Turning *Coders* into *Makers*: The Promise of Embedded Design Generation

*Rohit Ramesh, **Richard Lin**, Antonio Iannopollo, Alberto Sangiovanni-Vincentelli, Björn Hartmann, Prabal Dutta*

Berkeley EECS
ELECTRICAL ENGINEERING & COMPUTER SCIENCES

COMPUTER SCIENCE AND ENGINEERING
UNIVERSITY OF MICHIGAN

SITP Retreat 2017

Embedded Development is a key part of the maker movement.

Embedded Development is a key part of the personal fabrication movement.

ARDUINO

sparkfun ELECTRONICS

adafruit INDUSTRIES

More accessible and usable parts.

Embedded Development is a key part of the personal fabrication movement.

ARDUINO

sparkfun ELECTRONICS

adafruit INDUSTRIES

More accessible and usable parts.

BAC

ADVANCED CIRCUITS

Cheaper board fabrication.

Embedded Development is a key part of the personal fabrication movement.

ARDUINO sparkfun ELECTRONICS adafruit INDUSTRIES

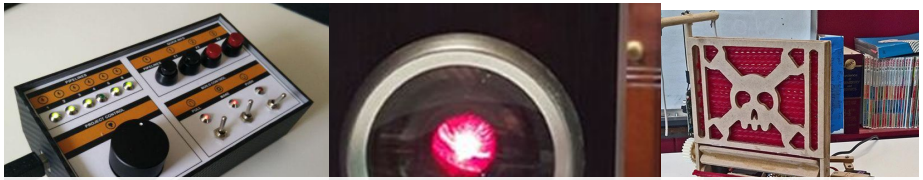
More accessible and usable parts.

BAC ADVANCED CIRCUITS

Cheaper board fabrication.

Low entry requirements.

Embedded Development is a key part of the personal fabrication movement.



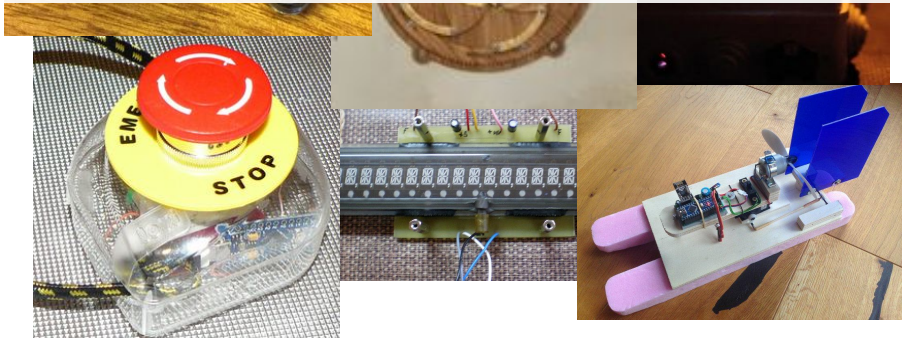
ARDUINO

sparkfun ELECTRONICS

adafruit INDUSTRIES

More accessible and usable parts.

Design is still a major bottleneck!

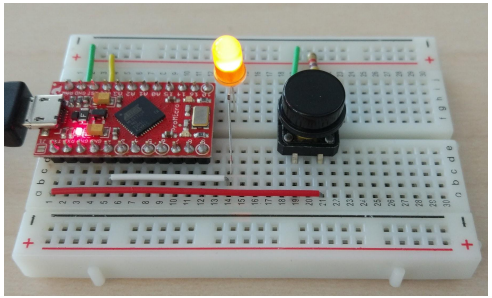


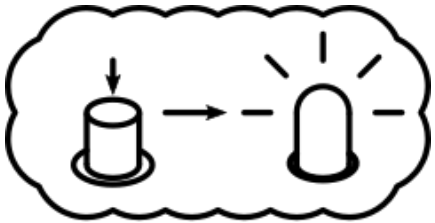
Cheaper board fabrication.

Low entry requirements.

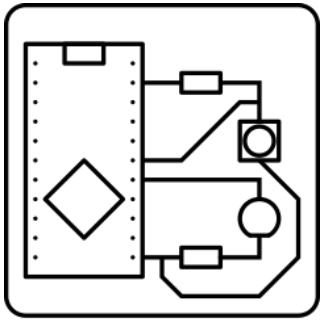
We want to go from idea to finished device.

When the button is pressed, the light should blink.





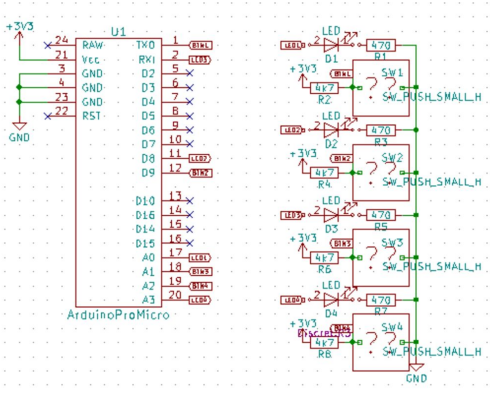
Idea

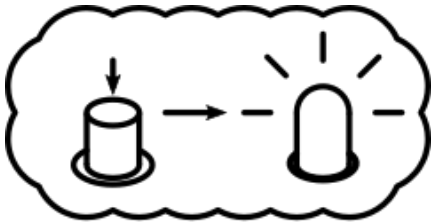


Completed Board

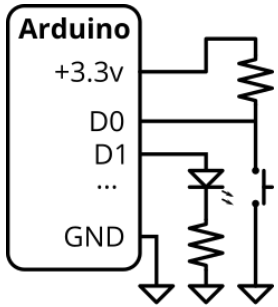
Designing the circuit takes significant domain knowledge.

When the button is pressed, the light should blink.





Idea

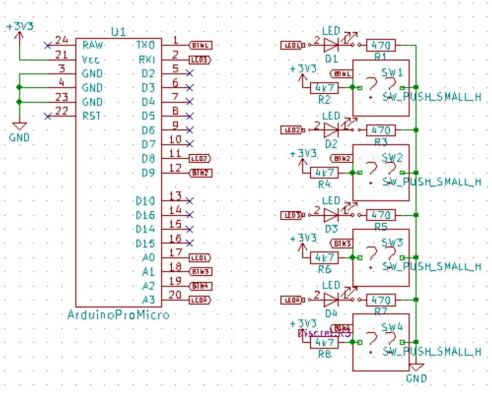


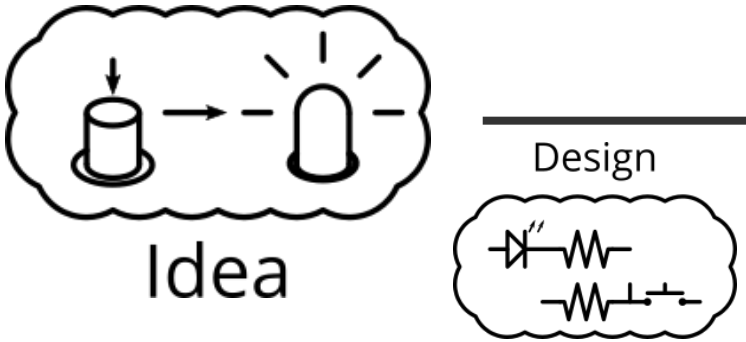
Netlist-level Schematic

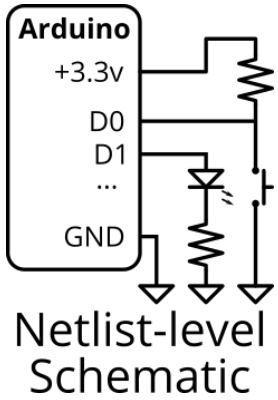
Designing the circuit takes significant domain knowledge.

When the button is pressed, the light should blink.

- What should the circuit have in it?



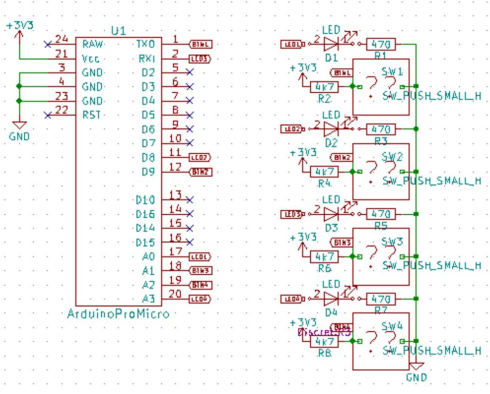


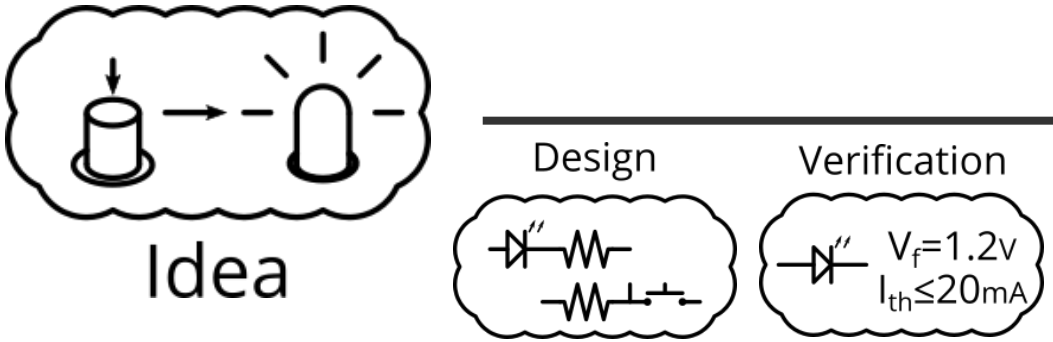


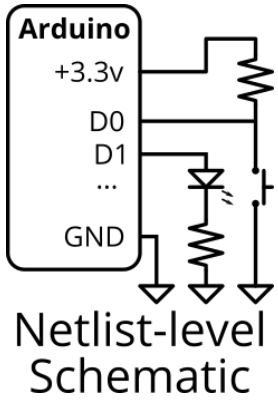
Designing the circuit takes significant domain knowledge.

When the button is pressed, the light should blink.

- What should the circuit have in it?
- What do I need to check in order to verify part compatibility?



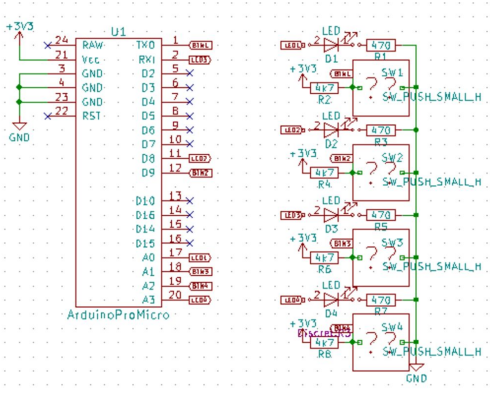


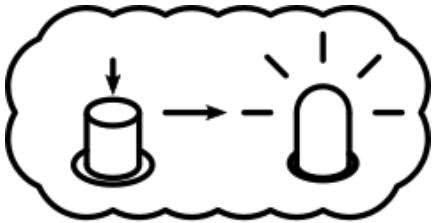


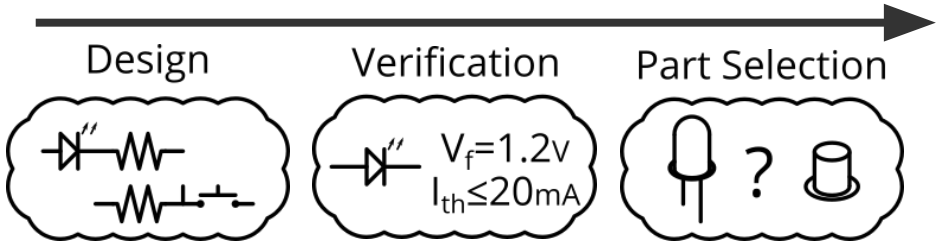
Designing the circuit takes significant domain knowledge.

