction. The Darlington transistors were wired in pairs to increase their current driving capability.

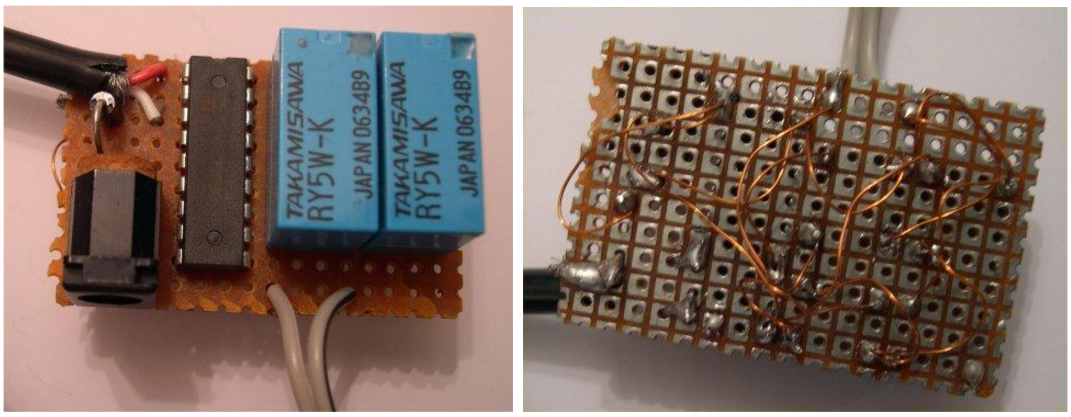


Figure 4 Sender motor control physical construction

All the exhibit's circuits are constructed on breadboard (Figure 4). Connections between the components are made using shielded copper wire. By heating the wire's end with a soldering iron and some solder the wire's enamel insulation melts away, allowing it to be soldered to a component's pin. The power required for all the experiment's circuits is obtained from each computer's USB port, thus doing away with the need to deploy additional power supply units.

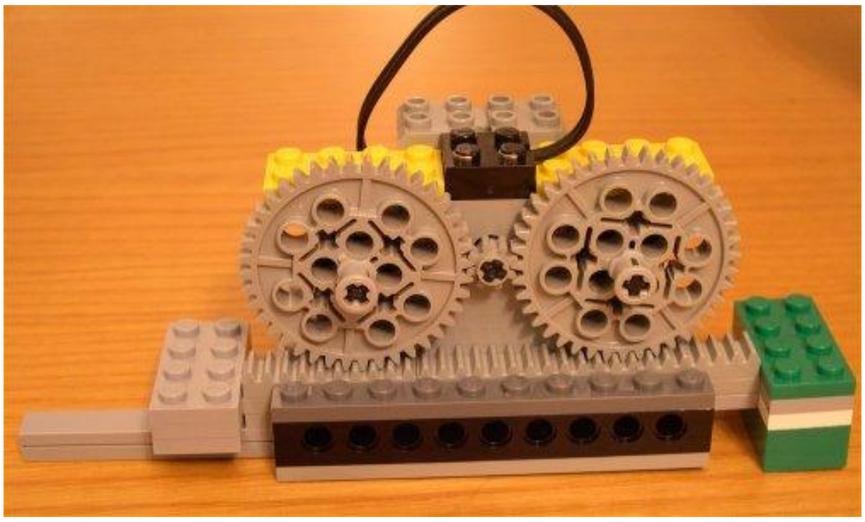


Figure 5 Junction driver construction. On each end of the rack are the constraining brakes.

For the sake of simplicity, the motor runs in an open-loop configuration, i.e. the controlling software obtains no feedback regarding the junction's position. Instead, the movement of the gear that drives the function is physically constrained on both ends (Figure 5), and the software overcompensates on the time it allows the motor to run.

