CLEMSON UNIVERSITY

Ekho

Realistic and Repeatable Experimentation for Tiny Energy-Harvesting Sensors

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SenSys'14—November 3, 2014

Hi everyone, I'm Josiah, and today I'm going to talk about the future of sensing.
The future of sensing will rely on tiny, robust, and inexpensive devices.
Tomorrows sensors will depend on energy harvesting and may not have batteries because they age and wear out over time, are environmental risks, and can take up a lot of space.
People in this room are working hard to make this future possible, but they don't have the tools they need.
They can't predict how their energy harvesting sensors will behave in the wild, and they don't even have an easy way to compare different hardware and software configurations in a rigorous way.

This Talk

1. Testing small devices

2. Energy harvesting difficulties

3. A Tool (Ekho)

In this talk I'm going to tell you…

- about how challenging it is to do repeatable experimentation on tiny RFID scale sensors
- why energy harvesting is at the core of the problem
- and finally how Ekho, a new device for recording and emulating energy harvesting conditions, can help restore sanity to the design and experimentation of sensors that rely on solar, RF, kinetic and other types of harvestable energy

...but first, I want to be clear about the kind of devices that I'm talking about.

RFID-Scale Devices

UMass Moo

I’m talking about devices that are small...really small.
I’m talking about devices that may have tiny batteries, or they may just use a capacitor, like this {Moo}.
This device stores 8 orders of magnitude less energy than the battery in your cell phone.
That’s like the mass difference between this african elephant, and this ant.

RFID-Scale Devices

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RFID-Scale Devices

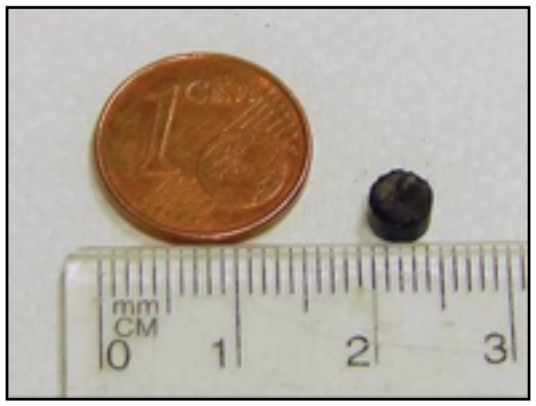
UMass Moo

As small as possible

- Minimal energy storage (Cap)
- Harvest energy (RF, Solar, Glucose)

Run when you can

- Frequent failures
- Erratic supply

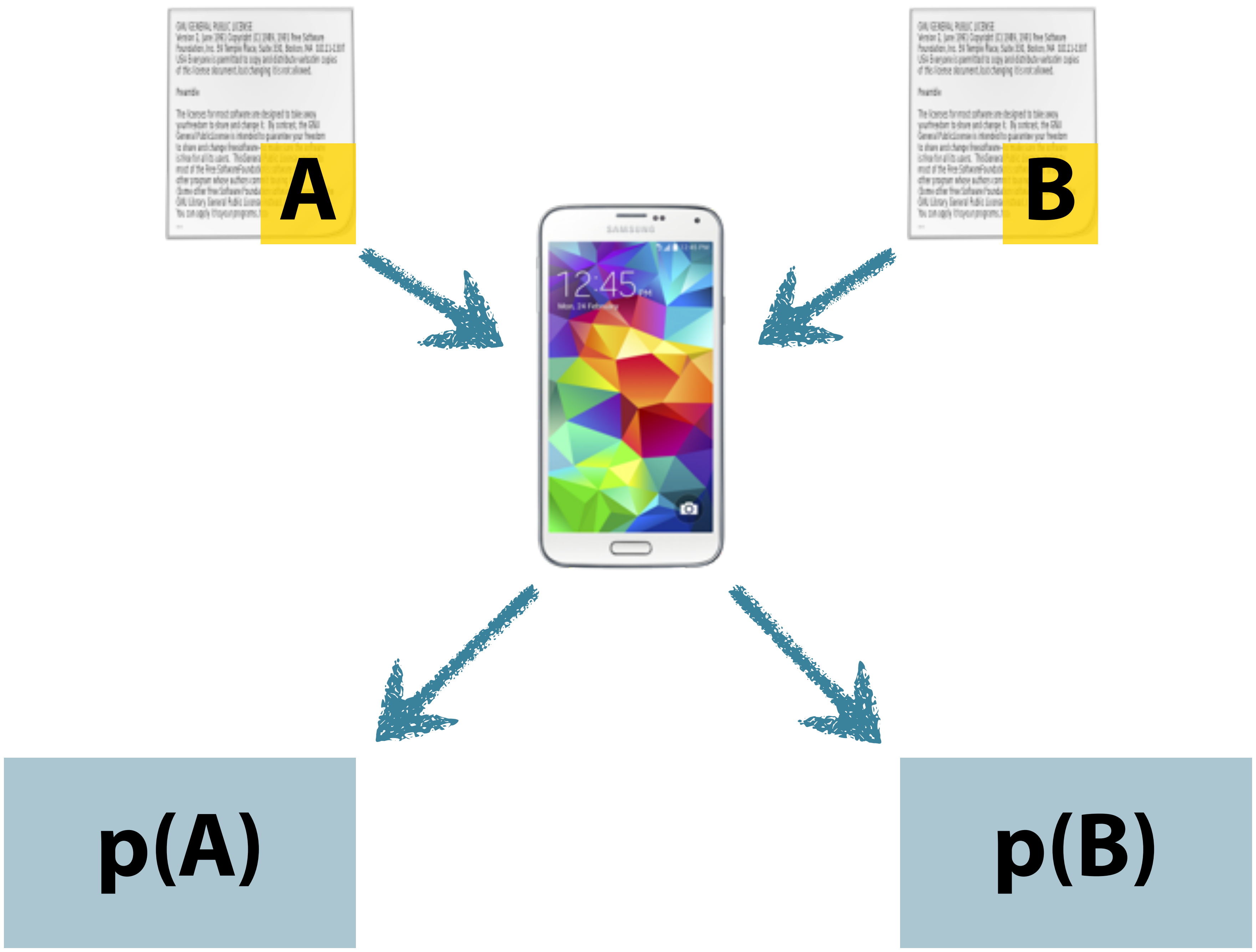


I’m talking about devices with so little energy storage that
energy harvesting becomes essential,
supply voltages — which are normally stable and clean — become erratic,
and power failures become more common events.
But this talk is not about building better sensors, it’s about testing and experimentation.

Comparable Outcomes

When designing a system, we usually have more than one way to solve a particular problem, and we need some way to figure out which method is faster, more energy efficient, or better in some other way.
(transition)
The focus of this talk is on how to provide realistic comparisons between different configurations for RFID scale devices. On more traditional devices with a wired power supply or large batteries, such as your phone, this is easy...

Comparable Outcomes



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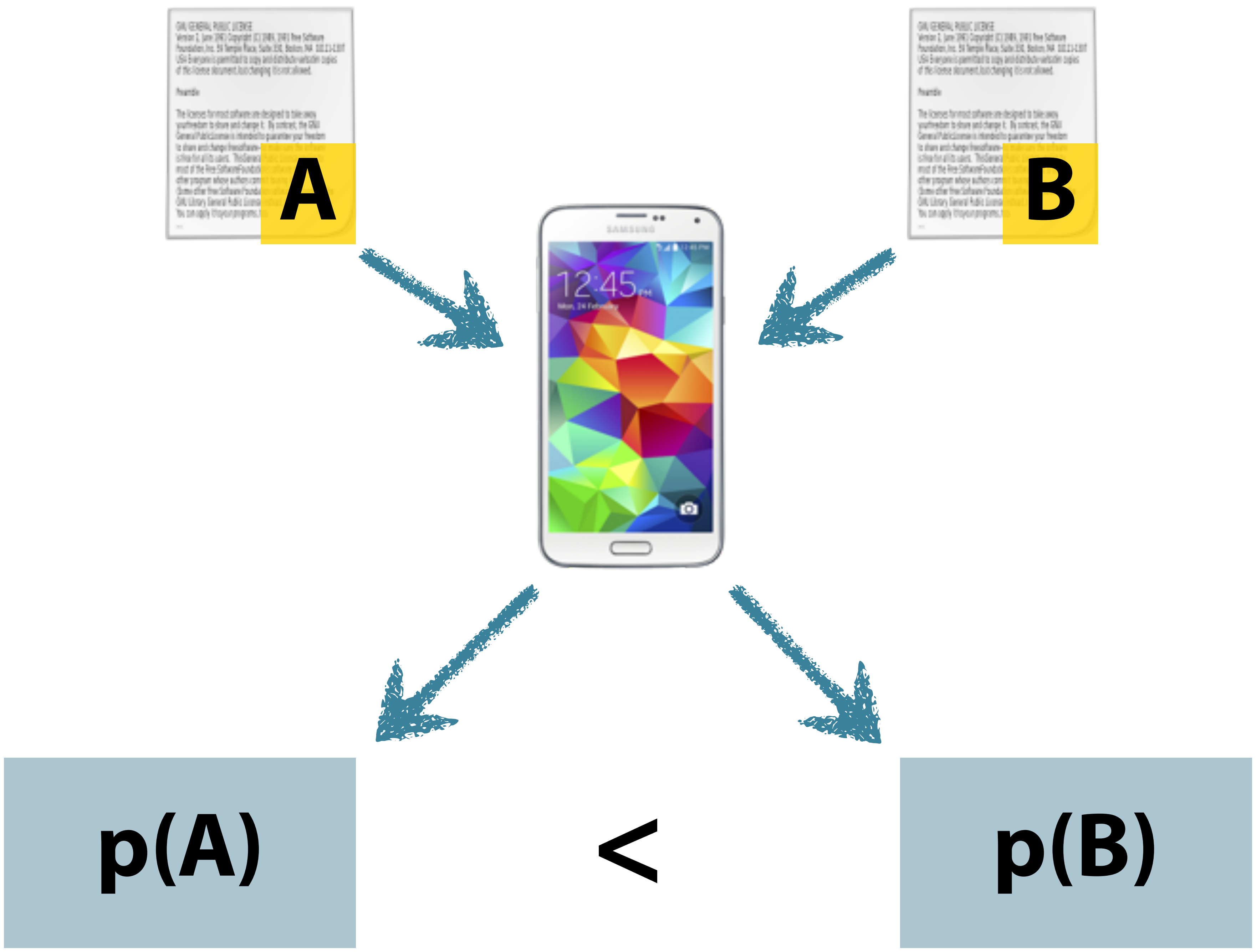

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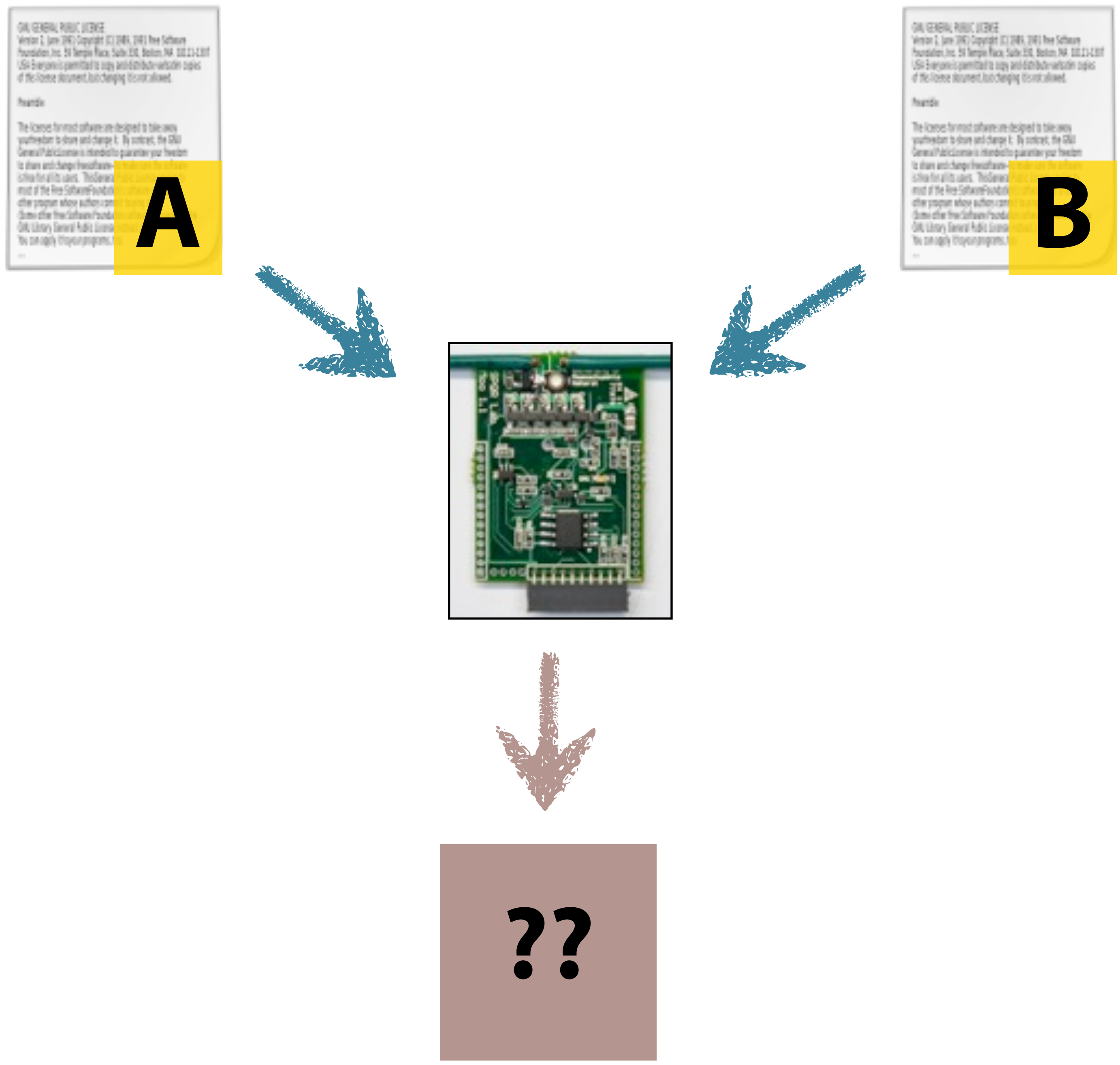
Comparable Outcomes