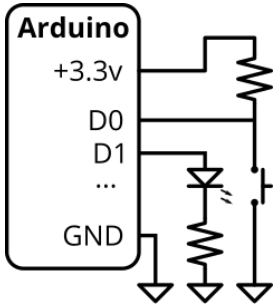
When the button is pressed, the light should blink.

- What should the circuit have in it?
- What do I need to check in order to verify part compatibility?
- How do I even figure out what parts I want to use?





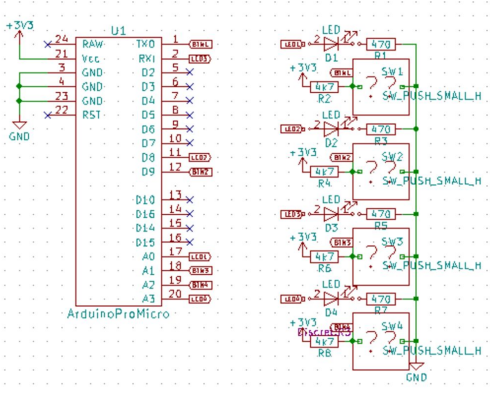




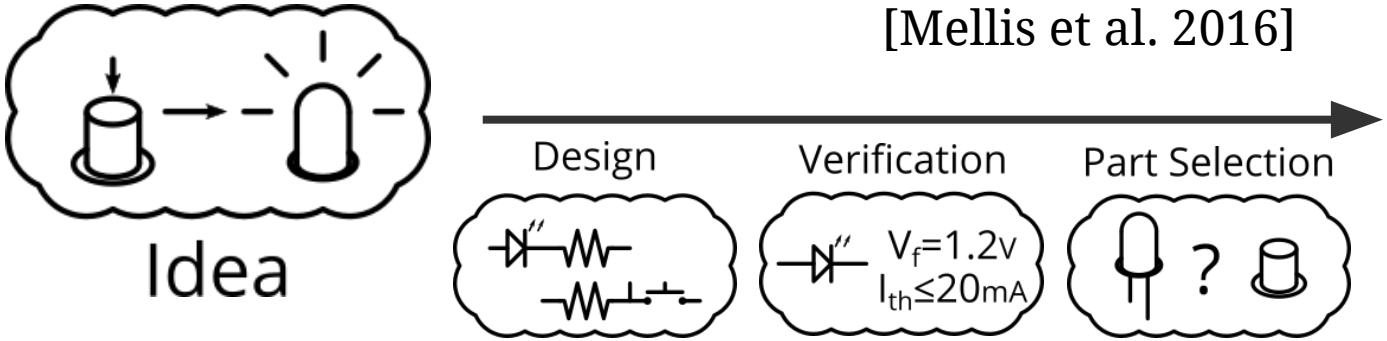
This domain knowledge is often hard for novices to acquire.

When the button is pressed, the light should blink.

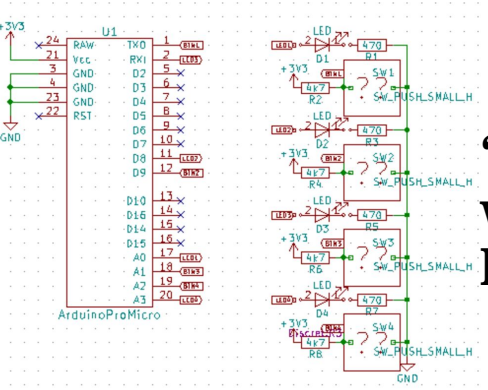
“What I found challenging was to understand what are the components that have to be paired with the basic components that you are buying.”



- Luisa, closing discussion [Mellis et al. 2016]

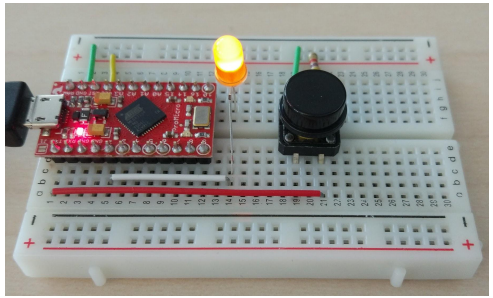


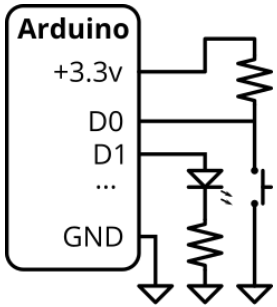
Automation makes PCB design much easier.



“The auto-router was magical. It was cool watching all the wires go bo-bo-bo-bop.”

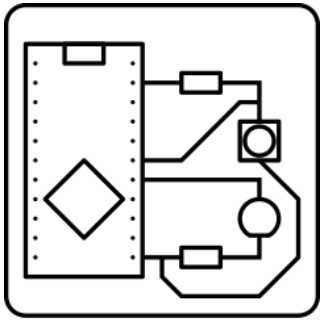
- Tyler [Mellis et al. 2016]





Netlist-level Schematic

Breadboard Design, Manual PCB Design, or Autorouting

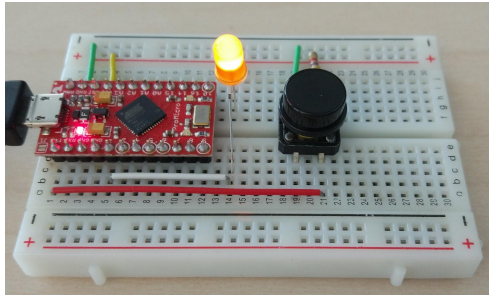


Completed Board

Working with the firmware is just coding.

```
#import "arduino.h"
#import "button_driver.h"

BUTTON button;
GPIOLED light;

void setup() {
  button.init(GPIO3);
  light.init(GPIO4);
}

void loop() {
  if(button.isPressed()){
        light.toggle();
  } else {
        light.off();
  }
  delay(1000); //milliseconds
}
```

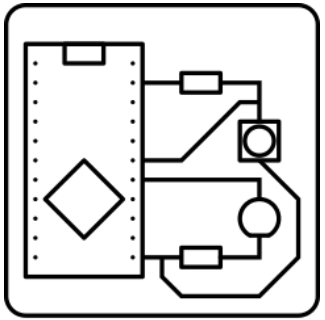
- The circuit has to be designed first so we have information about connectivity and interfaces.
- Arduino and other frameworks wrap low-level abstractions in nice, comprehensible interfaces.



```
void loop {
  led = 1;
```

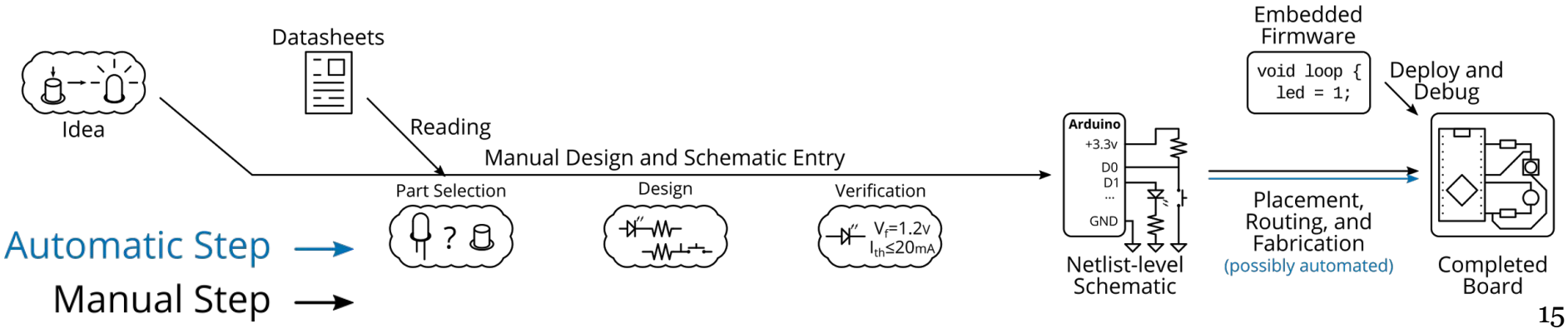
Embedded Firmware

Debug and deploy firmware



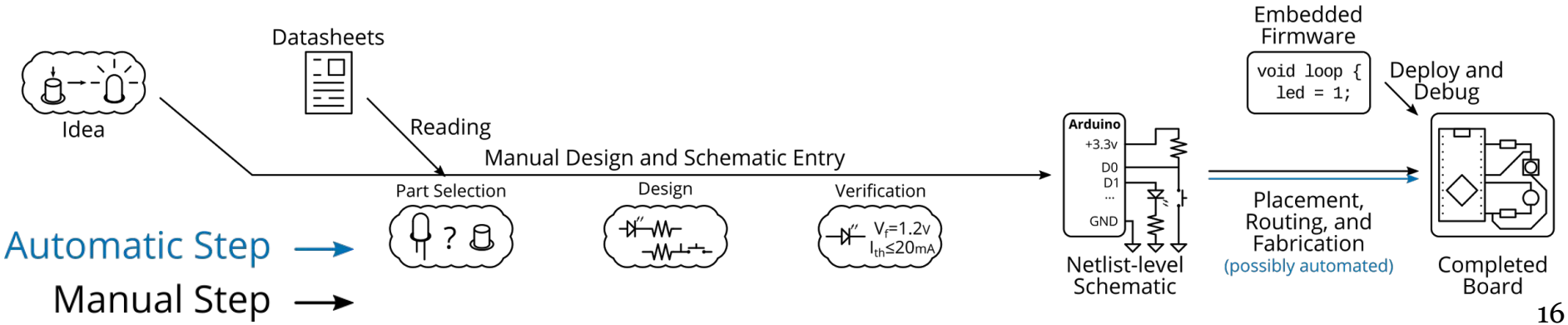
Completed Board

We want to minimize the amount of knowledge needed to design electronics.



Anyone who can program should be able to design an embedded device

- There are many more programmers than electrical engineers.
- This applies for professionals *and* hobbyists.



Embedded firmware requires domain knowledge to write.

```
#import “arduino.h”
#import “button_driver.h”

BUTTON button;
GPIOLED light;

void setup() {
  button.init(GPIO3);
  light.init(GPIO4);
}

void loop() {
  if(button.isPressed()){
    light.toggle();
  } else {
    light.off();
  }
  delay(1000); //milliseconds
}
```

Requires finished circuit diagram, and the knowledge to create it.

Captures the function of the device at a high level.

We can make a version that doesn't need that domain knowledge.

Annotated Code

A mockup of the input format for EDG, designed to allow people to specify devices without needing to know electrical engineers.

```
peripheral button = new MomentarySwitch();

peripheral light = new LED(color = Red);


void loop() {
  if(button.isPressed()){
    light.toggle();
  } else {
    light.off();
  }
  delay(1000); //milliseconds
}
```

Ask for properties that matter to you, don't waste time picking parts.

Captures the function of the device at a high level.