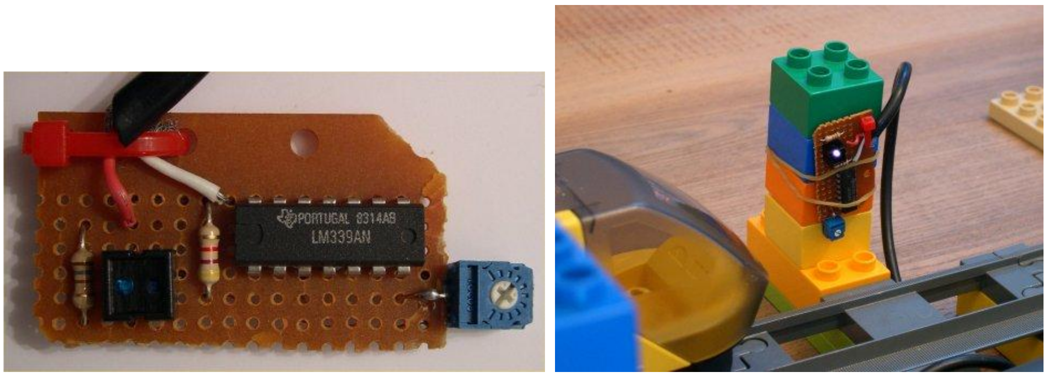


Figure 6 Train sensor board and its mounting

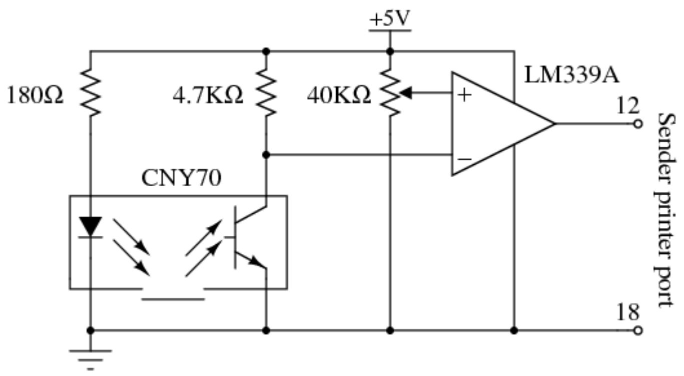


Figure 7 Train sensor board circuit

The sender side also needs to sense when a train is approaching in order to transmit the next pixel. This task is performed by a sensor board mounted vertically by the side of the rails (Figure 6). The sensor circuit (Figure 7) is based on an integrated reflective optical sensor with transistor output (Vishay 2012). This combines in a single package a 950nm infrared emitter and a matching phototransistor. The package's window contains a daylight blocking filter, thus improving the construction's noise immunity. The transistor's output is fed to a voltage comparator designed to operate from a single power supply (Fairchild 2012). This is used to convert the phototransistor's varying output voltage into a TTL-compatible digital signal that can be fed as input to the computer's printer port. The comparator's reference voltage is set by means of a trimmer potentiometer allowing the precise adjustment of the sensor's triggering condition.

The sender-side software is written in the *Processing* programming language (Read and Fry 2007). The image to transfer (a human stick figure) is stored in a rectangular array of Boolean values, which is initialized from an image drawn in the source code using so-called ASCII art. This provides a visual representation of the figure in the code, as can be seen in the following code excerpt.

```
// Initialize the img array from its textual image representation
String simg = " # " +
              "###" +
              " # " +
              " # " +
              "# #";
```

```
for (int r = 0; r < rows; r++)
    for (int c = 0; c < cols; c++)
        img[r][c] = (simg.charAt(r * cols + c) == '#');
```

Programs written in *Processing* have by default an implicit event and drawing loop, which continuously calls the program's *draw* function. To guide the program's control flow I coded the operation of the *draw* function as a simple state machine (see Figure 8). The program starts its operation in the *Waiting* state. Once the detector senses a passing train, it advances the row and column that must be sent, turns on the motor in the appropriate direction, and initializes a timer. In 250ms the state becomes *Idle*, indicating a state where the program waits for the trim to pass through the function. Two seconds later, the program will enter the *Waiting* state, waiting for the train to make its next round.