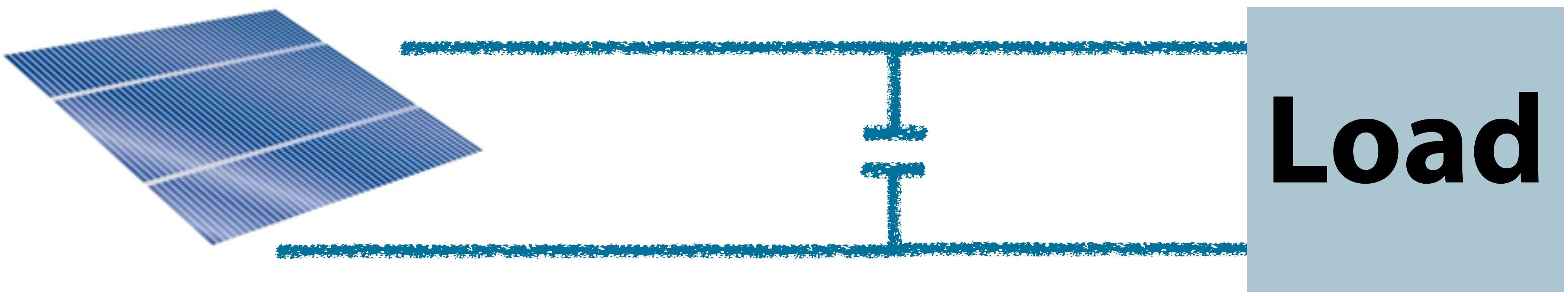


...but on RFID scale devices this has always been a problem.

So why is this hard?

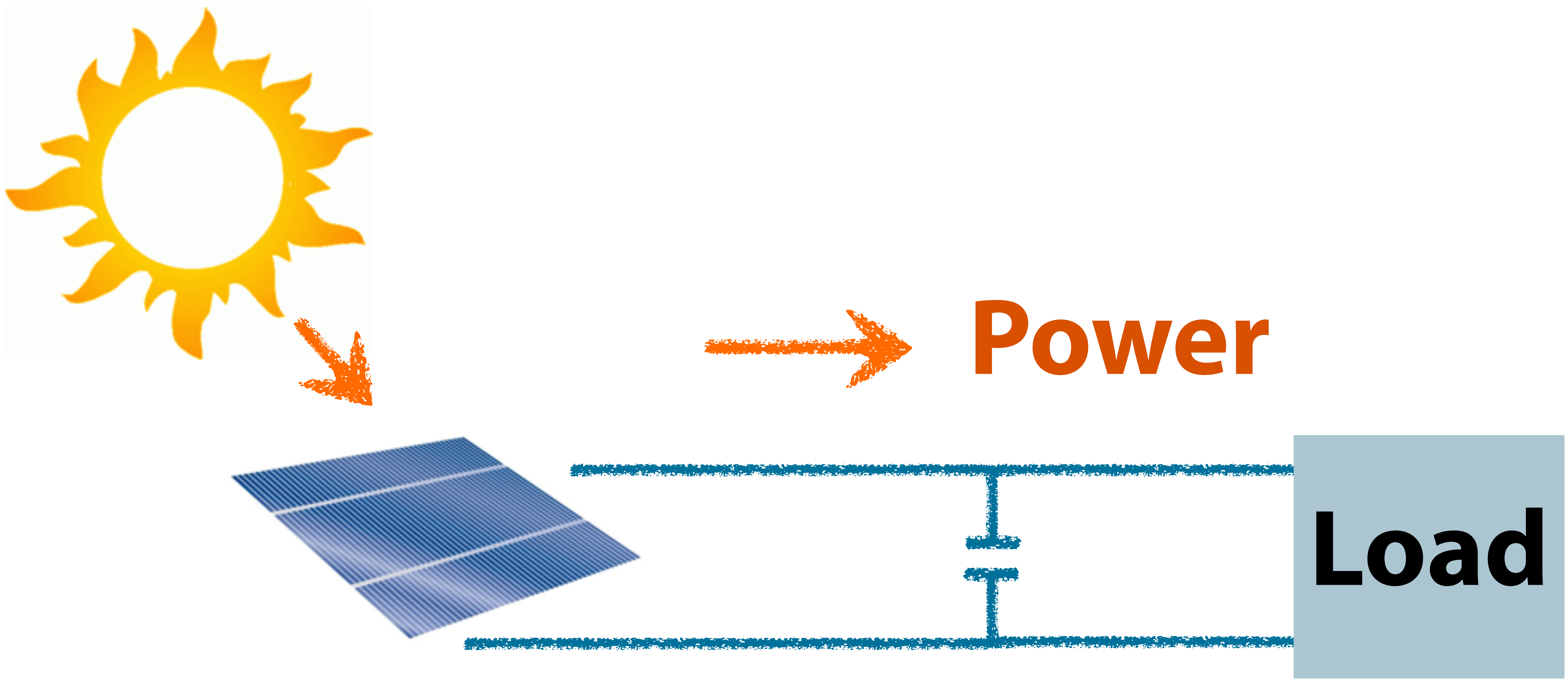
Let me tell you; the first problem is...

Solar Example



...we as computer scientists sometimes simplify things a little too much.
Consider this simplified system with a solar panel, a capacitor that stores energy, and a load, which could include a microcontroller, sensors, and other electrical components.
Sometimes, we imagine that energy harvesting works like this. Light hits a solar panel, and power shoots out.
In reality, it doesn't work this way. (transition)
In reality, the amount of power that you harvest depends on how much energy is already stored on the capacitor, in other words, the supply voltage..

Solar Example



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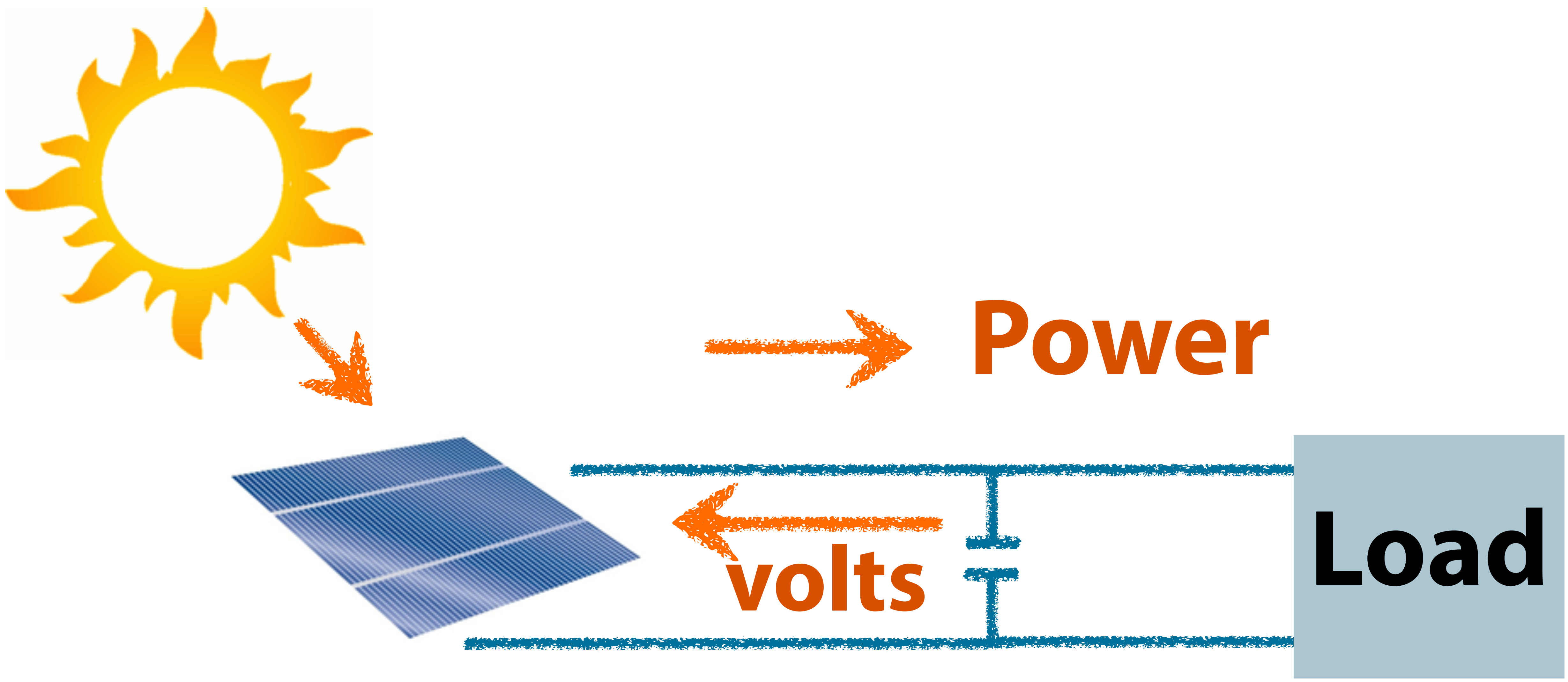