EDG takes annotated code and a library of parts and produces SW and HW.

```
peripheral button = new MomentarySwitch();

peripheral light = new LED(color = blue);

void loop() {
  if(button.isPressed()){
          light.toggle();
  } else {
          light.off();
  }
  delay(1000); //milliseconds
}
```

Annotated Code

```
#pragma edg
led(red)
```

Parse

Describe Hardware

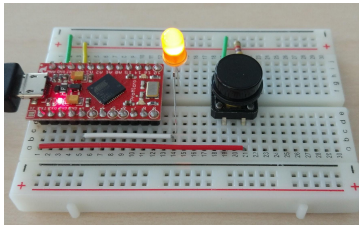
Idea

Datasheets

Library Creation

EDG-Based Dev Tool

```
#import "arduino.h"
#import "button_driver.h"

BUTTON button;
GPIOLED light;

void setup() {
  button.init(GPIO3);
  light.init(GPIO4);
}

void loop() {
  if(button.isPressed()){
          light.toggle();
  } else {
          light.off();
  }
  delay(1000); //milliseconds
}
```

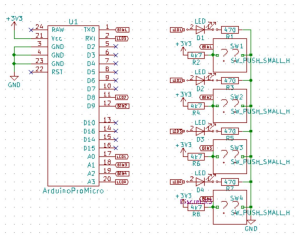


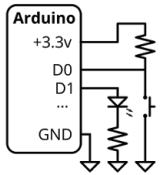
Design Instantiation

Embedded Firmware

```
void loop {
led = 1;
```

Deploy and Debug

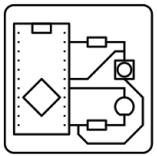




Netlist-level Schematic

Placement, Routing, and Fabrication

(possibly automated)



Completed Board

Automatic Step →

Manual Step →

Embedded design generation uses constraint solving tools to do this.

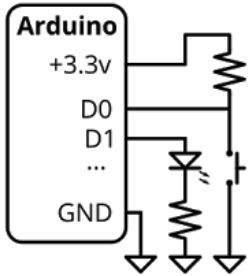
Annotated Code

```
#pragma edg
led(red)
```

Datasheets

Embedded Firmware

```
void loop {
  led = 1;
```



Netlist-level Schematic

Embedded design generation uses constraint solving tools to do this.

Space of Possible Designs

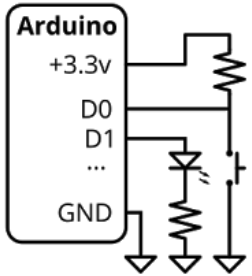
Annotated Code

```
#pragma edg
led(red)
```

Datasheets

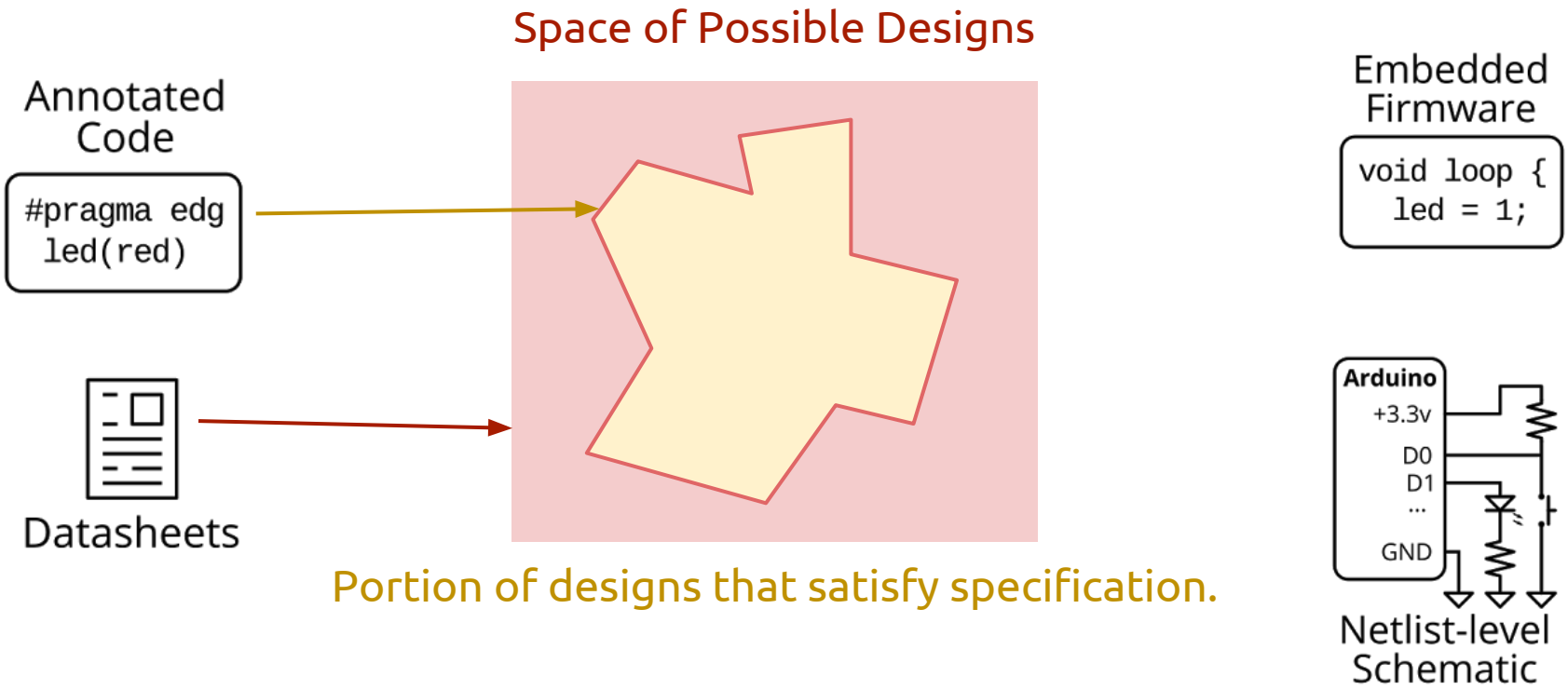
Embedded Firmware

```
void loop {
  led = 1;
```

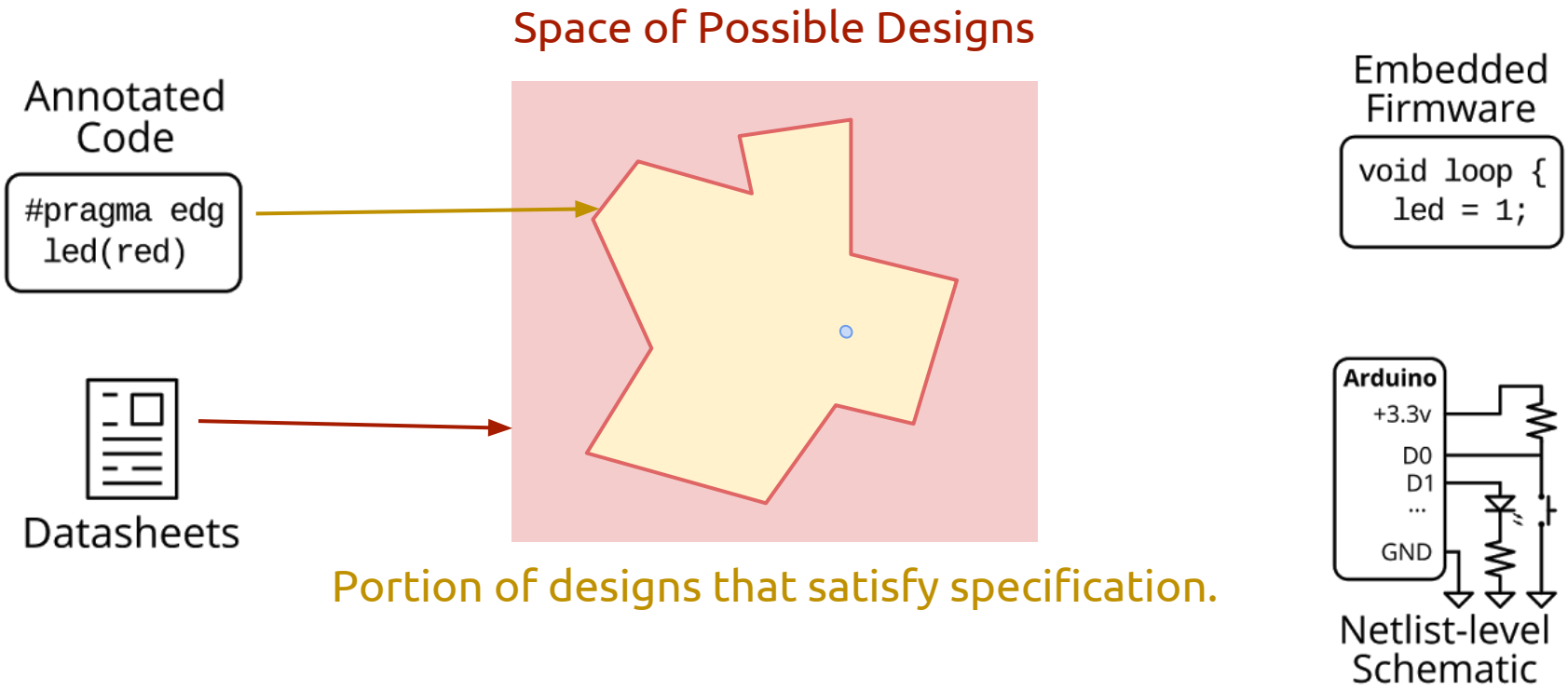


Netlist-level Schematic

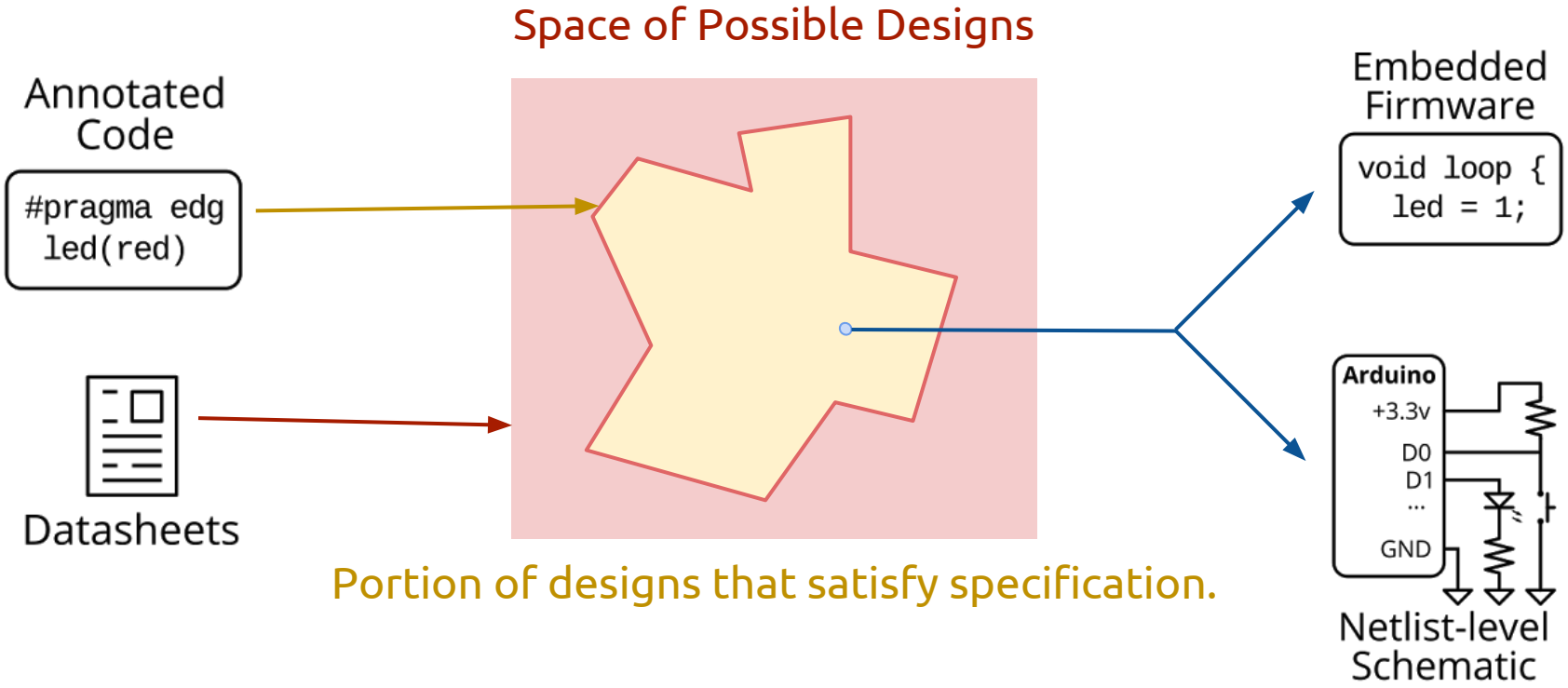
Embedded design generation uses constraint solving tools to do this.