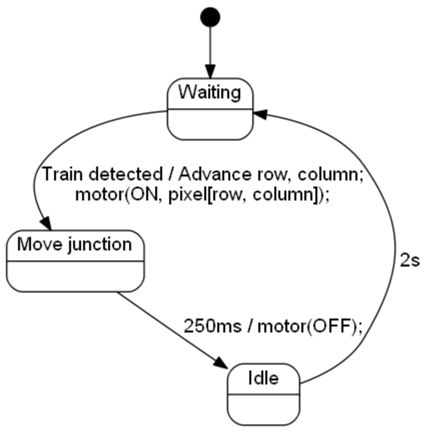

Waiting
Train detected / Advance row, column; motor(ON, pixel[row, column]);
Move junction
2s
250ms / motor(OFF);
Idle

Figure 8 State transition diagram depicting the program's operation

The *draw* function will also redraw the image being sent, flashing the pixel in transit with a duty cycle of 500ms. This is done with the following code.

```
for (int r = 0; r < rows; r++)
    for (int c = 0; c < cols; c++) {
        if (r == sendingRow && c == sendingCol &&
             ((millis() / 500) & 1) == 0) {
            if (img[r][c])
                // Flash ON pixel
                drawFill(color(180, 64, 64));
            else
                // Flash OFF pixel
                drawFill(color(64));
        } else if (img[r][c])
             // Draw ON pixel
            drawFill(color(255, 0, 0));
        else
             // Draw OFF pixel
            drawFill(color(0));
        drawPixel(r, c);
    }
```

The *Processing* language is based on Java, which cannot directly access I/O ports. Complicating matters further, modern versions of the Windows operating system, do not allow any user-mode program to access I/O ports. These two restrictions were lifted by downloading and installing the *ParallelPort* Java class, which uses the Java native code interface (JNI) to access the parallel port, and the *UserPort* device driver, which allows user-mode programs to access the I/O ports.

Receiver implementation

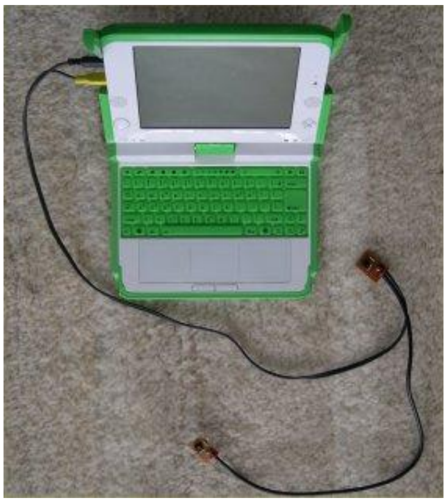


Figure 9 The receiving computer

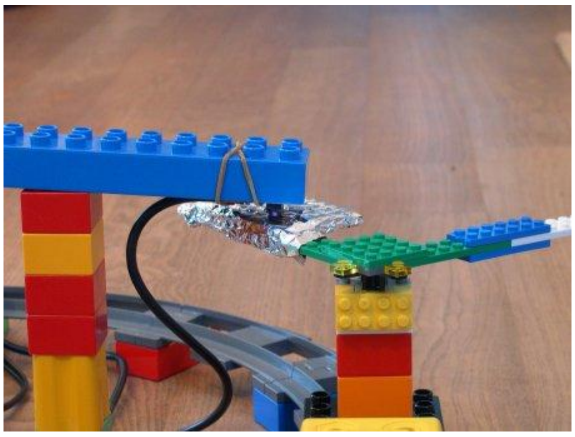
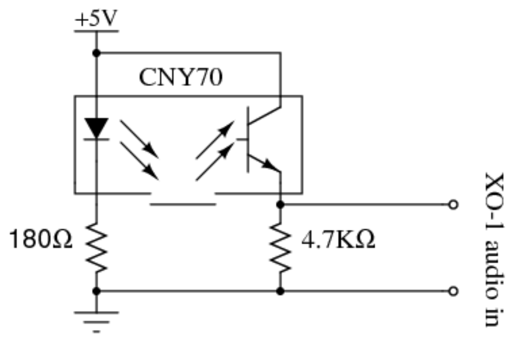


Figure 10 The rotating device mounted on the train and the bit sensor

The receiving computer is based on a late-prototype of the One Laptop per Child XO-1 computer, in order to demonstrate the platform’s effectiveness as an experimentation and teaching aid (Figure 9). Two sensors are used: a vertically mounted one to detect the approaching train and a horizontally mounted one to sense the value of the bit that the train is carrying on its top (Figure 10).