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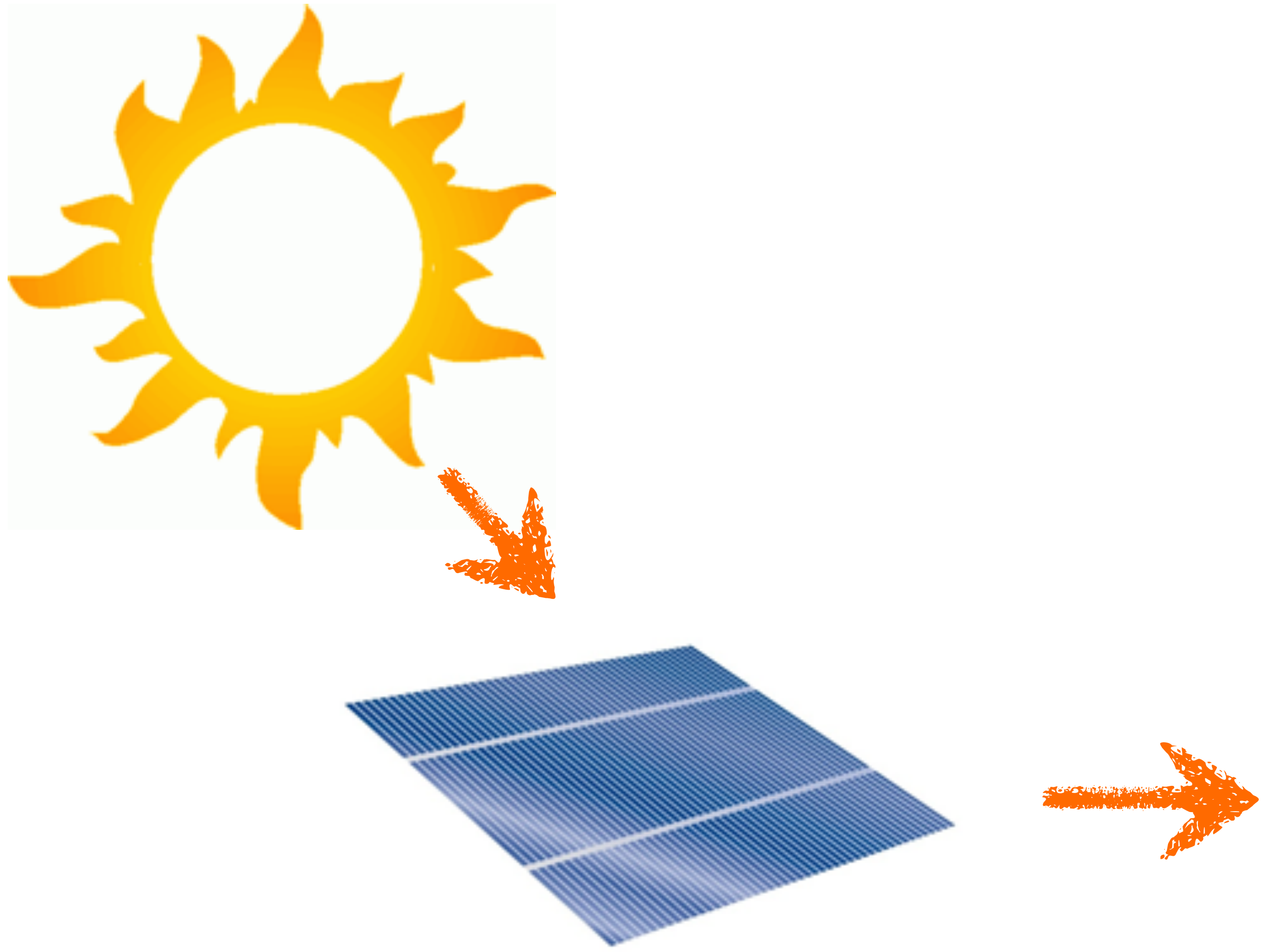
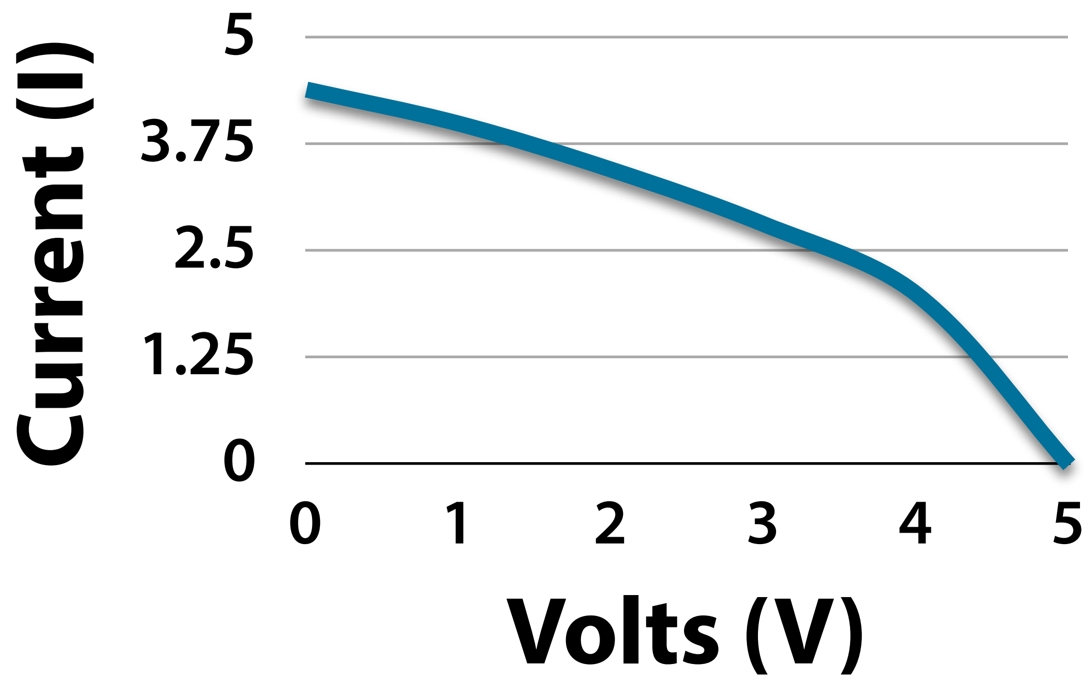
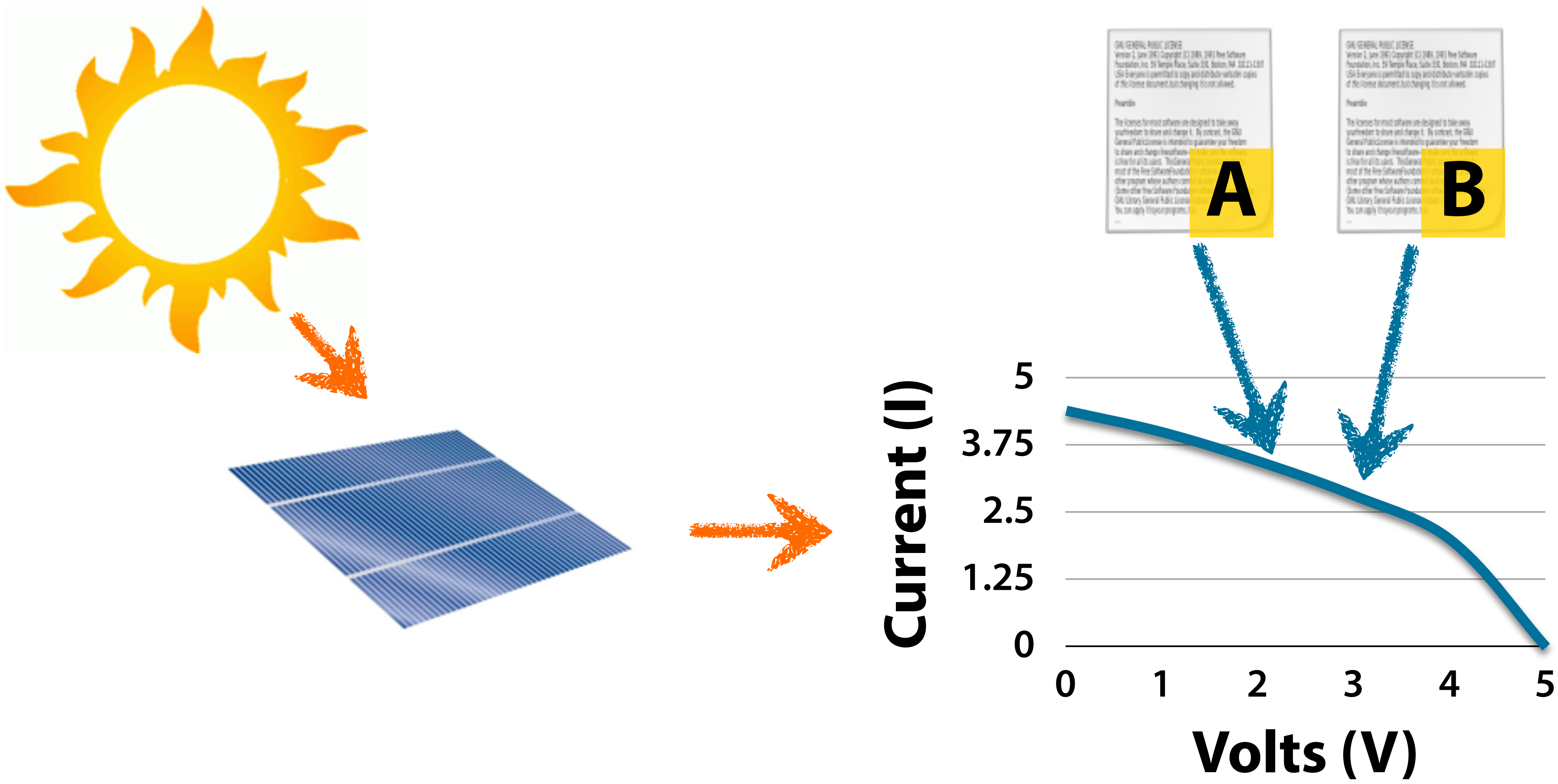




Power, P=IV

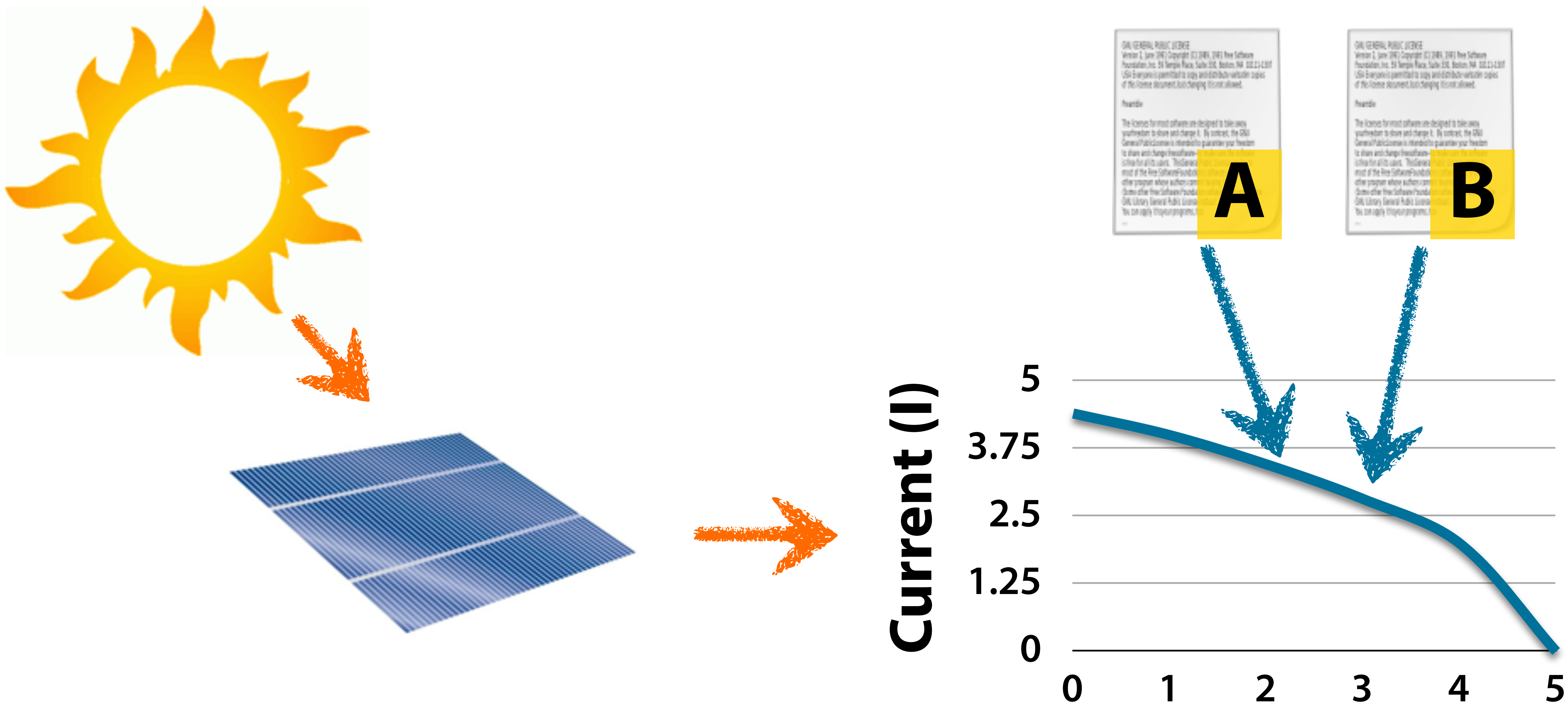
Another way to think about it, is that when light hits a solar panel, it produces a function that describes how much harvested current will flow, at each capacitor voltage. This IV-curve represents energy conditions at an instant in time.

Predicting Outcomes



Since current consumed depends on the supply voltage, this means that If two different programs harvest different amounts of energy they will see different power traces.

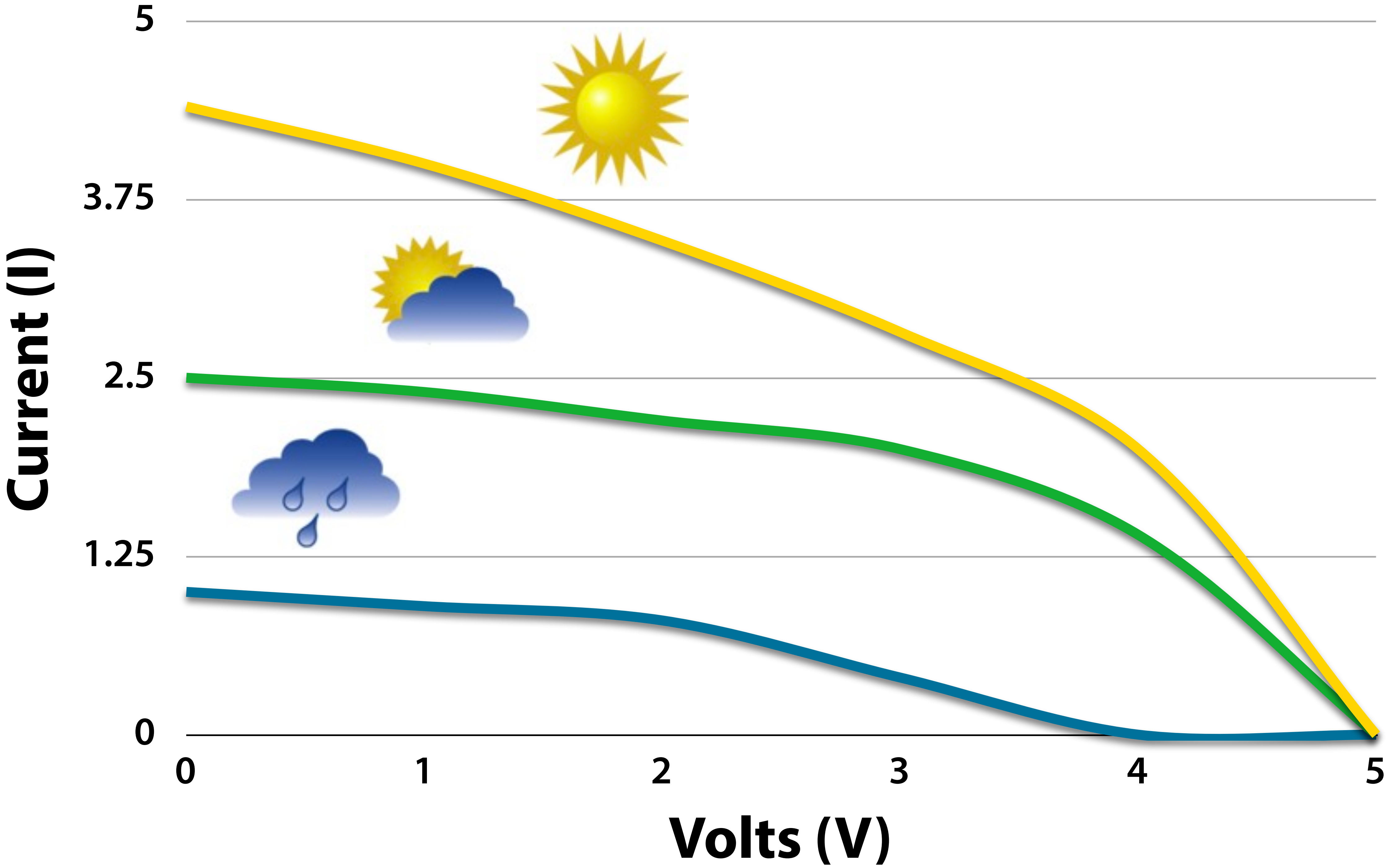
Predicting Outcomes



A and B see different power traces.