Embedded design generation uses constraint solving tools to do this.



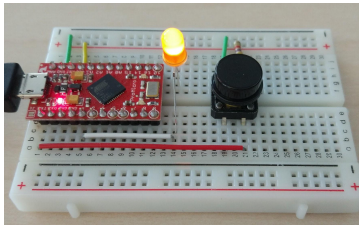
Embedded design generation uses constraint solving tools to do this.



Turn coders into makers, through the power of constraint solvers

```
peripheral button = new MomentarySwitch();

peripheral light = new LED(color = blue);

void loop() {
  if(button.isPressed()){
          light.toggle();
  } else {
          light.off();
  }
  delay(1000); //milliseconds
}
```

```
#import "arduino.h"
#import "button_driver.h"

BUTTON button;
GPIOLED light;

void setup() {
  button.init(GPIO3);
  light.init(GPIO4);
}

void loop() {
  if(button.isPressed()){
          light.toggle();
  } else {
          light.off();
  }
  delay(1000); //milliseconds
}
```



Annotated Code

```
#pragma edg
led(red)
```

Parse

Describe Hardware

Idea

Datasheets

Library Creation

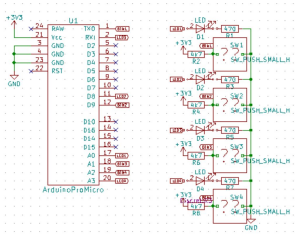
EDG-Based Dev Tool

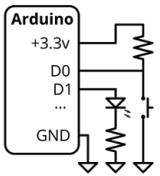
Design Instantiation

Embedded Firmware

```
void loop {
led = 1;
```

Deploy and Debug

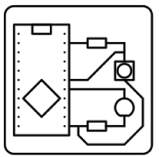




Netlist-level Schematic

Placement, Routing, and Fabrication

(possibly automated)



Completed Board

Automatic Step →

Manual Step →

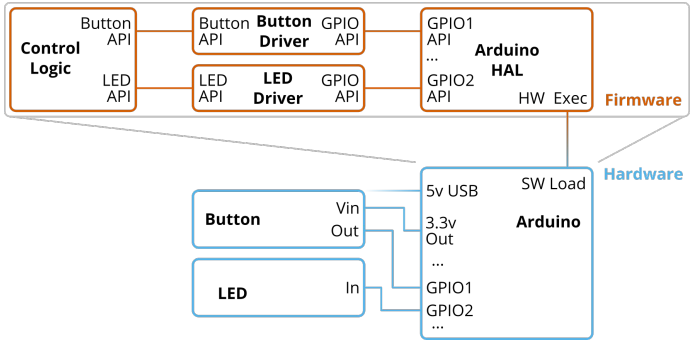
Outline

- The EDG Methodology
- Proof-of-Concept and Evaluation
- Discussion and Future Work

The EDG Methodology

How do we represent the parts our tool has available?

We represent hardware and firmware components as blocks in a block diagram



Blocks are made up of a number of sub elements.

Blocks are made up of a number of sub elements.

Ports

Digital Signal Input

User Facing Button API and Hardware API

Blocks are made up of a number of sub elements.

Ports

Digital Signal Input

User Facing Button API and Hardware API

Implementation

Code that wraps the HW API in a nice interface.

Blocks are made up of a number of sub elements.

Ports	Digital Signal Input	User Facing Button API and Hardware API
Implementation		Code that wraps the HW API in a nice interface.
Metadata	LED Color, Input Voltage	API use and connectivity

Blocks are made up of a number of sub elements.

Ports

Digital Signal Input

User Facing Button API and Hardware API

Implementation

Code that wraps the HW API in a nice interface.

Metadata

LED Color, Input Voltage

API use and connectivity

Conditions

Conditions allow us to specify the operating conditions of a component.

Conditions allow us to specify the operating conditions of a component.

LiPo Battery

Mains Power

Conditions allow us to specify the operating conditions of a component.

LiPo Battery

Mains Power

Input Voltage = 3.7v

Metadata

Input Voltage = 120v

Conditions allow us to specify the operating conditions of a component.

LiPo Battery

Mains Power

Input Voltage = 3.7v

Metadata

Input Voltage = 120v

Input voltage is **above 1.2v** and **below 5v**

Conditions

Input voltage is **above 1.2v** and **below 5v**

Conditions encode the functional correctness of a block.

Ports	Digital Signal Input	User Facing Button API and Hardware API
Implementation		Code that wraps the HW API in a nice interface.
Metadata	LED Color, Input Voltage	API use and connectivity
Conditions	Input voltage is above 1.2v and below 5v	If button API is used, then GPIO API must be active

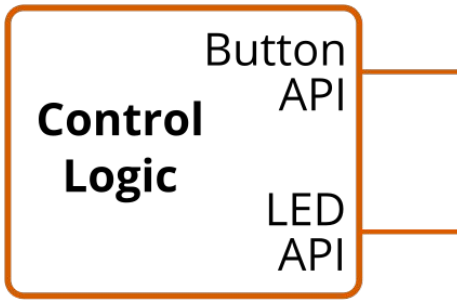
The annotated code has to actually run on the device, and can be in a block.

```
peripheral button = new MomentarySwitch();

peripheral light = new LED(color = Red);

void loop() {
  if(button.isPressed()){
    light.toggle();
  } else {
    light.off();
  }
  delay(1000); //milliseconds
}
```

The annotated code has to actually run on the device, and can be in a block.

Control Logic:

Block created by parsing annotated code, which will eventually run on the device.

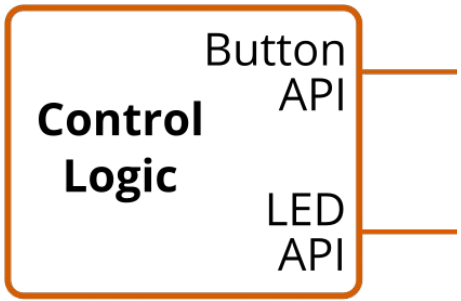



```
peripheral button = new MomentarySwitch();

peripheral light = new LED(color = Red);

void loop() {
  if(button.isPressed()){
    light.toggle();
  } else {
    light.off();
  }
  delay(1000); //milliseconds
}
```

The annotated code has to actually run on the device, and can be in a block.

Control Logic:

Block created by parsing annotated code, which will eventually run on the device.



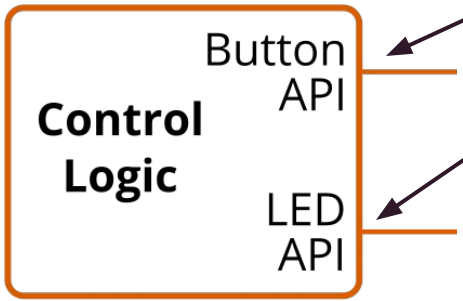
Implementation

```
peripheral button = new MomentarySwitch();

peripheral light = new LED(color = Red);

void loop() {
  if(button.isPressed()){
    light.toggle();
  } else {
    light.off();
  }
  delay(1000); //milliseconds
}
```

The annotated code has to actually run on the device, and can be in a block.

Control Logic:

Block created by parsing annotated code, which will eventually run on the device.



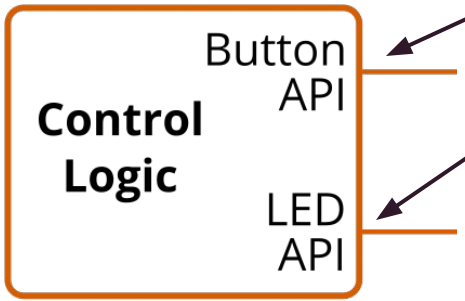

```
peripheral button = new MomentarySwitch();

peripheral light = new LED(color = Red);

void loop() {
  if(button.isPressed()){
    light.toggle();
  } else {
    light.off();
  }
  delay(1000); //milliseconds
}
```

Implementation

The annotated code has to actually run on the device, and can be in a block.

Control Logic:

Block created by parsing annotated code, which will eventually run on the device.




```
peripheral button = new MomentarySwitch();

peripheral light = new LED(color = Red);

void loop() {
  if(button.isPressed()){
    light.toggle();
  } else {
    light.off();
  }
  delay(1000); //milliseconds
}
```

Implementation

Conditions

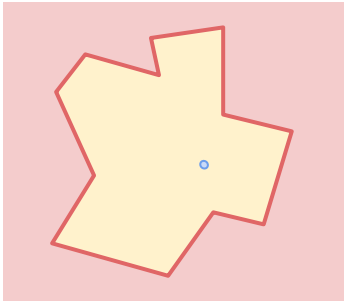
Both the ports must be provided a valid api to the corresponding physical component.

Solvers find variable assignments such that some set of constraints hold;