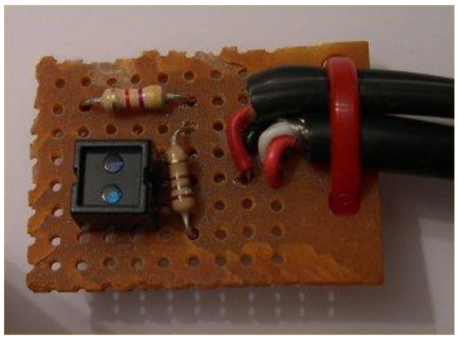


Figure 11 Receiving-end sensor circuit and board

In contrast to the circuit of the sending-end computer, the receiving-end sensor circuit (Figure 11) does not convert the phototransistor's analog voltage level into a digital signal. Instead, it utilizes a hardware design feature of XO-1 that allows its audio input to be used as a sensor for analog values. This feature is there to aid experimentation and does indeed simplify the sensor's connection. Thus, the two sensors are directly connected to the XO-1 audio input.

The receiver's software was implemented in the Squeak (Ingalls et al 1997) EToys environment (Gaelli et al 2006) as ported to the XO-1 laptop (Freudenberg et al 2009). The XO-1 laptop port allows EToys to be used from within the XO-1 shell by adopting the look and feel of other OLPC activities, by providing support for the persistence of programming projects through the environment's journal facility rather than files, and by allowing the sharing of projects between pupils. In addition, the port addresses particularities of the laptop's hardware, such as the higher screen resolution, a processor with relatively low performance (433MHz), a color scheme that is not based on sub-pixel color components, and the ability of the audio jack to be used for sensor input. This last feature requires the analog to digital converter hardware to be switched from AC mode into a DC mode thereby removing the filtering of an audio signal's DC component. A new object, called "World Stethoscope" supports the use of the microphone jack as a sensor.