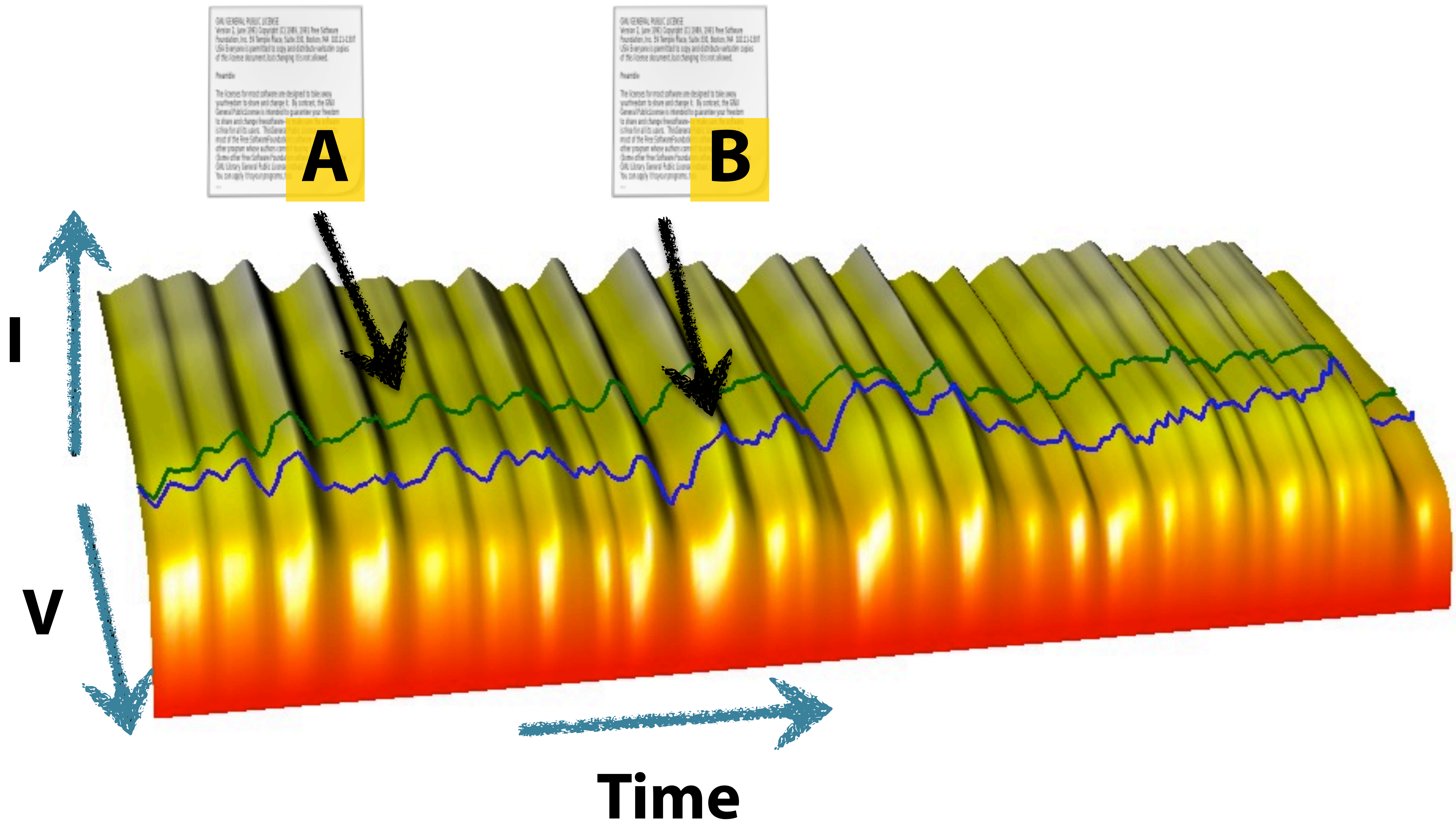
Since current consumed depends on the supply voltage, this means that If two different programs harvest different amounts of energy they will see different power traces.

I-V Curves



However, the IV-curve is not constant; As the amount of light hitting the solar panel changes, the IV-curve changes, but it still keeps roughly the same shape.
And, of course, environmental conditions change over time.

An Added Dimension



And, so instead of a single IV curve, energy harvesting behavior can be described by a series of different IV-curves combined into a 3 dimensional I-V surface....
This is what energy harvesting looks like.
Different programs will follow different paths across this IV-surface...and the amount of energy they harvest will change depending on how much energy they consume.
It turns out that IV-surfaces aren't just for representing solar conditions...
You get a surface like this whether you are harvesting solar energy, thermal energy, kinetic energy, RF energy, or even vibrational energy.
In all cases, the same abstraction is able to capture any energy harvesting technology we have tried.

Ekho

Generality

- Based on I–V Surfaces
- Solar, RF, Kinetic, Thermal

Flexibility

- Replicates energy harvesting in hardware

In order to take advantage of this general purpose abstraction for representing energy harvesting conditions, we've developed a tool, called Ekho...

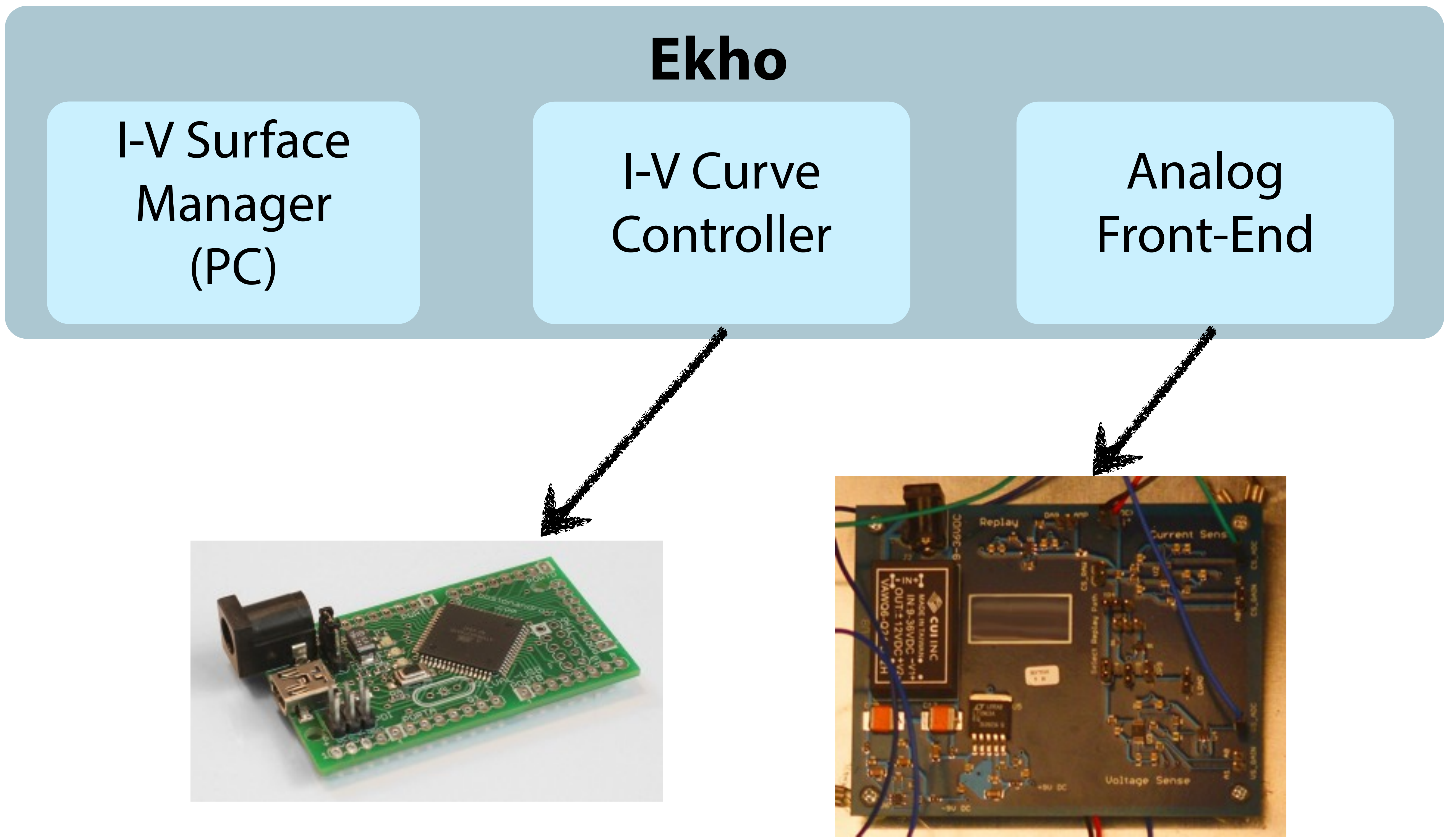
Ekho enables you to record IV-surfaces in the wild, and reproduce them in the lab.

Because Ekho is based on IV-surfaces, it works with solar, RF, kinetic, Thermal, and any other type of energy harvester.

Besides generality, Ekho is flexible.

Ekho replicates the electrical characteristics of energy harvesting, so unlike simulators, it's simple to compare hardware changes as well as software changes, just swap the configuration.

So how does it work?



Ekho consists of three components. A IV-surface Manager that manages timing, creation, and delivery of IV-surfaces, an IV-controller, which handles updating of individual IV-curves, and a analog front-end, that measures current and voltage of a device.