Variables

Constraints

→ *Solve* → **Solution**



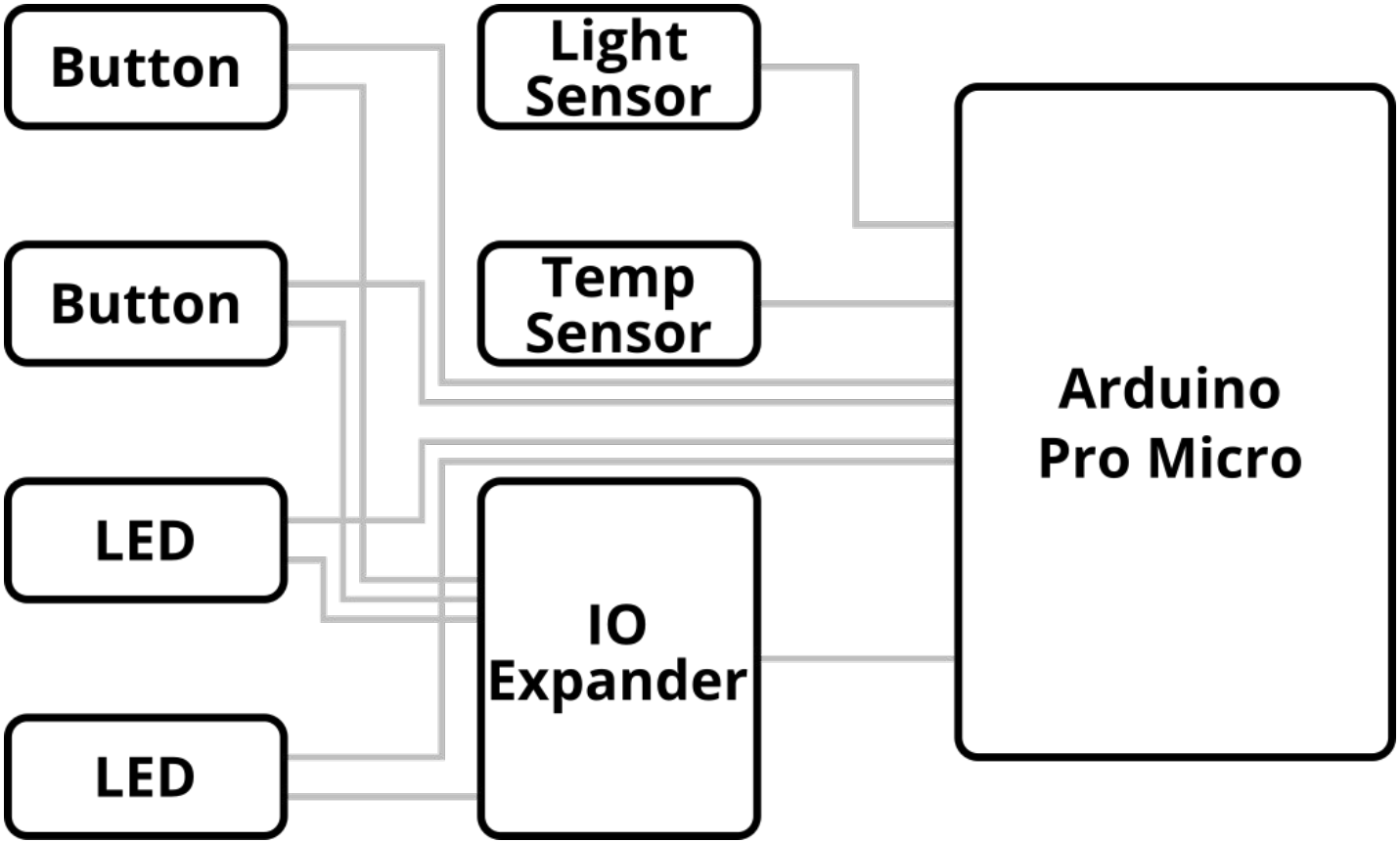
$A < 12$
$B = 3 + A$
$C > 0$
$C = 3 - A$

→ *Solve* →

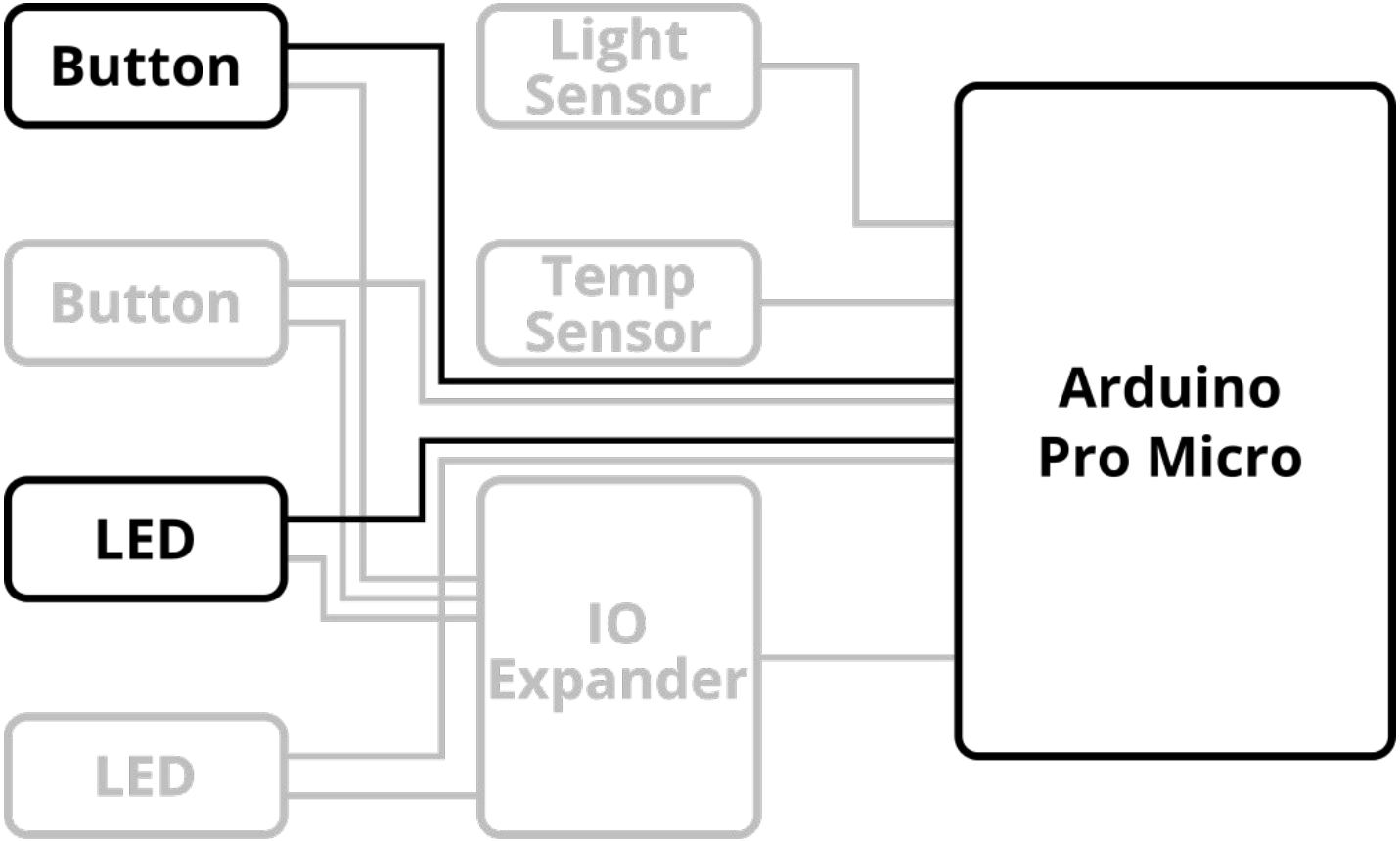
$A = 2$
$B = 5$
$C = 1$

- The solver finds *one* assignment such that *every* constraint is met
- The solver is nondeterministic and might output any of the valid assignments.

We can combine every block in the library, and all possible potential links.



A pegboard connection is a block diagram

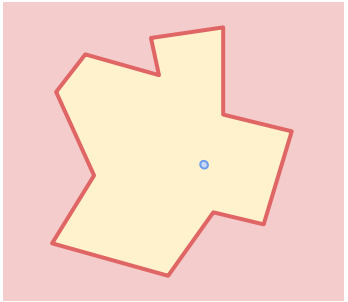


Mix with block conditions and control logic, and bake

Metadata → **Variables**

Conditions → **Constraints**

Variables + **Constraints** → *Solve* → **Solution** → **Block Diagram**



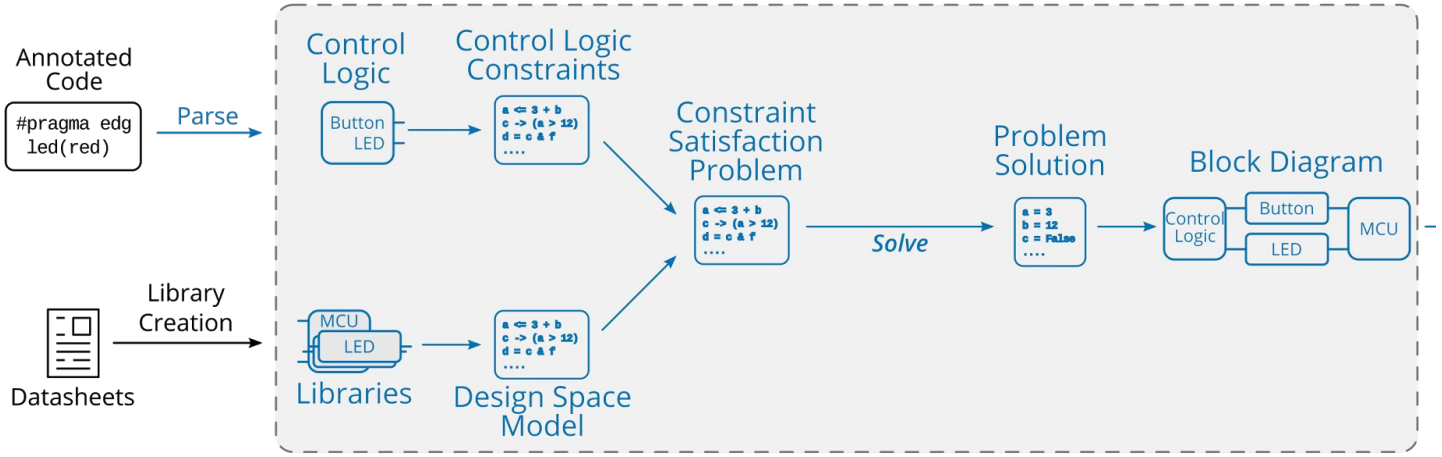
$A < 12$
$B = 3 + A$
$C > 0$
$C = 3 - A$

Solve

$A = 2$
$B = 5$
$C = 1$

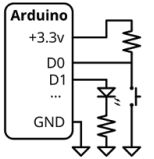
- The solver finds *one* assignment such that *every* constraint is met
- The solver is nondeterministic and might output any of the valid assignments.