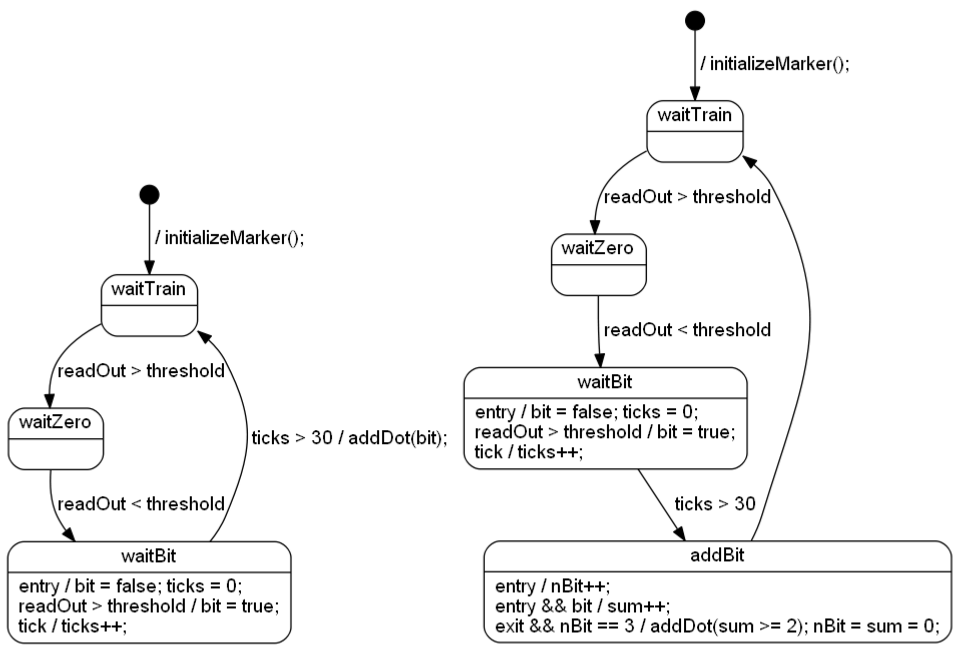


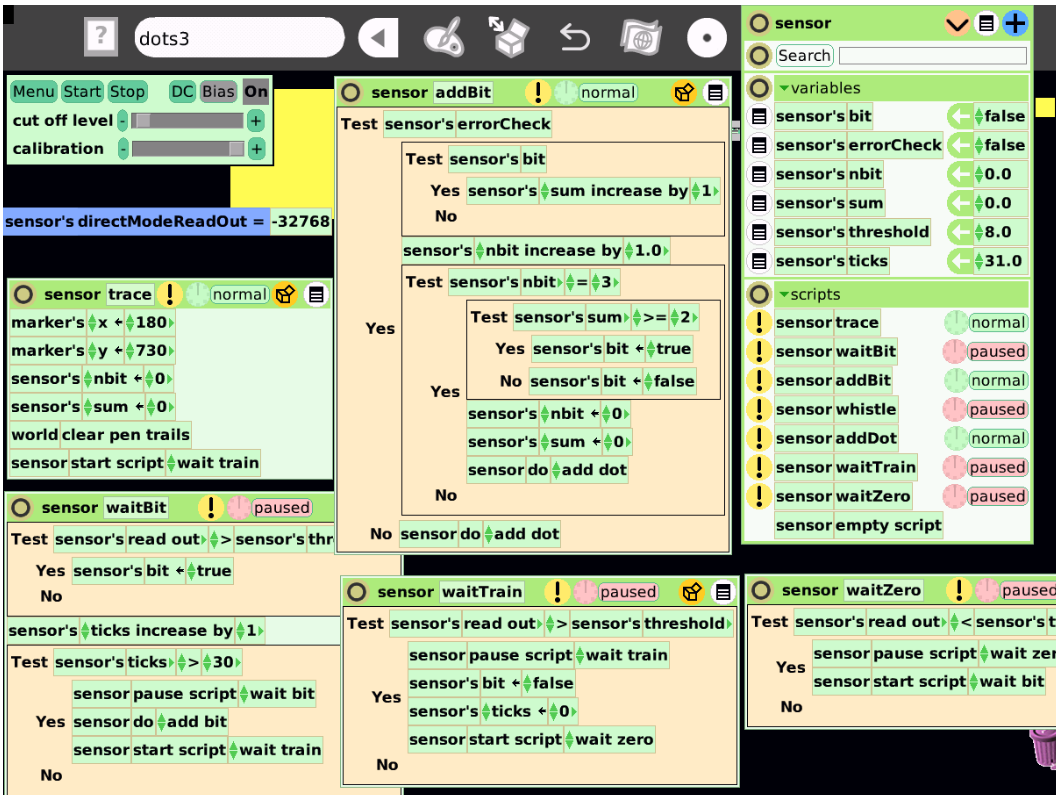
Figure 12 Receiver state machine: plain (left), error correcting (right)

Given that the EToys' World Stethoscope object provides only a single input it is used to handle the input both from the sensor detecting the train's approach and the sensor detecting the bit's value. This is done by implementing in software what is effectively a frequency modulation decoder. The software waits for a fixed time interval after a train passes to see if a "1" bit is detected by the bit value sensor. If the sensor does not detect such a value, the software assumes that the value is "0".

The receiver is implemented as a state machine (see Figure 12 left). In the `waitTrain` state the software waits for a train to approach. When the sensor's read out value rises above a pre-determined threshold, the software enters into the `waitZero` state, where the software waits for the train to move away from the train sensor. This happens when the sensor's read out value falls below the threshold value. At that point the software enters the `waitBit` state, where it zeroes a `tick` counter and the bit value and waits for a bit sensor value to appear. If the sensor's read out value rises above the threshold, the bit value is set to true (1). After 30 ticks, a dot (pixel) with the recorded bit value is added to the image reconstructed on the screen, and the image's current coordinates are updated. (The image is transmitted as a series of pixels; the receiver has hard-coded the image's dimensions.)

The experiment also allows the demonstration of error detection and correction. Under this scheme, each pixel is transmitted three times; at least two "1" values indicate a pixel with an "on" value, while at least two "0" values indicate a pixel with an "off" value. Errors can be easily introduced by manually manipulating the direction of the train's L-shaped data carrier. The corresponding state machine diagram is illustrated in Figure 12 (right). An additional state, `addBit`, counts the number (`nBit`) and sum (`sum`) of the bits received. When three bits have been received (the train has passed three times from the receiving station), a pixel is added based on the bits' `sum` value, and the two counters are zeroed.