Ekho

Two Modes

Record

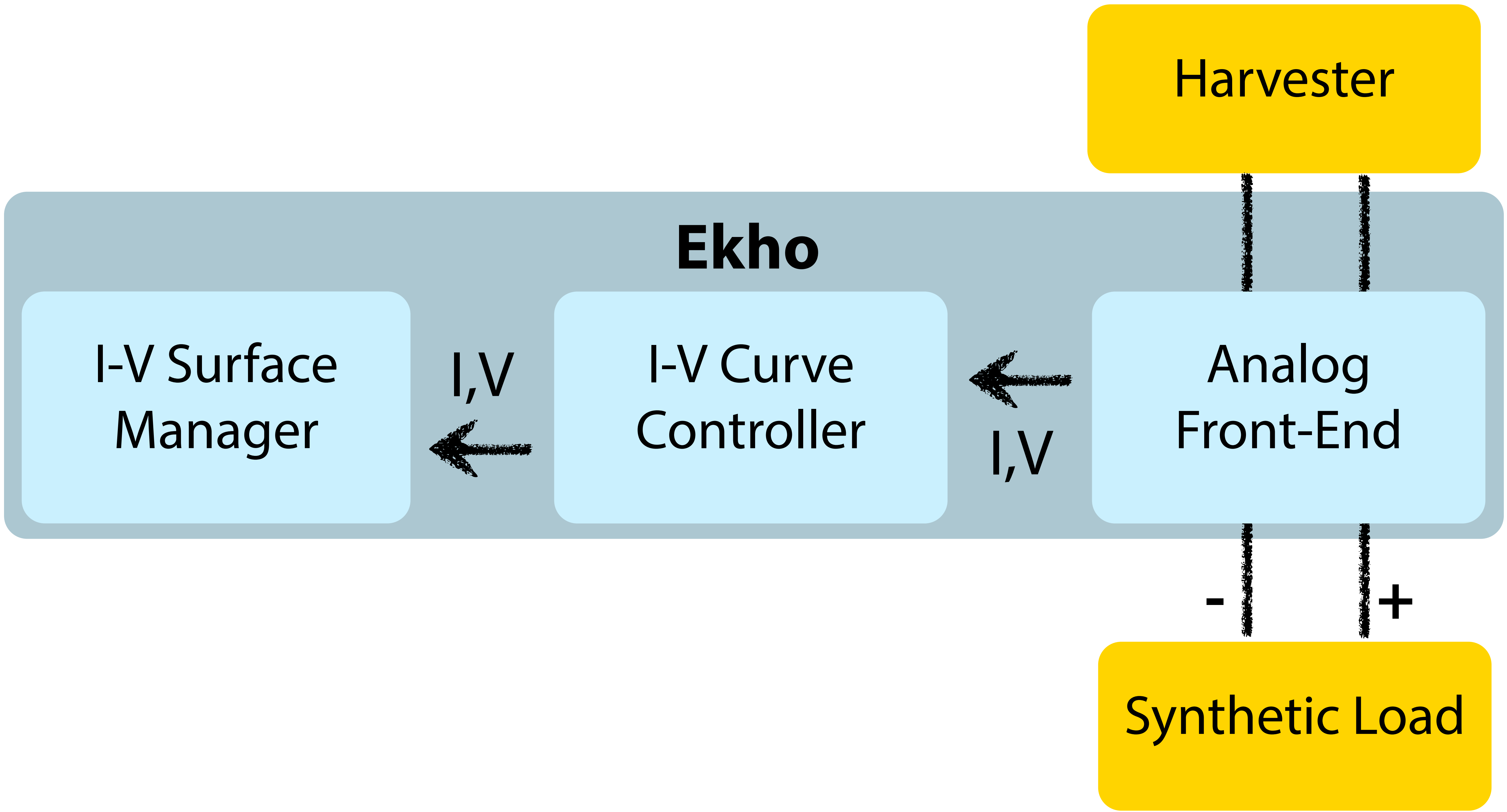
- Estimate an I–V Surface

Emulate

- Replay an I–V Surface

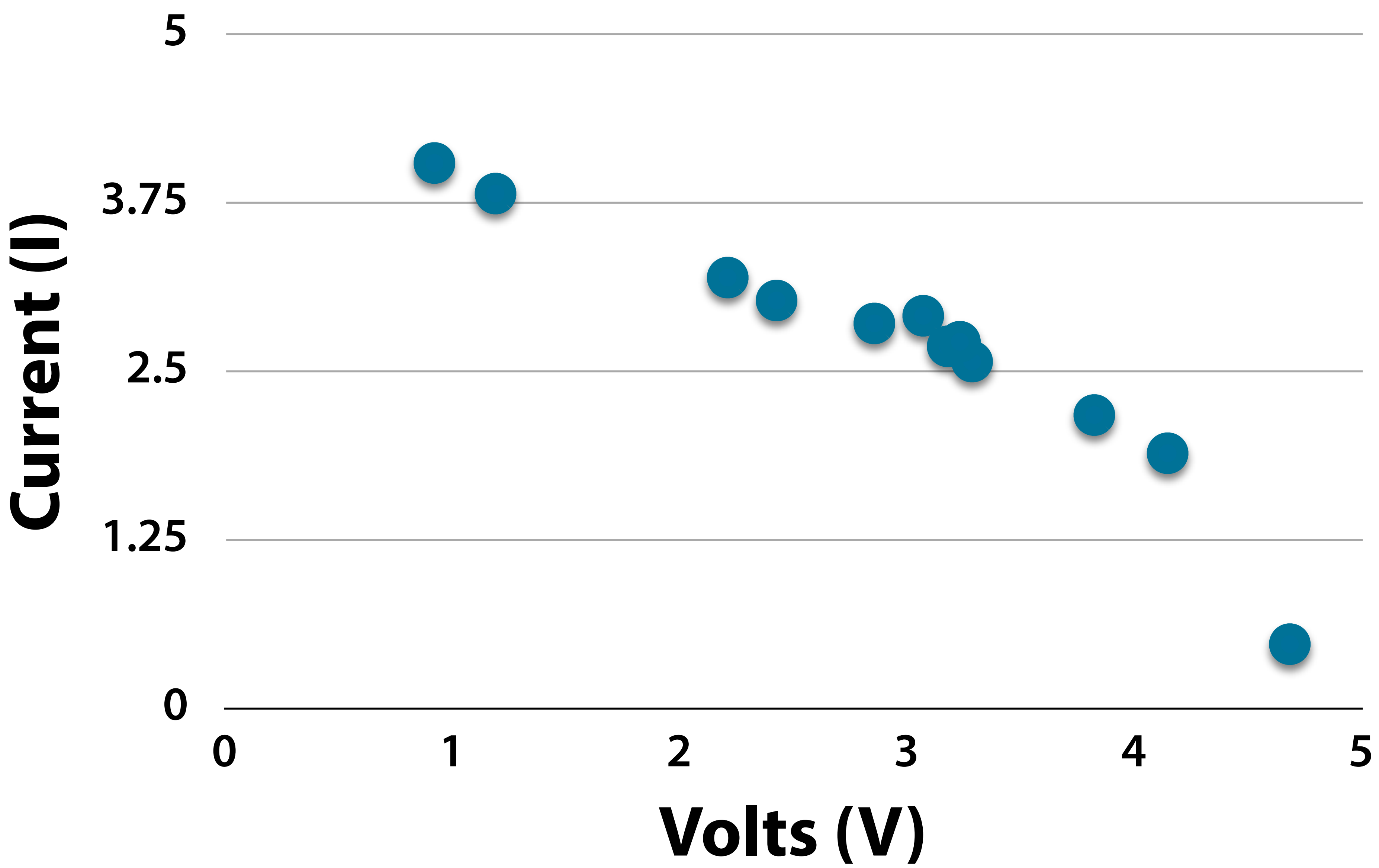
Ekho operates in two modes, record mode, and emulate mode.

Record



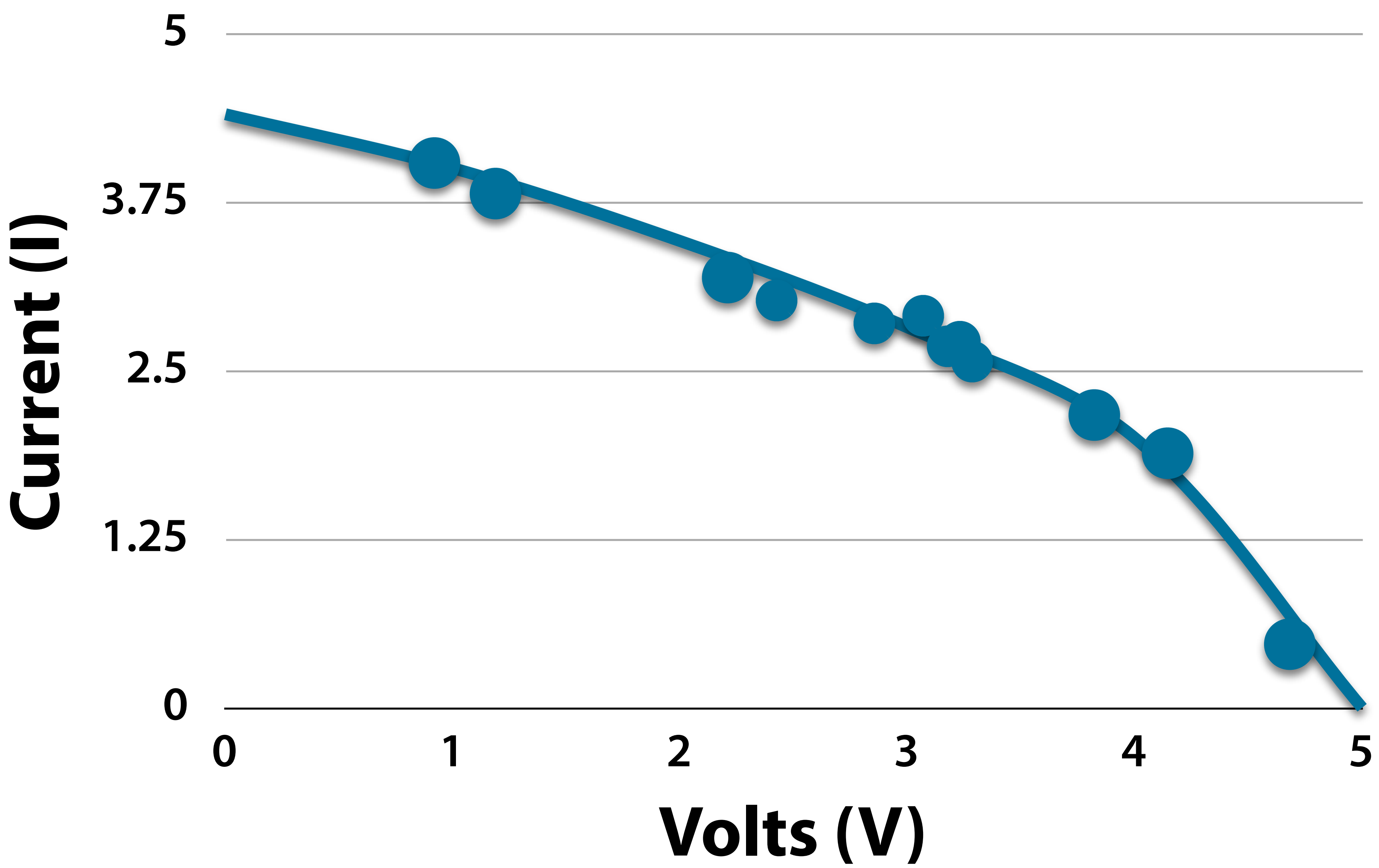
In record mode, Ekho's job is to estimate IV-curves. It does this by taking current and voltage measurements from an energy harvester, while it is harvesting energy.

Estimating I-V Curves



Ekho takes all the captured IV-pairs for some time window, and estimates the shape of the IV-curve at that point in time from the point cloud using simple curve-fitting techniques.

Estimating I-V Curves



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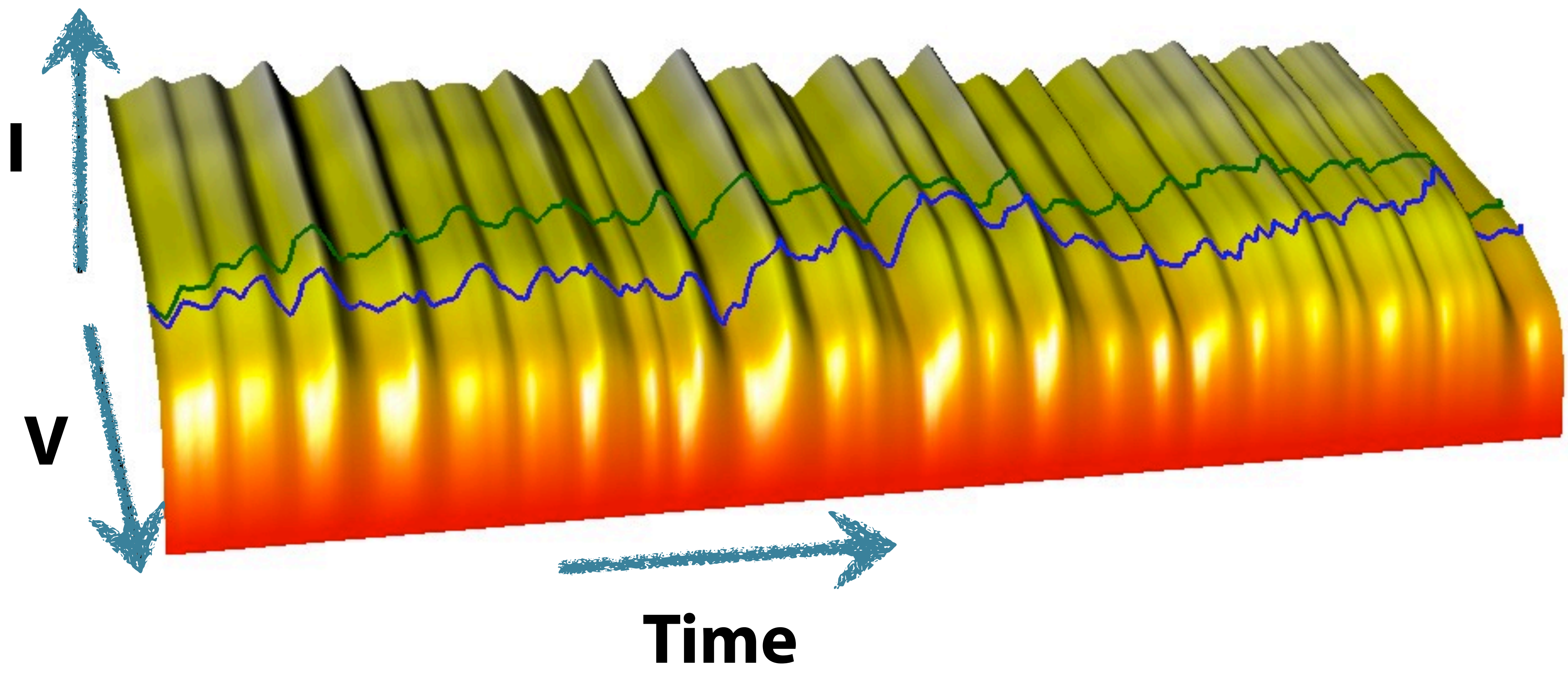
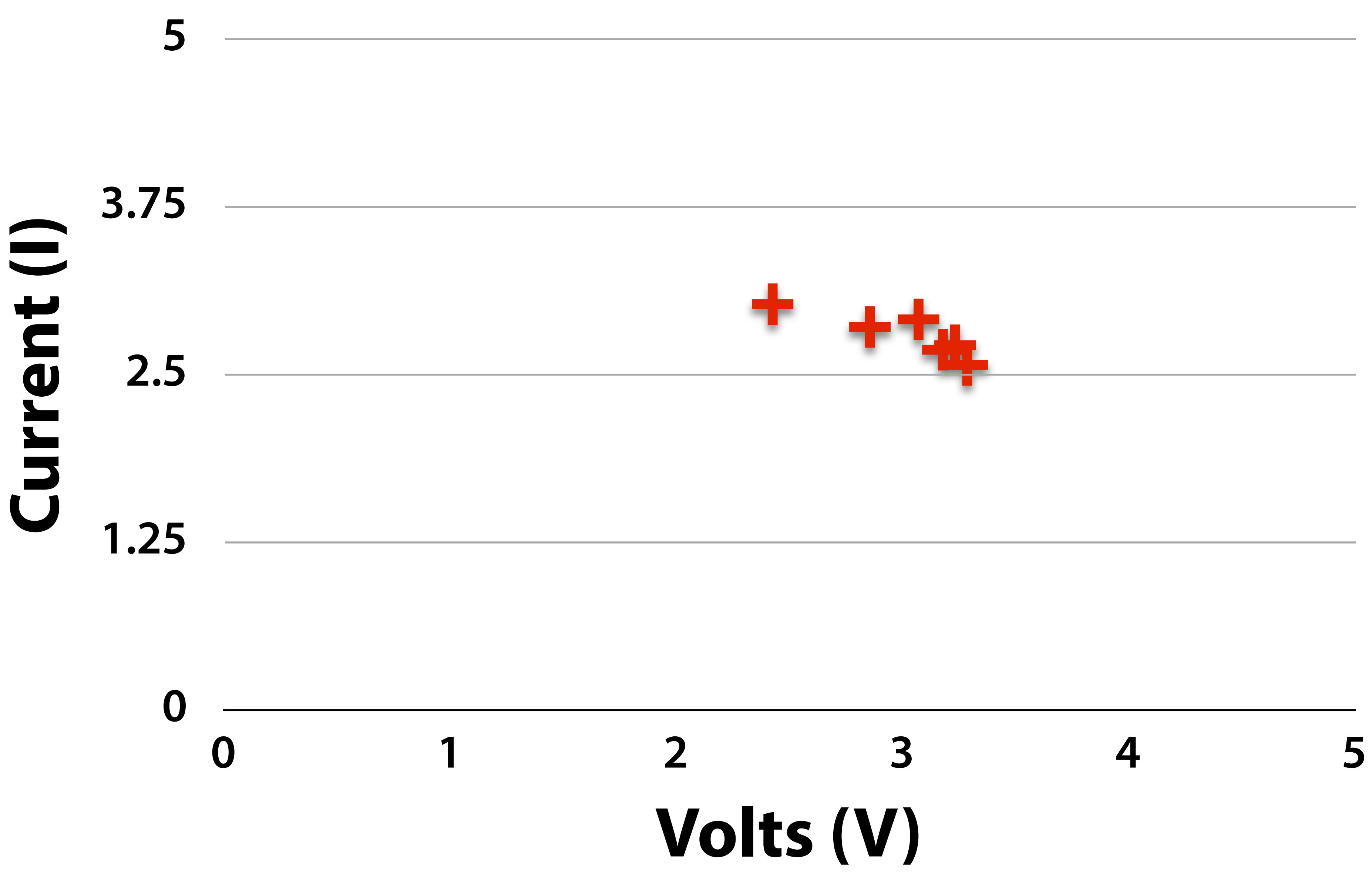
Estimating a Surface