We can instantiate a design from the solver output



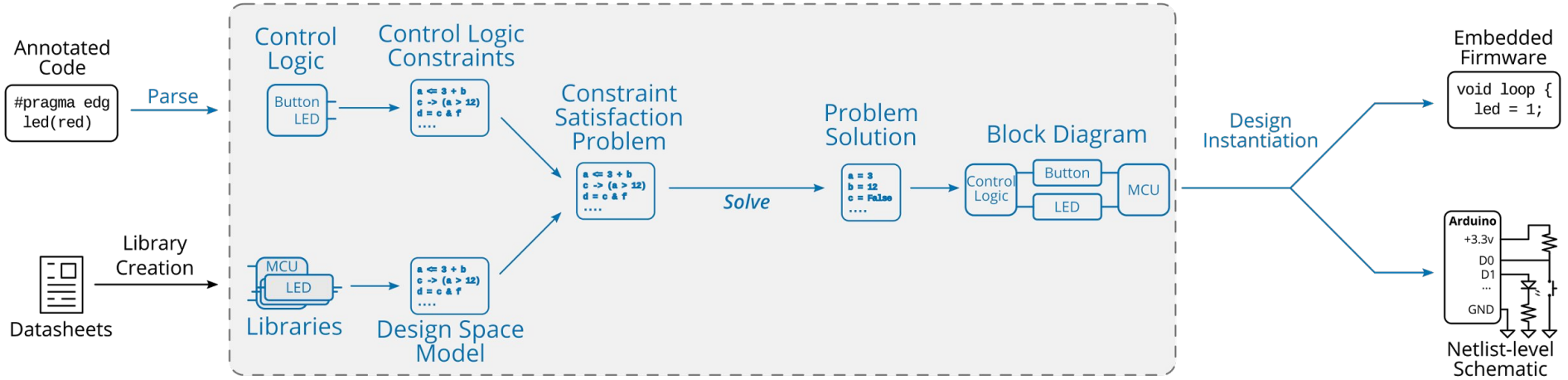
Embedded Firmware

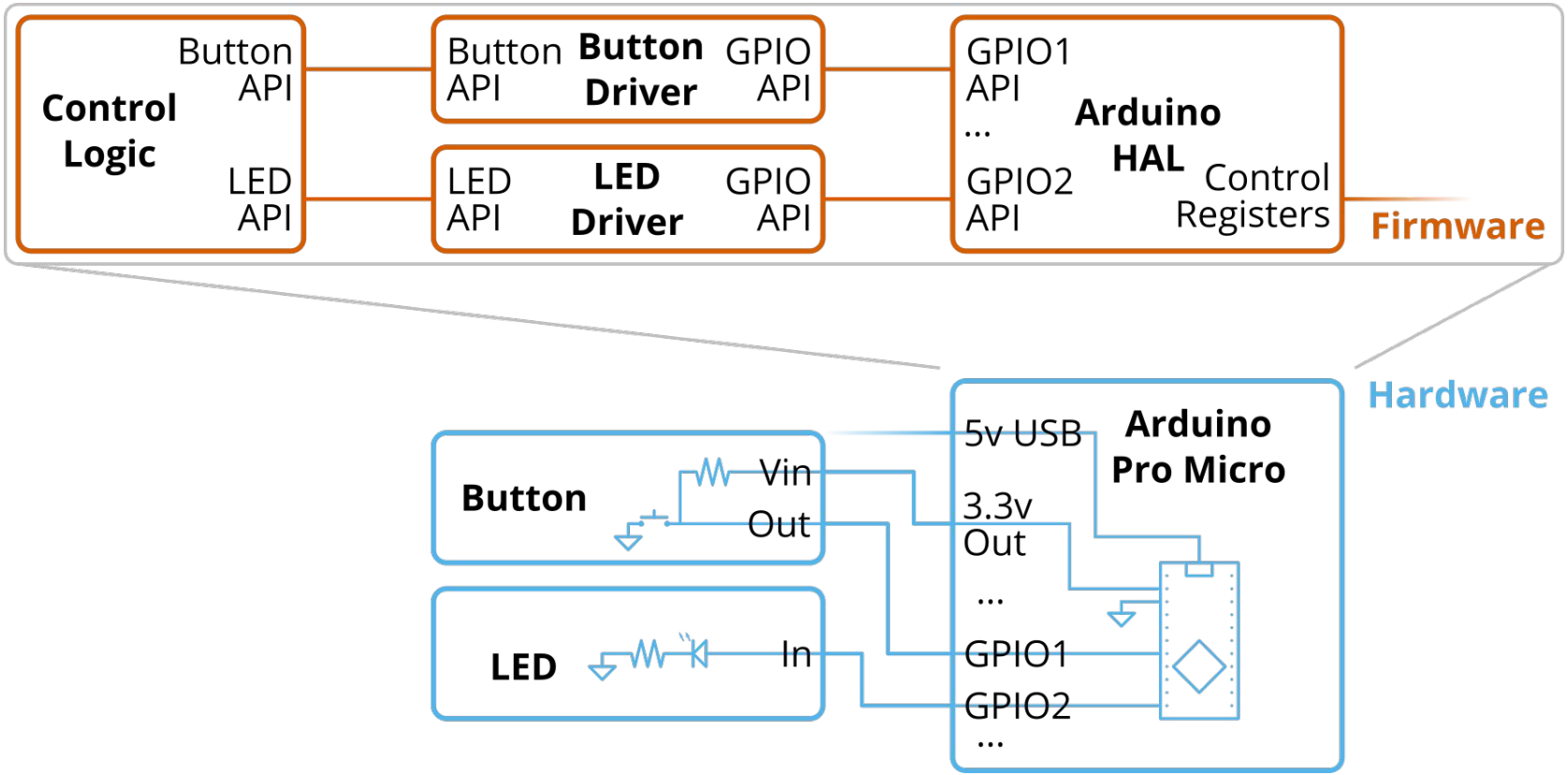
```
void loop {
  led = 1;
```

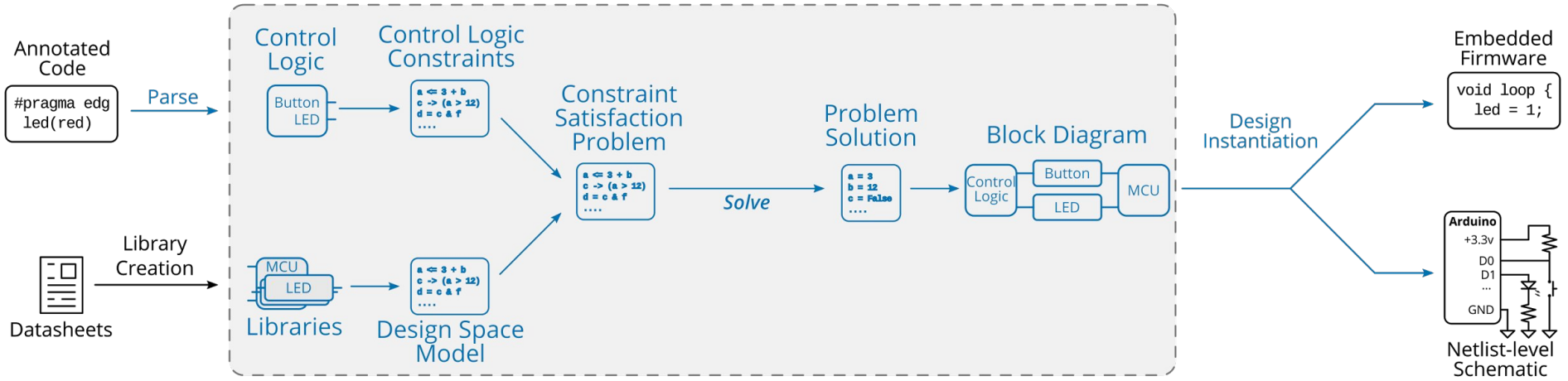


Netlist-level Schematic

We can instantiate a design from the solver output



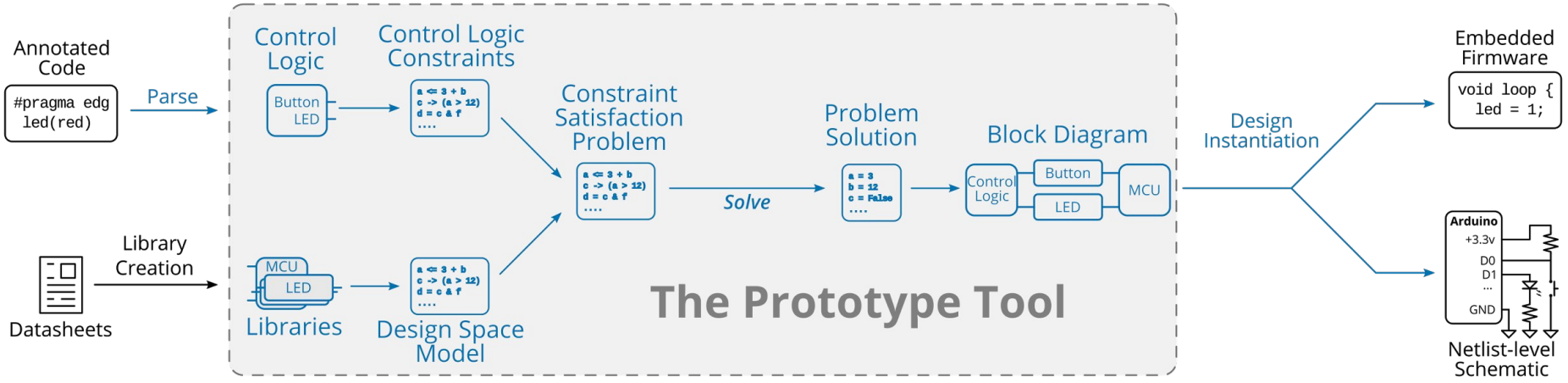

Control Logic
Button API
LED API
Button API
Button Driver
GPIO API
LED API
LED Driver
GPIO API
GPIO1 API
...
GPIO2 API
Arduino HAL
Control Registers
Firmware
Hardware
Button
Vin
Out
LED
In
5v USB
3.3v Out
...
GPIO1
GPIO2
...
Arduino Pro Micro



We have gone from a high-level specification and a set of parts, to a design that can be realized.

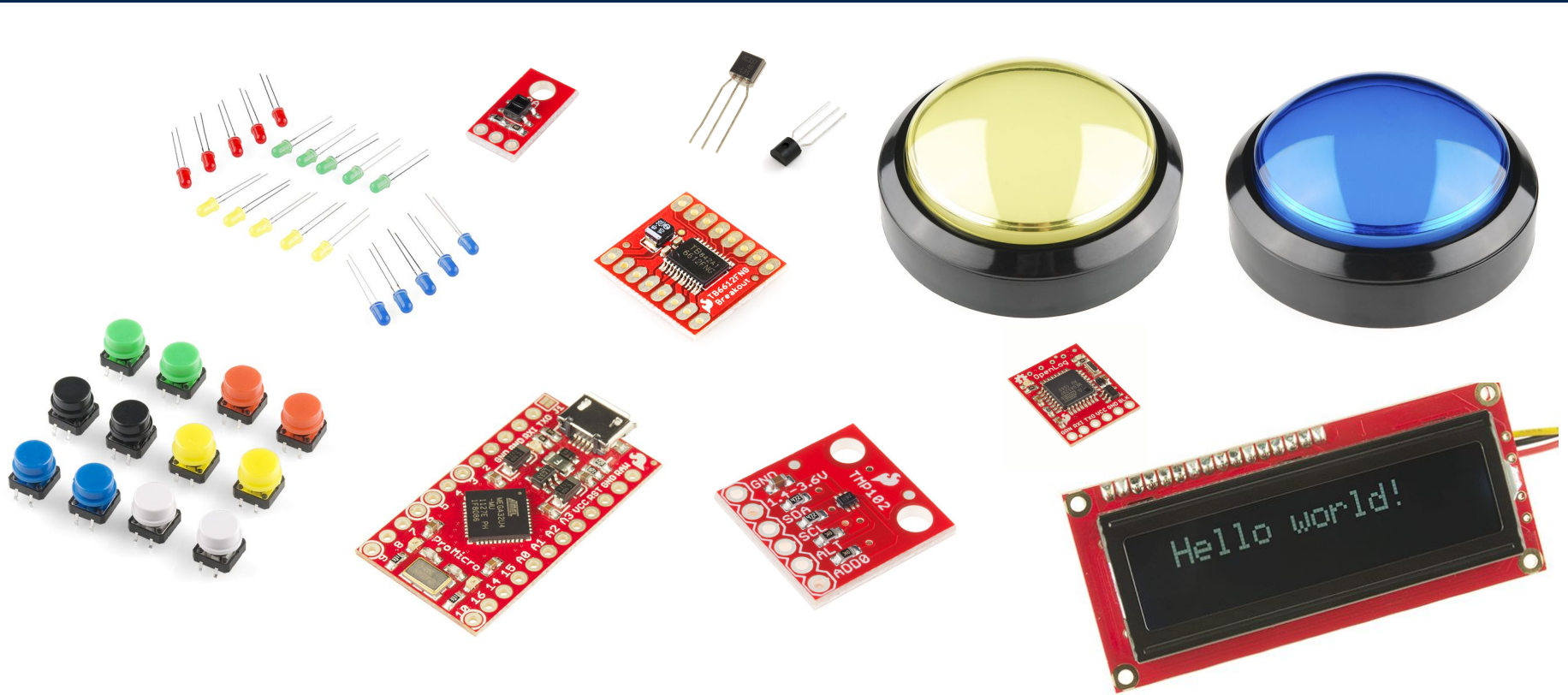
Proof-of-Concept and Evaluation

Our prototype translates the EDG methodology onto available tools.



- The tool is built with Haskell on top of the Z3 constraint solver.
- Parsing and design instantiation is still manual to allow for faster iteration on the system internals.