The ETоys factor



```
sensor's directModeReadOut = -32768

sensor trace   normal
marker's x ← 180
marker's y ← 730
sensor's nbit ← 0
sensor's sum ← 0
world clear pen trails
sensor start script wait train

sensor waitBit   paused
Test sensor's read out > sensor's thr
    Yes sensor's bit ← true
    No
sensor's ticks increase by 1
Test sensor's ticks > 30
        sensor pause script wait bit
    Yes sensor do add bit
        sensor start script wait train
    No

sensor addBit   normal
Test sensor's errorCheck
    Test sensor's bit
        Yes sensor's sum increase by 1
        No
    sensor's nbit increase by 1.0
    Test sensor's nbit = 3
  Yes       Test sensor's sum >= 2
                Yes sensor's bit ← true
                No sensor's bit ← false
        Yes sensor's nbit ← 0
            sensor's sum ← 0
            sensor do add dot
        No
    No sensor do add dot

sensor waitTrain   paused
Test sensor's read out > sensor's threshold
        sensor pause script wait train
    Yes sensor's bit ← false
        sensor's ticks ← 0
        sensor start script wait zero
    No

sensor waitZero   paused
Test sensor's read out < sensor's t
    Yes sensor pause script wait zer
        sensor start script wait bit
    No
```

sensor

variables	
sensor's bit	false
sensor's errorCheck	false
sensor's nbit	0.0
sensor's sum	0.0
sensor's threshold	8.0
sensor's ticks	31.0

scripts	
sensor trace	normal
sensor waitBit	paused
sensor addBit	normal
sensor whistle	paused
sensor addDot	normal
sensor waitTrain	paused
sensor waitZero	paused
sensor empty script	

Figure 13 Programming the EToys World Stethoscope object on the XO-1 laptop

Figure 13 illustrates the EToys programming environment running on the XO-1 laptop. Programming the receiver in the EToys environment proved to be a productive and enjoyable experience. The integration of the analog sensor within EToys was a pleasant surprise compared to the pain associated with the three barriers that needed to be overcome (Processing, Java, Windows) in order to access the printer port on the sender side. Furthermore, the World Stethoscope object, whose controller and observer appear on the top left of Figure 13, made it easy to observe directly the sensor's value and create an appropriate threshold for detecting objects.

Interestingly, there is a one-to-one correspondence between each state of the state machine that describes the receiving software functioning and an EToys script. This makes it easy to understand how the state machine functions and to observe its operation. Scripts in EToys can be running or paused. Pausing a script and starting another one is the equivalent of moving from one state to another. During development it was easy to set the machine to a specific state, simply by clicking on the corresponding script's clock icon to have the script begin "ticking" and thereby made active.

Similarly, all the variables and states associated with the receiver were easily visible as a sensor pane (top right on Figure 13). This made it easy to debug the software during development, but, more importantly, it also allowed me to explain its operation when the experiment was demonstrated to children. For instance, it was fascinating to see the tick count begin to decrease once the train passed through the first sensor. In addition, explaining the error correction functionality without seeing the corresponding variables would have been futile.

Experience and lessons learned

The experiment was exhibited in a scientific experiment contest organized by the CAIDA non-profit organization and the Eugenides Foundation in Athens, Greece. There it was awarded one of the contest's three prizes. The stated goal of the experiment was to demonstrate to children the basic elements of information theory (Shannon 1948): conversion of an image from analog to digital form, the transmission of information as bits, the reconstruction of an image from digital bits, and reliable communication in the presence of errors. The experiment's Lego construction and the rapidly moving train attracted many children to the stand. A large proportion stayed to see the experiment in action, and many asked questions and appeared to understand the concepts behind it. Given the types of parents who take the children to science fairs, it was no surprise that many parents also asked questions, not only about the theory about behind the experiment, but (mostly) concerning its implementation.

The experiment's construction and operation proved to offer something for everyone. A toddler would look at the rotating train and listen it whistle as it passed from the receiving station, and even help the construction of the tracks. An older child could help with the other parts of the Lego construction, and observe how a train could transmit a picture pixel-by-pixel from one computer to the other. Those with an interest in programming could observe the receiving end's script operation, while the more mathematically inclined would appreciate the error correction algorithm. The design and soldering of the hardware as well, the sender implementation in the Processing language, and (probably) the design of the receiver software were tasks that required an adult.