Ekho combines these IV-curves as time passes to create an IV-surface, which can be saved in a digital format to be replayed later.
That may sound simple, but it is not the whole story.

Estimating I-V Curves



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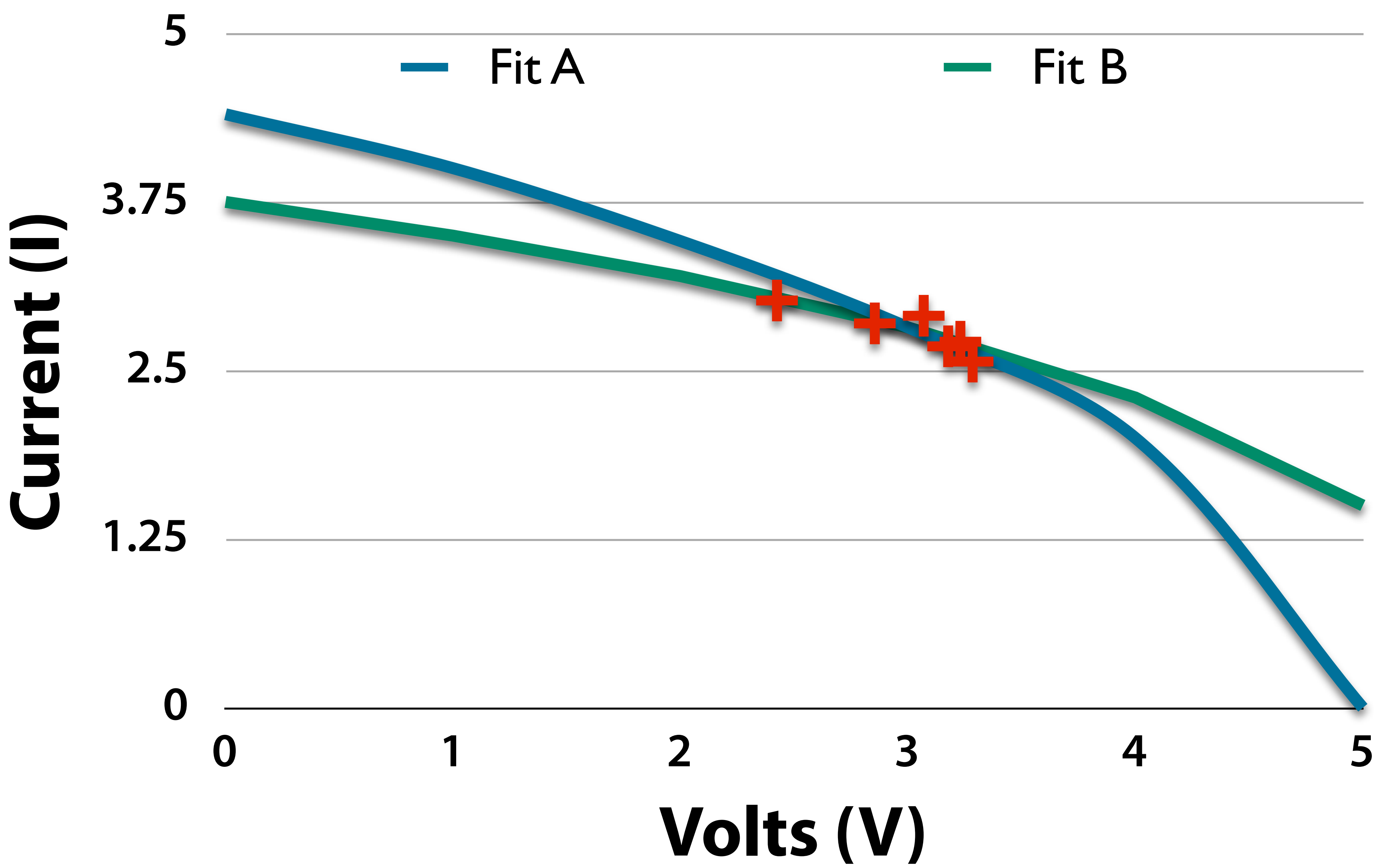
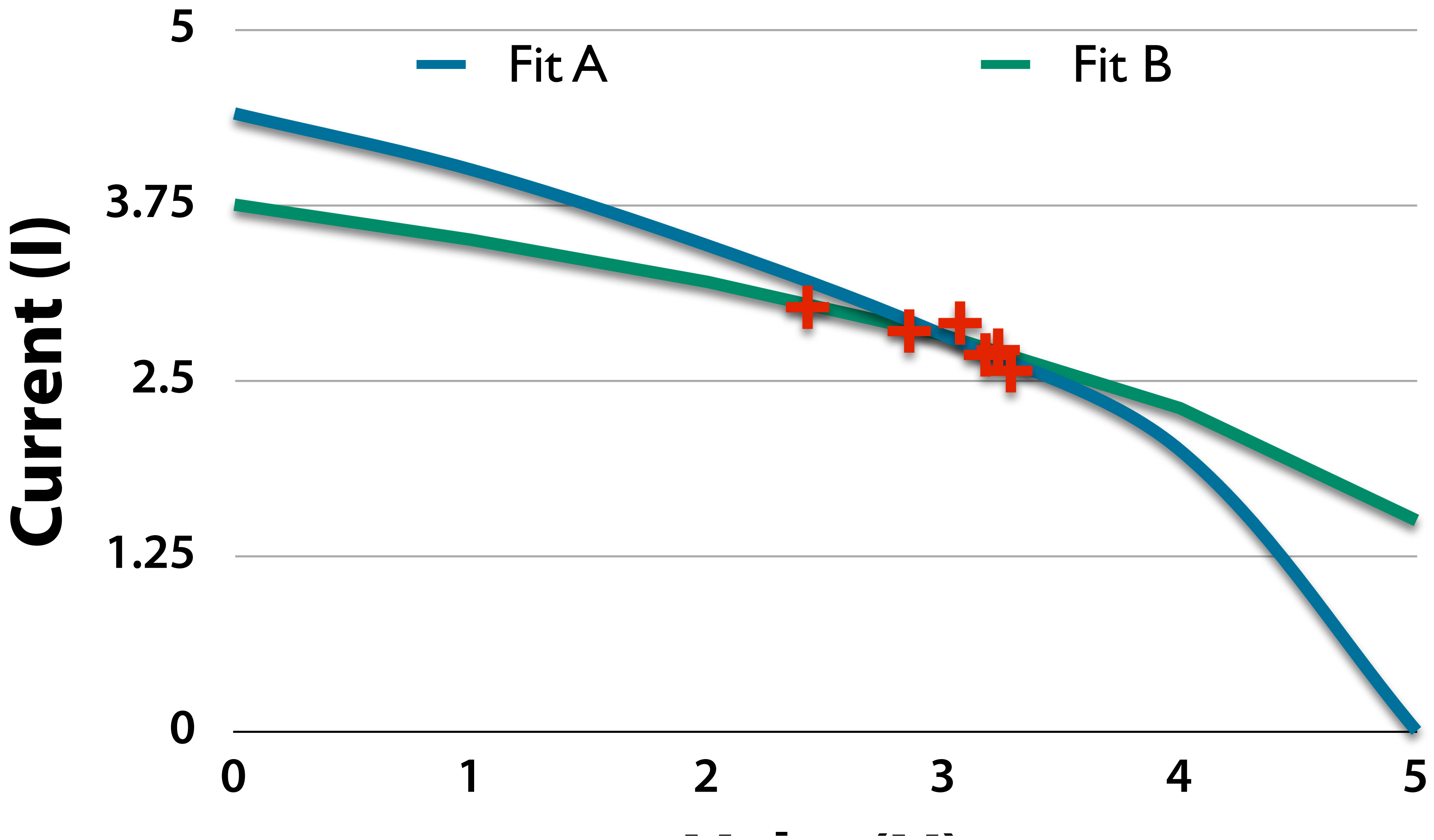
In order to capture each IV curve, we need current measurements at many different voltages, and if we use just any load, we will likely end up with a lot of measurements, clustered around a small part of the curve.

Estimating I-V Curves



A typical test device just does not cause enough variation to see the entire curve. This means that many different IV-curves can fit the sparse data. To get a better fit we need more data.

Estimating I-V Curves



Need a smart load.