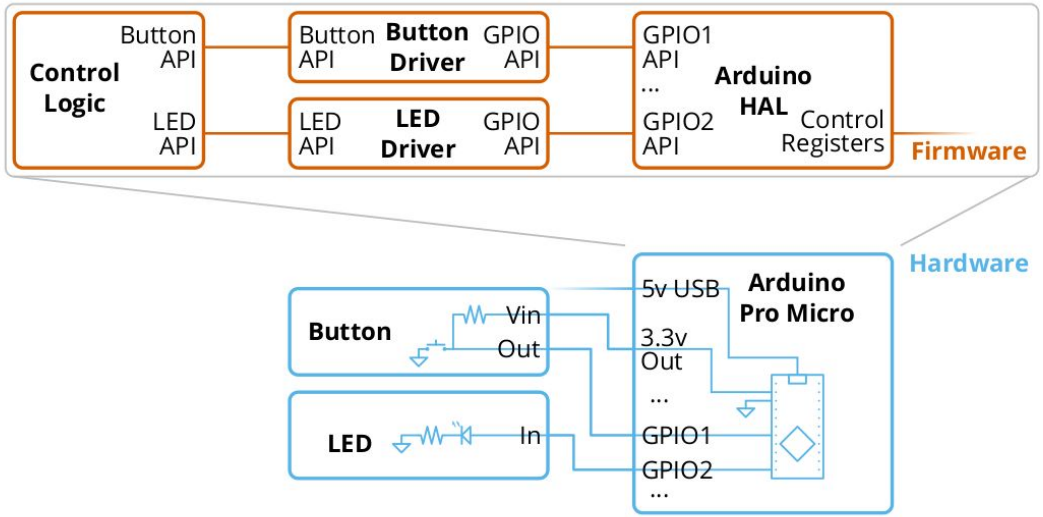
Our test library has a wide variety of parts



Images from sparkfun.com, under a CC-BY 2.0 license

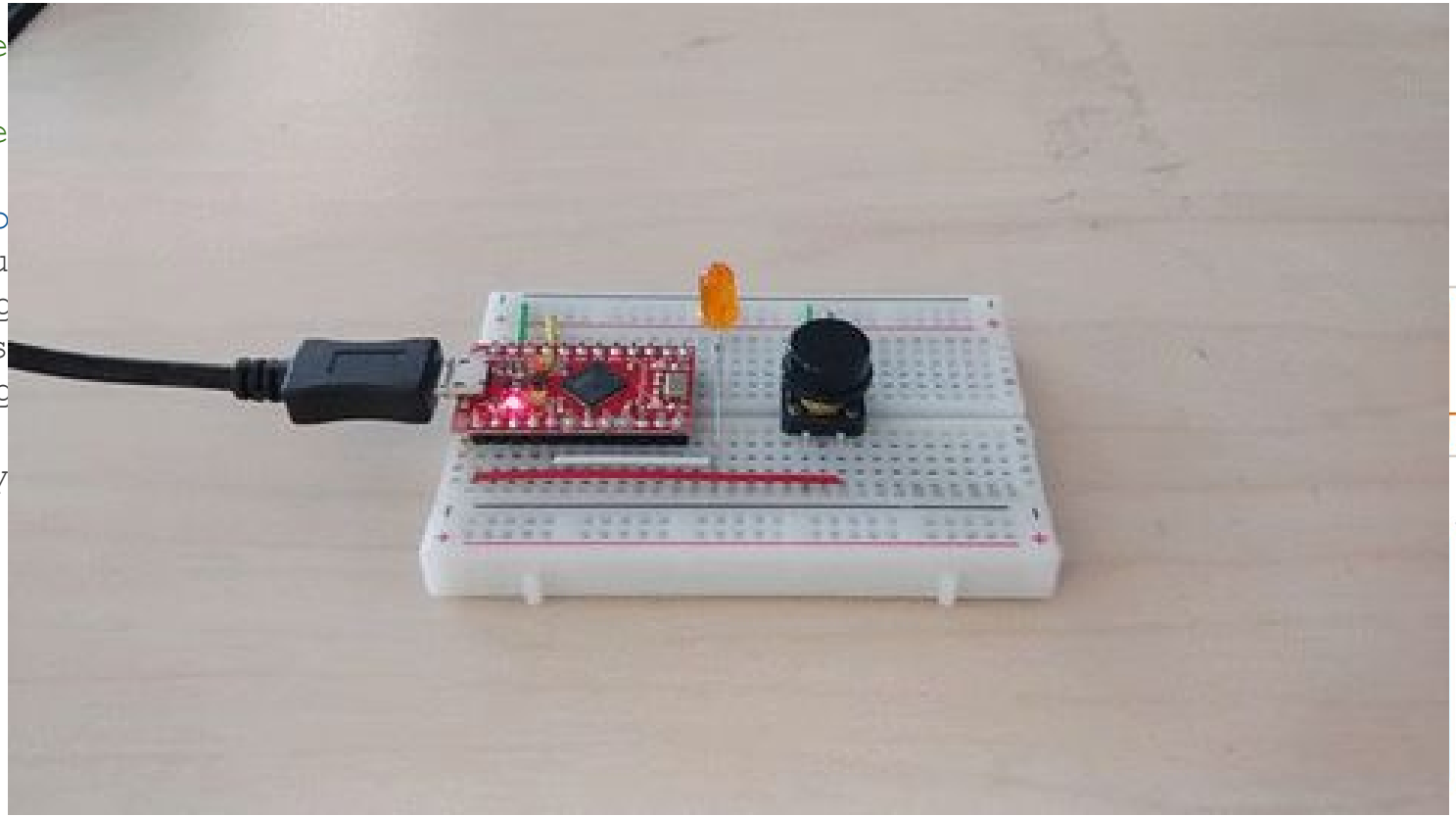
Can we generate designs at all?

```
peripheral button = new MomentarySwitch();

peripheral light = new LED(color = Red);

void loop() {
  if(button.isPressed()){
    light.toggle();
  } else {
    light.off();
  }
  delay(1000); //milliseconds
}
```



Can we generate designs at all? Yes!

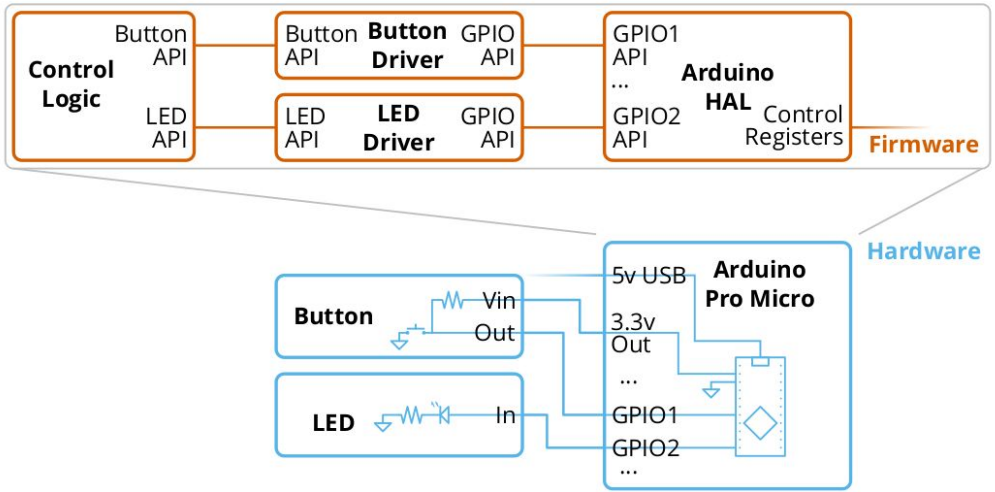
```
periphe

periphe

void lo
  if(bu
    lig
  } els
    lig
  }
  delay
}
```



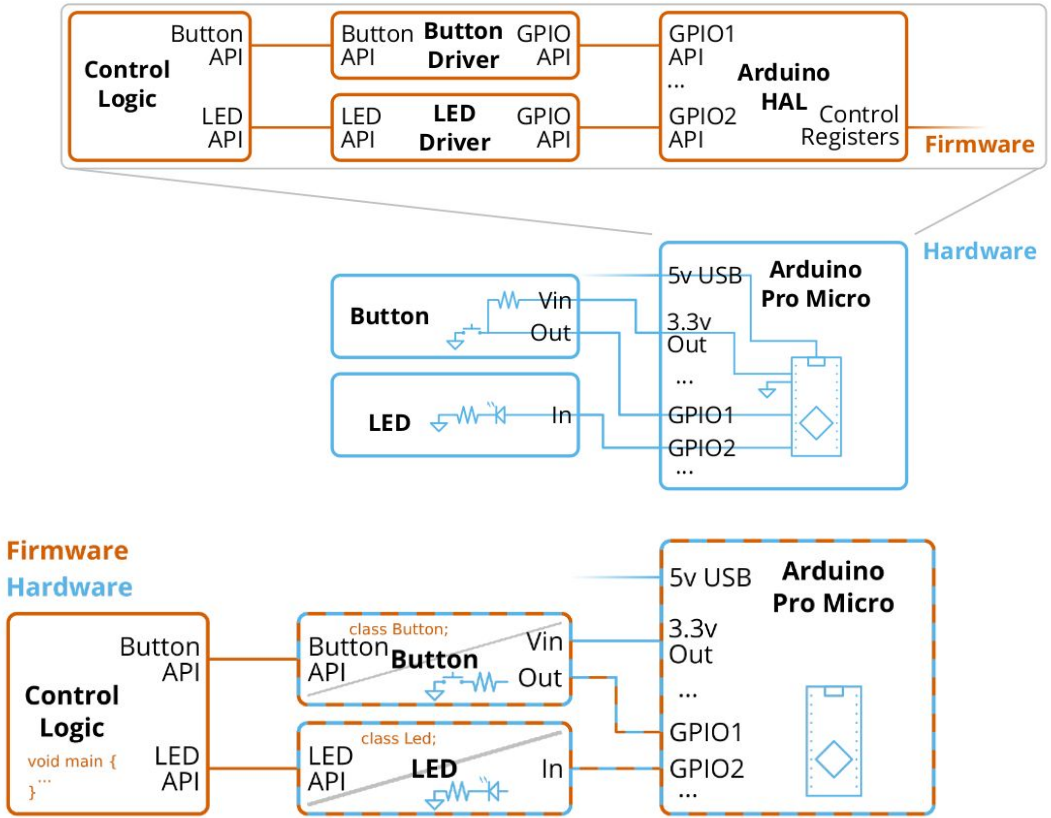
Firmware

Hardware

We use symmetries to collapse the rest of our diagrams further.



We use symmetries to collapse the rest of our diagrams further.