A need to involve an adult in the process should not be taken as a negative verdict on EToys. There are many interesting and worthwhile activities that children without the help of an adult can perform in EToys in general, and using the World Stethoscope object in particular. Examples include games, animations, demonstrations, and setups to react to the outside world. For instance a child could connect a photo-resistor to the XO-1's input and have a sun on a scene rise and set based on the light the resistor receives. Or it could build a simple alarm, by monitoring a switch to trigger a horn sound. Nevertheless, the World Stethoscope object could benefit from some polishing to make it more child-friendly. The elimination of terms like "Bias", "DC", and "calibration" from its user interface and operation, would go a long way toward this direction. Instead of the various adjustments, the corresponding operations could be performed transparently behind the scenes based on the input the object receives.

EToys proved, once again (see Spinellis, 2008), to be an interesting platform to demonstrate non-trivial programming concepts. Alan Kay, a driving force behind Squeak on which EToys runs, has written that to learn science we "have to find ways to make the invisible visible" (Kay, 2003). This credo was made possible at many levels during the development of the experiment. Most obviously children could see the bits carried around on the train making their way into the picture. At a deeper level, elements of the receiver program were also visible. The state machine's states, rather than being hidden behind an opaque variable, as is usually the case in such implementations (Thomas and Hunt 2002), were visible as separate scripts implementing the transitions. More impressively, the active state was also clearly visible during the operation as the currently running EToys script as a "running" script, whereas the scripts associated with the other states appeared as "paused". Similarly visible were the values of all the program's variables (see Figure 13). This allowed be to demonstrate to observers how the physical world (the train) interacted with the program: how the program's variables changed as the train passed through the sensors and the scripts run and paused.

The experiment's modular construction allowed each part to be designed, constructed, and tested in isolation, allowing the experiment to be gradually implemented in a period of months. The modular construction also made it easy to transport the experiment: all parts could fit in a suitcase and could be readily assembled on site. Switching the junction motor with relays proved to be an easy and reliable method, in contrast to solid-state approaches tried for another task. In early phases of the construction the clicking of the relays provided reassuring feedback that the wiring and the software were working correctly. In contrast, the detection of objects using infrared sensors proved a tricky affair. Various integrated and transmitter/receiver pair sensors were tried with mixed success. Even the sensor used proved to have difficulty operating within the relatively large distance tolerances of the Lego train set. (The sensor's intended use was optoelectronic encoder assemblies, such as index and coded disk scanning.) In the end, and an adequate signal level was obtained by covering the Lego parts that the sensor should detect with aluminum foil.

Given the experiment's vertical integration and its diverse elements (large scale, normal scale and Technic Lego parts, electronic sensors and actuators, laptops, software platforms, software code) the instances where design choices obviated the need for additional work or elements made a considerable difference to the project's viability. These choices included the saving of two external power supplies by obtaining power from each laptop's USB port, the ability of the XO-1 to use its microphone input as a DC voltage analog to digital converter, and the integration of that converter within the EToys platform. Although each saving may appear trivial, all together they can add up contributing to a project's death by a thousand cuts. As a counterexample, accessing the printer port under Processing involved code written in C and in x86 assembly language.

Attendees asked about other projects that could be implemented in a similar way, and provided some interesting ideas. For instance, one suggested that the receiver could be implemented using a single sensor that would first detect the train and then the presence of a "1" bit. In general, mapping microscopic and extremely fast phenomena onto an observable experiment can have many other applications. Here are some examples. Demonstrate the functioning of hard-disk secondary memory by physically storing bits (e.g. Lego blocks) on a large rotating disk. Make a concrete application out of the hard disk memory by storing a game's high score. Show analog-to-digital and digital-to-analog conversion by loading a discrete number of blocks into a carriage. Explain printing by taking pictures with a physical camera and printing them using a motor-driven carriage driving a drawing servo-motor. The possibilities are endless.

Perhaps the most important lesson I learned from the experiment was the importance of accessibility. The experiment provided affordances that allowed direct manipulation of many aspects of its operation. Children could readily observe the signal carried atop the train, stop the train to delay the signal, and change the value of the carried bit to see the effect on the receiving and or on the error-correction system. On the XO-1 EToys end children could also see the software's operation laid bare like a cross-cut of a working car engine. Although I started with this as a design goal, I feel fortunate that this aspect worked better than my most optimistic expectations.

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