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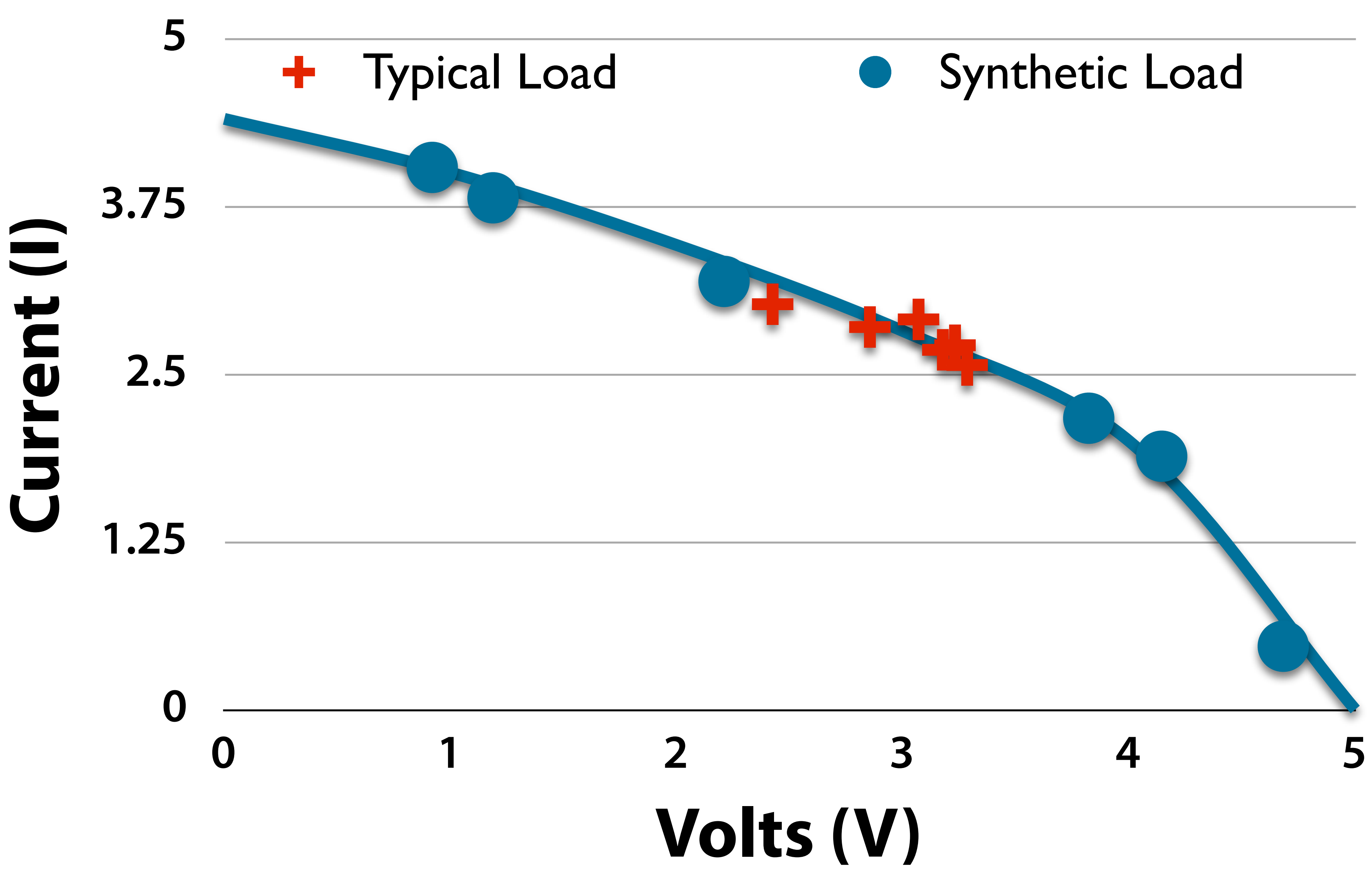
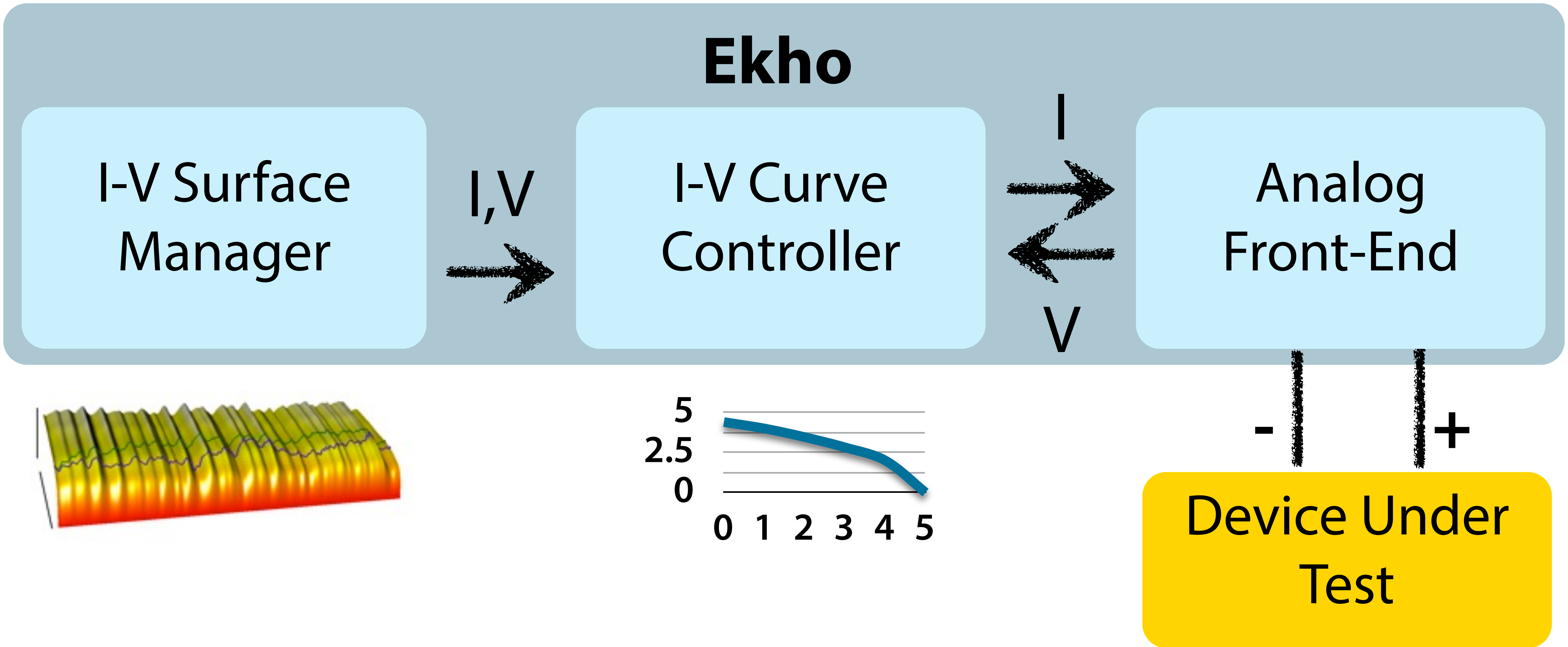
Estimating I-V Curves



To fix this, we designed a synthetic load that varies the voltage enough to explore nearly the entire curve.
The synthetic load uses a digital potentiometer to rapidly change the load resistance, which causes rapid voltage changes.
Once we have an IV-surface recorded, we can then replay it in emulate mode.

Replay (emulate)



In emulate mode, Ekho takes the place of the harvester or energy source.
Ekho tracks progress through an IV-surface, playing out a single IV-curve at a time.

Emulating an I-V Curve

Repeat (quickly and accurately)

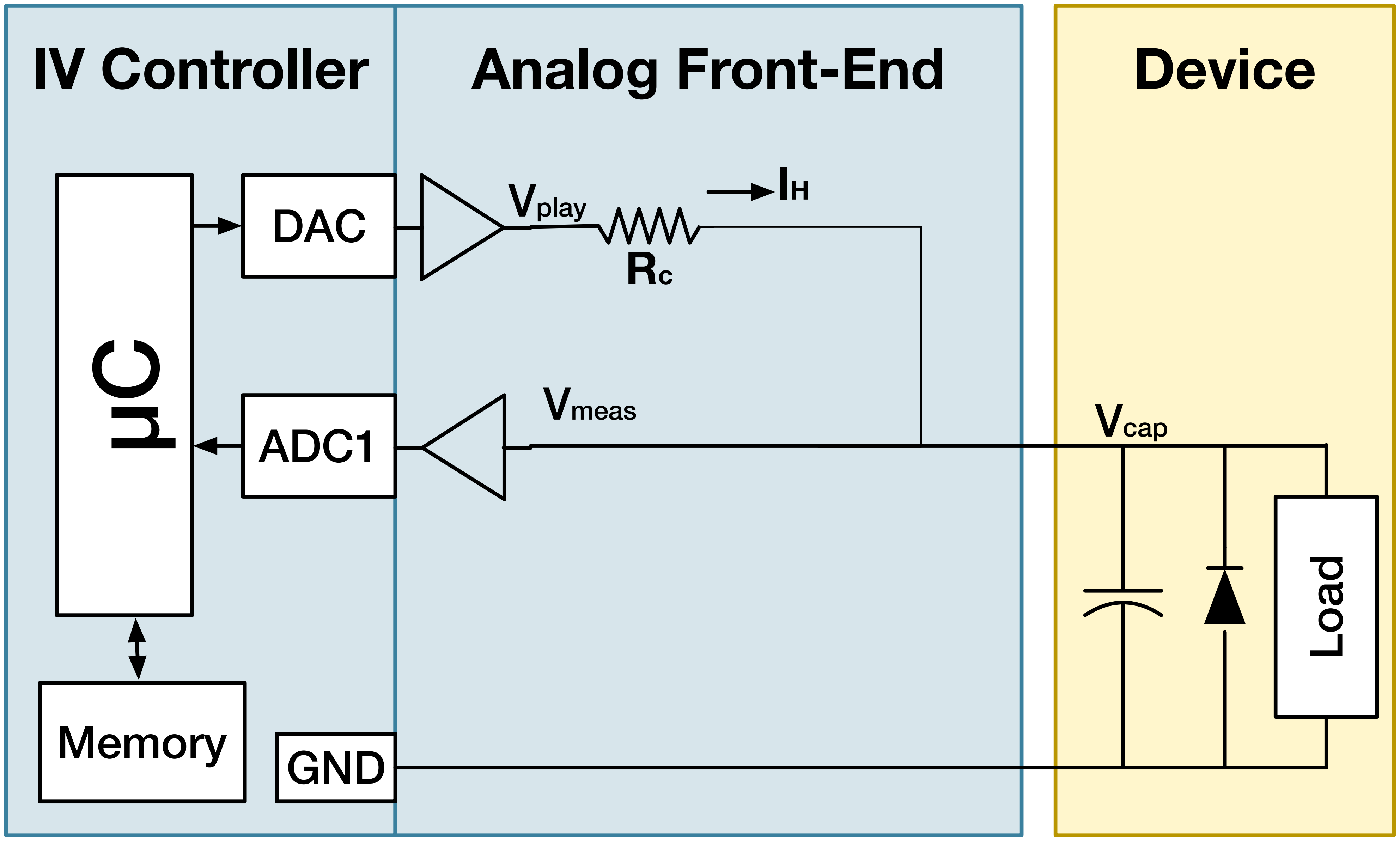
{

- Measure capacitor voltage (V)
- Look up current (I) from I-V curve
- Play back appropriate power

}

Ekho continuously reads the voltage on the test device's capacitor.
This voltage is used to lookup a current value on the IV-curve being emulated.

Controlling Power Output



Ekho then plays back the appropriate amount of power by outputting a voltage over a fixed resistance to vary the amount of current that flows to the capacitor.
This feedback loop is executed until the final IV-curve is played out.

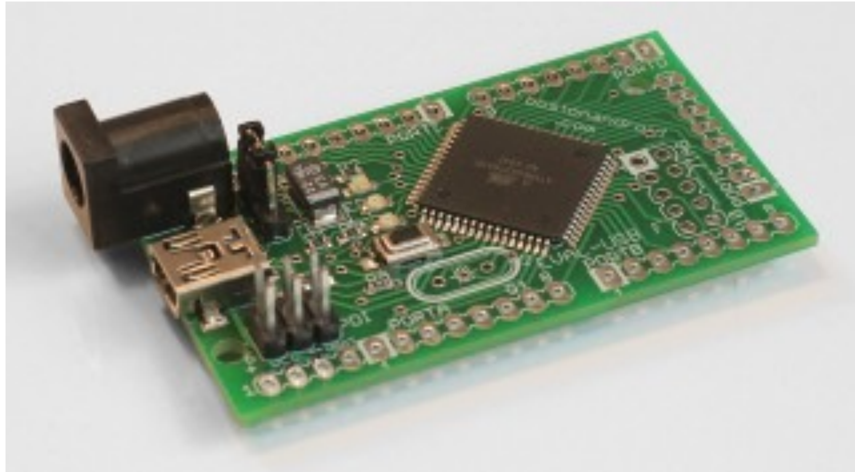
Implementation

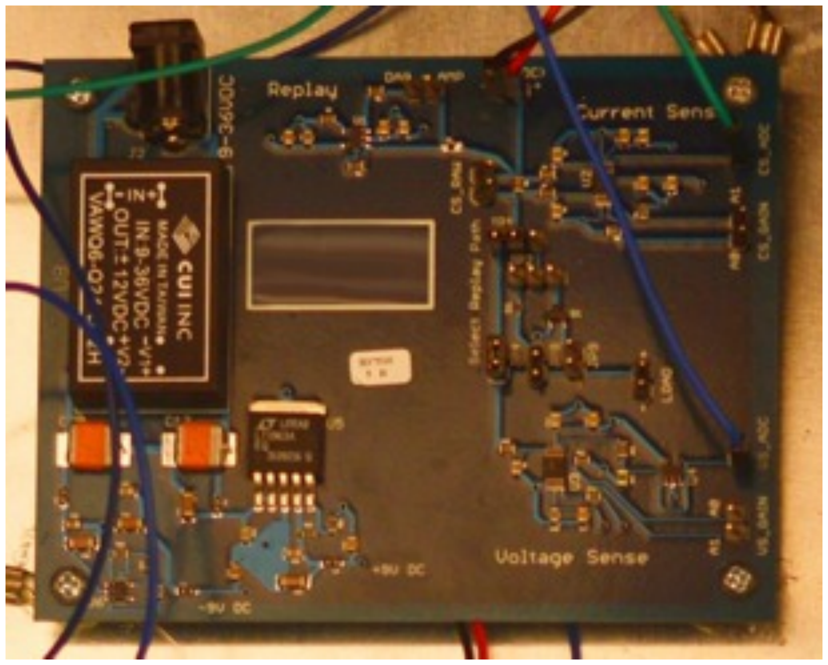
Prototype

- AVR Xmega
- Custom PCB

Coming soon

- Wearable Ekho



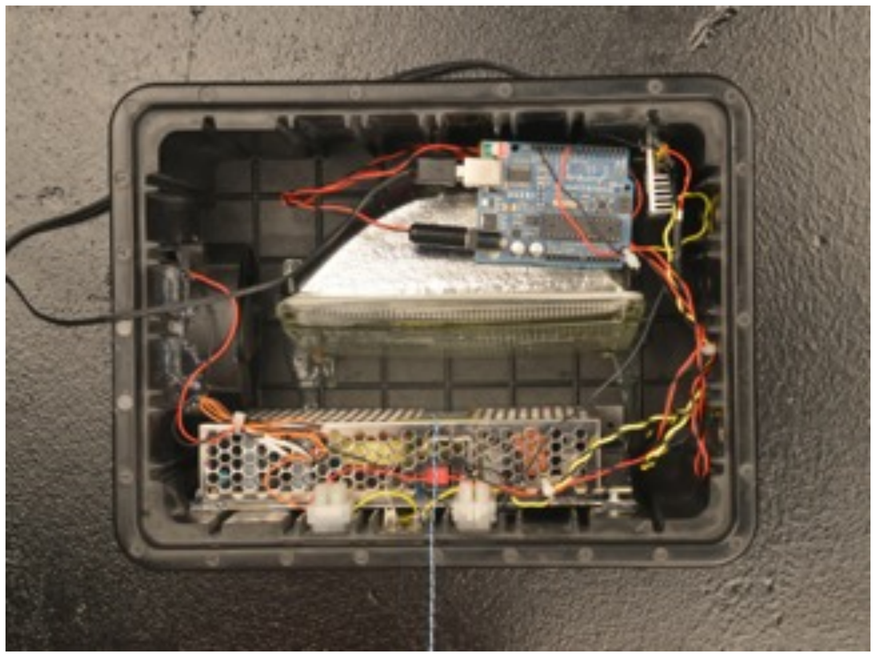


The main core of Ekho was implemented on a custom PCB that measures current and voltage.
Our IV-controller was an AVR Xmega breakout board with integrated fast DAC and ADC.
We also used an Arduino Uno to manage the synthetic load.
The initial prototype is a little big, because it made our experimentation easier, we are currently working on a much smaller wearable version that will make many more applications feasible.

Energy Environments

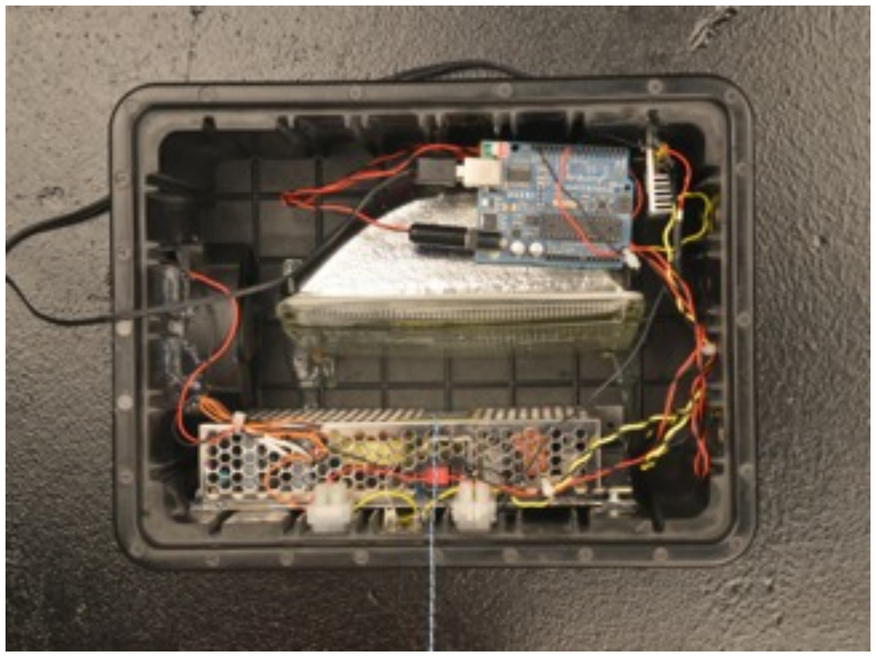
Light Box

- Headlight
- Solar Panel



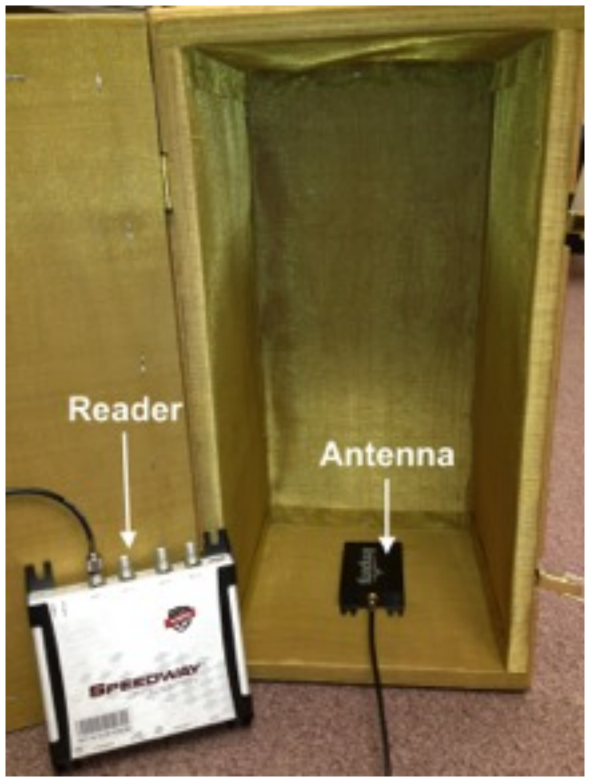
Besides the actual Ekho device, we also built programmable energy environments to act as a ground truth for our evaluation.
Programmable energy environments are devices that isolate an energy source, such as solar, RF, or vibrations, and create a repeatable environment to provide energy to a system.
We built two of these devices. The first is a light box, which consists of a jeep headlight, a solar panel, and a microcontroller. The intensity of the headlight is controlled by the microcontroller. The box is isolated in such a way that the solar panel harvests energy mainly from the headlight.

Energy Environments



Light Box

- Headlight
- Solar Panel



RF Box

- Faraday Cage
- RFID Reader

We also built an RF box, which is a faraday cage with a programmable RFID reader inside. RF powered devices can be locked inside and be isolated from most forms of interference and ambient energy.
Both these “boxes” provide a ground truth for Ekho, a comparison to show that the IV-surface abstraction actually works.

Results

Emulating I-V curves

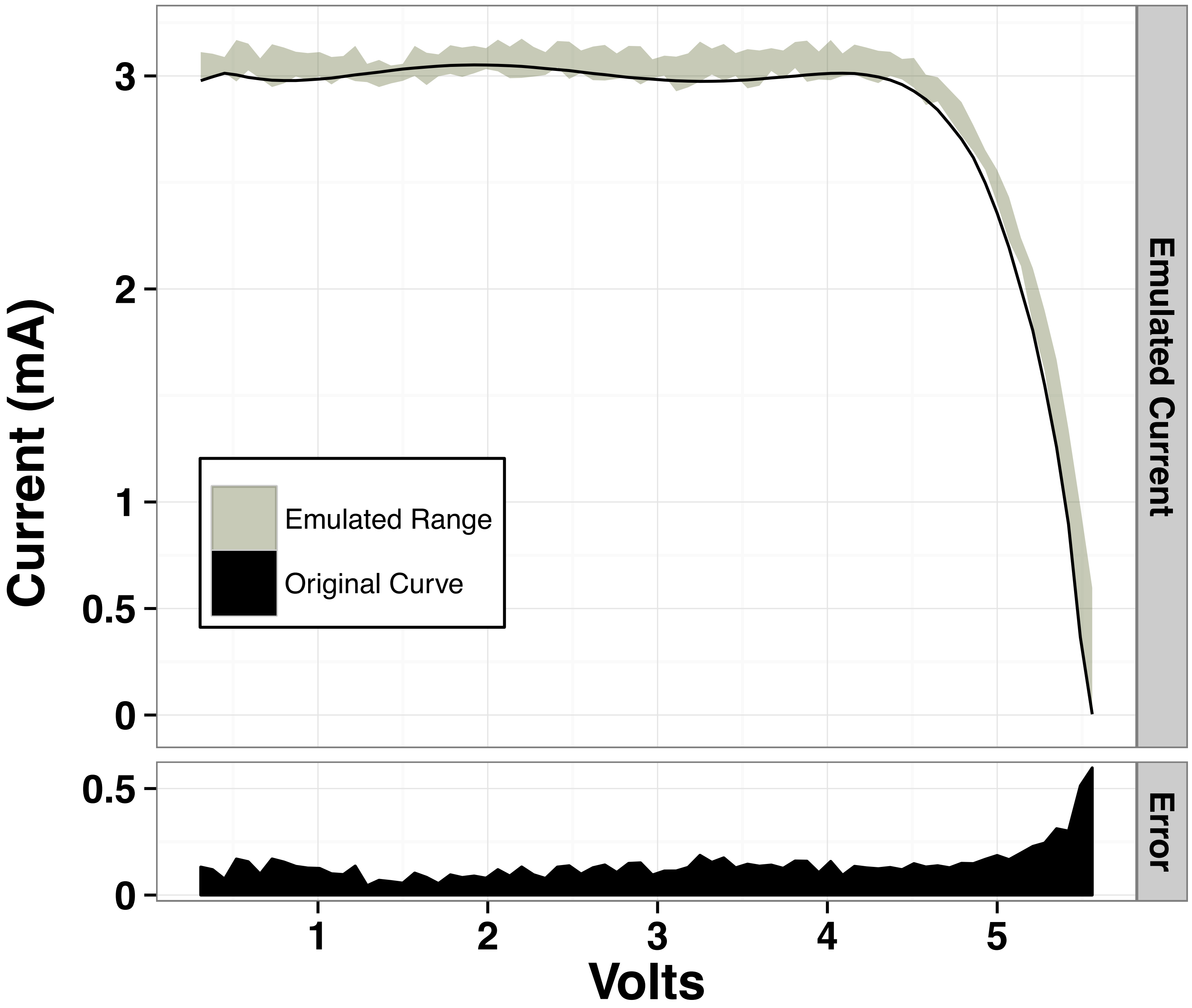
- Solar accuracy
- Error rates

RFID-Scale Devices

- Accuracy
- Consistency

So how well does Ekho actually work?
There is a lot of evaluation in the paper so Im going to show some takeaways from our results.
First I’ll show how well Ekho does emulating solar IV-curves.
Next I’ll show some interesting results from our experiments with recording, and replaying RFID IV-surfaces.

Results



Solar, within 77.4μA

We found that Ekho can emulate solar environments accurately to within 77.4μA, with consistency close to our light-box. This graph shows the actual emulated range for a particular IV—curve, and the target curve underneath it, the x-axis is the supply voltage on the capacitor, and the y-axis is the harvesting current. The error for each part of the curve is shown on the bottom of the figure.

RFID-Scale Results

Transmit Power	Harvested Energy	CRC Ekho Mean	CRC RF-Box Mean
+21.25dBm	0.55 mJ	23.6	21.0
+27.75dBm	2.57 mJ	208.7	189.2
+32.50dBm	3.88 mJ	237.3	266.2

Comparable accuracy

To evaluate Ekho's performance with RFID-scale devices, we used Ekho to record three different IV-surfaces for different RFID-reader transmit powers.
Ekho then replaced the RF energy harvester on a Umich Moo running a simple program that senses on its ADC, and CRCs the ADC reading; it does this as many times as possible before death. We then replayed these three surfaces, and compared the number of CRC's to the number of CRC's in the RF box. From this we found that Ekho has similar accuracy in terms of behavior to the RF-box.

RFID-Scale Results

Transmit Power	Harvested Energy	Ekho Error %	RF-Box Error %
+21.25dBm	0.55 mJ	2.3%	39.4%
+27.75dBm	2.57 mJ	0.3%	20.7%
+32.50dBm	3.88 mJ	0.5%	4.7%

Better consistency

We also found that Ekho can emulate RF energy environments more consistently than our RF box.
This table shows the error rates between multiple runs of Ekho on the same three transmit powers. Ekho beat the RF-box in terms of repeatability and consistency.

Summary

Ekho makes rigorous experimentation with RFID-scale systems possible.

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http://people.cs.clemson.edu/~jsorber/ekho

This talk has given you a quick overview of what Ekho is capable of.
We think Ekho is an exciting tool that helps conduct experiments that you could not do in the past.
If this sounds like something you are interested in, there are far more details and results in the paper.
You can also come check out our demo later today to see Ekho in action.
If you are really interested, and you want an Ekho for your lab, check out our website which will help you build your own for less than a $700.
Thank you.