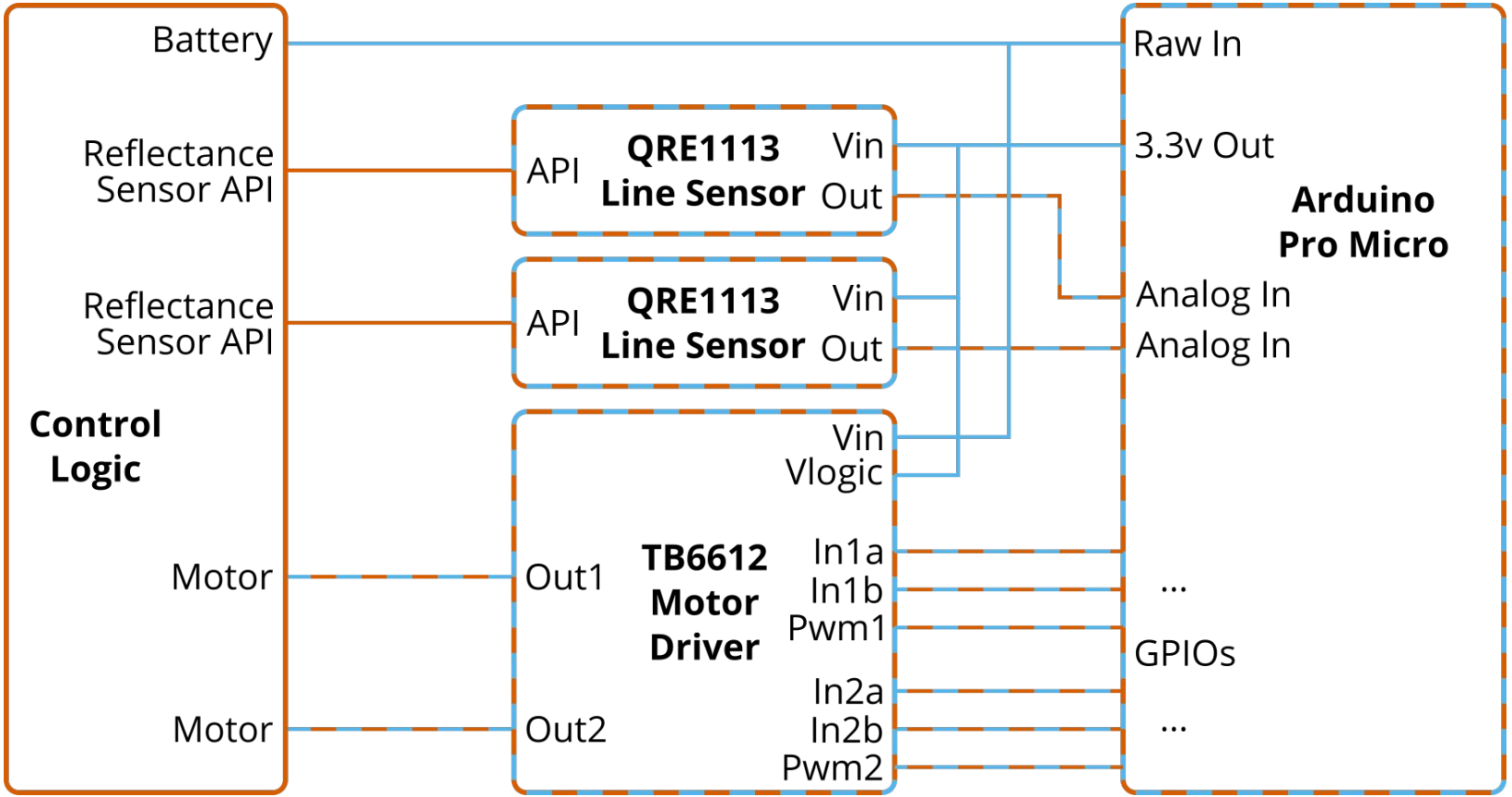
Can the user specify exact parts? Handle complex power systems?

```
AdafruitChassisMotor motorL();
AdafruitChassisMotor motorR = duplicate motorL;
ReflectanceSensor lineSenseL(distance >= 1cm);
ReflectanceSensor lineSenseR = duplicate lineSenseL;
Battery power(duration >= 10mins);

const int baseSpeed = 100;
const int baseTurn = 25;
const int lightThreshold = 70;

int loop(){
  static int differential = 0;
  ...
```

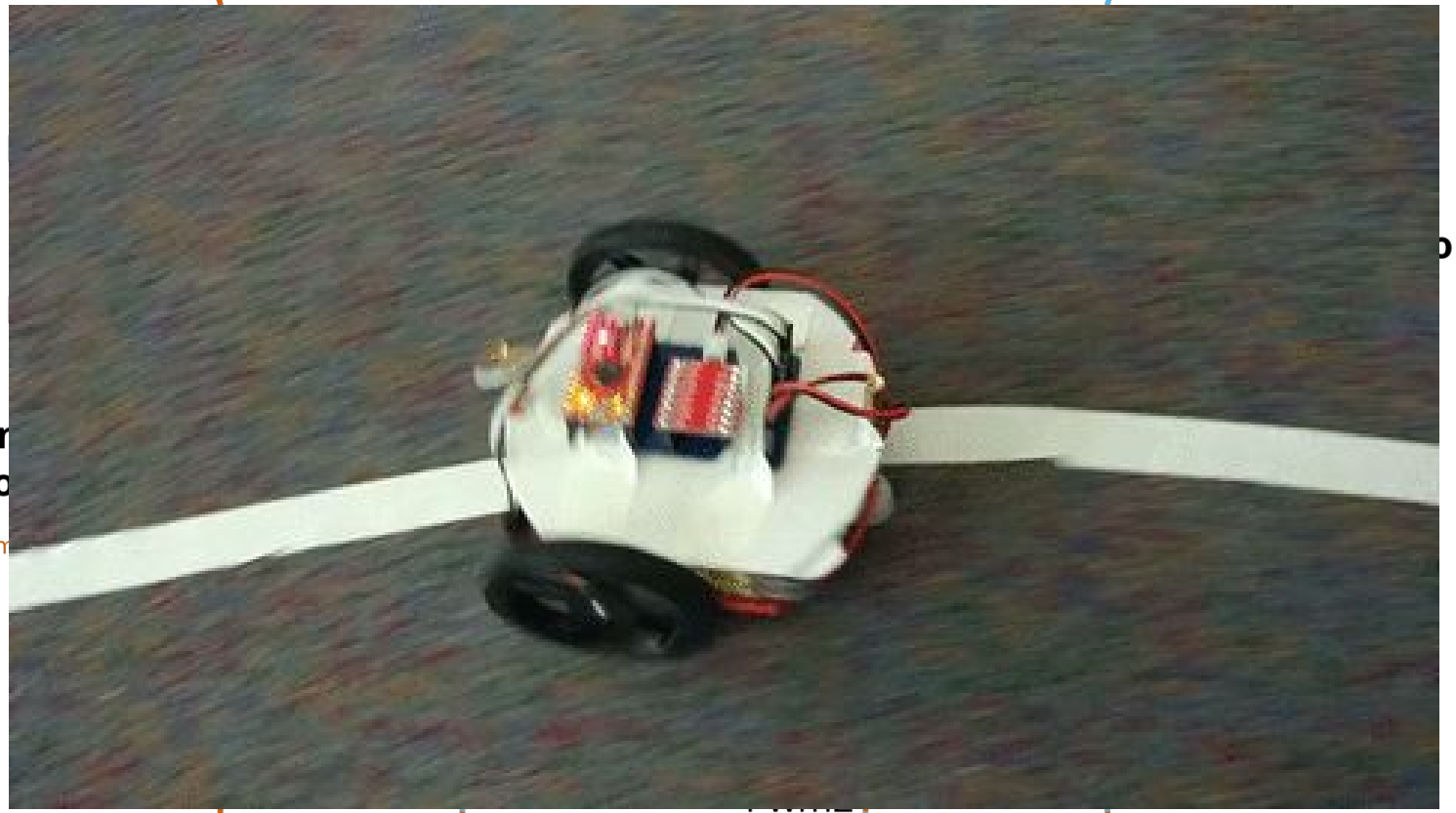
Can the user specify exact parts? Handle complex power systems?

```
AdafruitChassisMotor motorL();
AdafruitChassisMotor motorR = duplicate motorL;
ReflectanceSensor lineSenseL(distance >= 1cm);
ReflectanceSensor lineSenseR = duplicate lineSenseL;
Battery power(duration >= 10mins);

const int baseSpeed = 100;
const int baseTurn = 25;
const int lightThreshold = 70;

int loop(){
  static int differential = 0;
  ...
```

Can the user specify exact parts? Handle complex power systems?



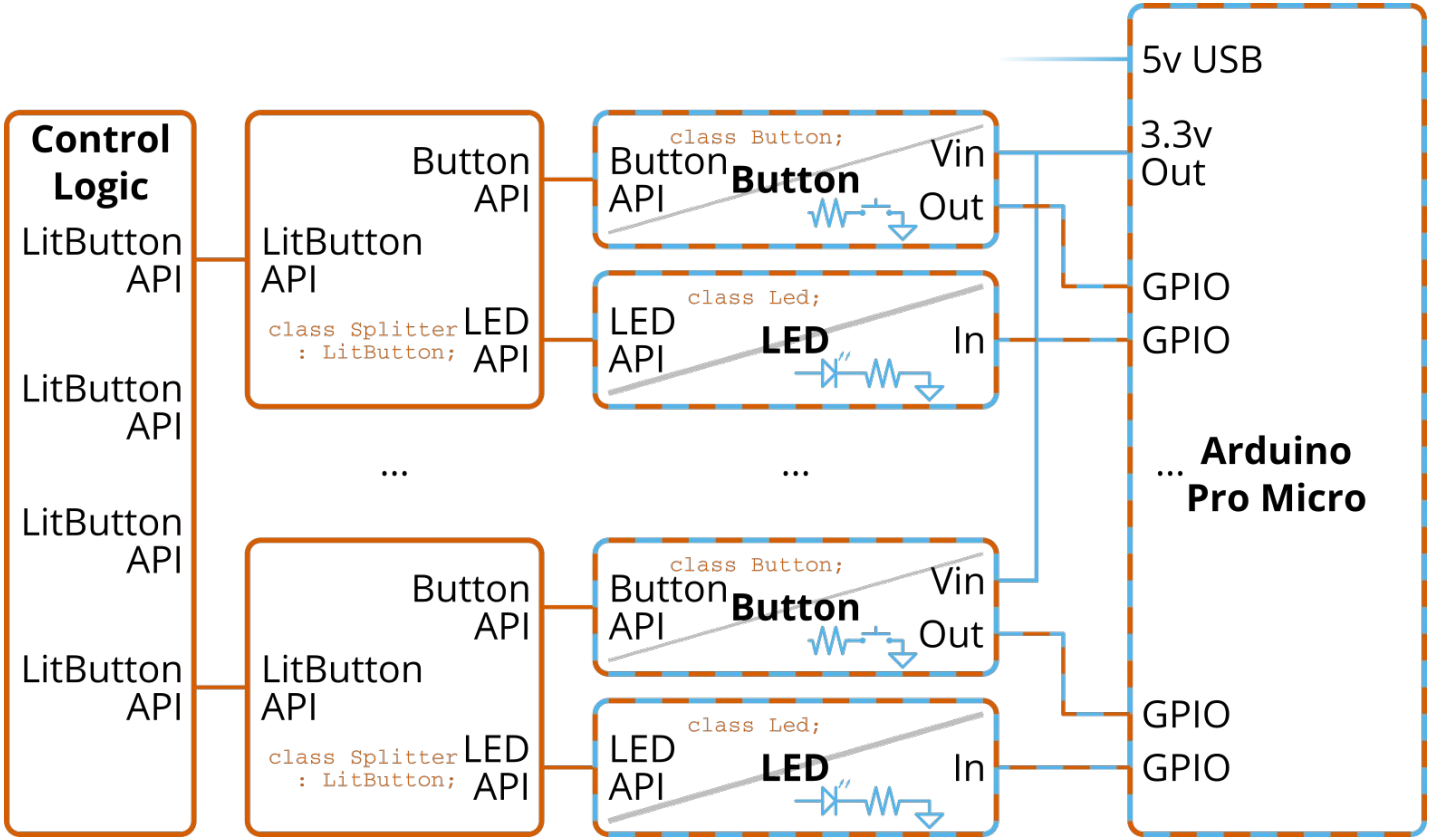
Can the user specify exact parts? Handle complex power systems? Yes



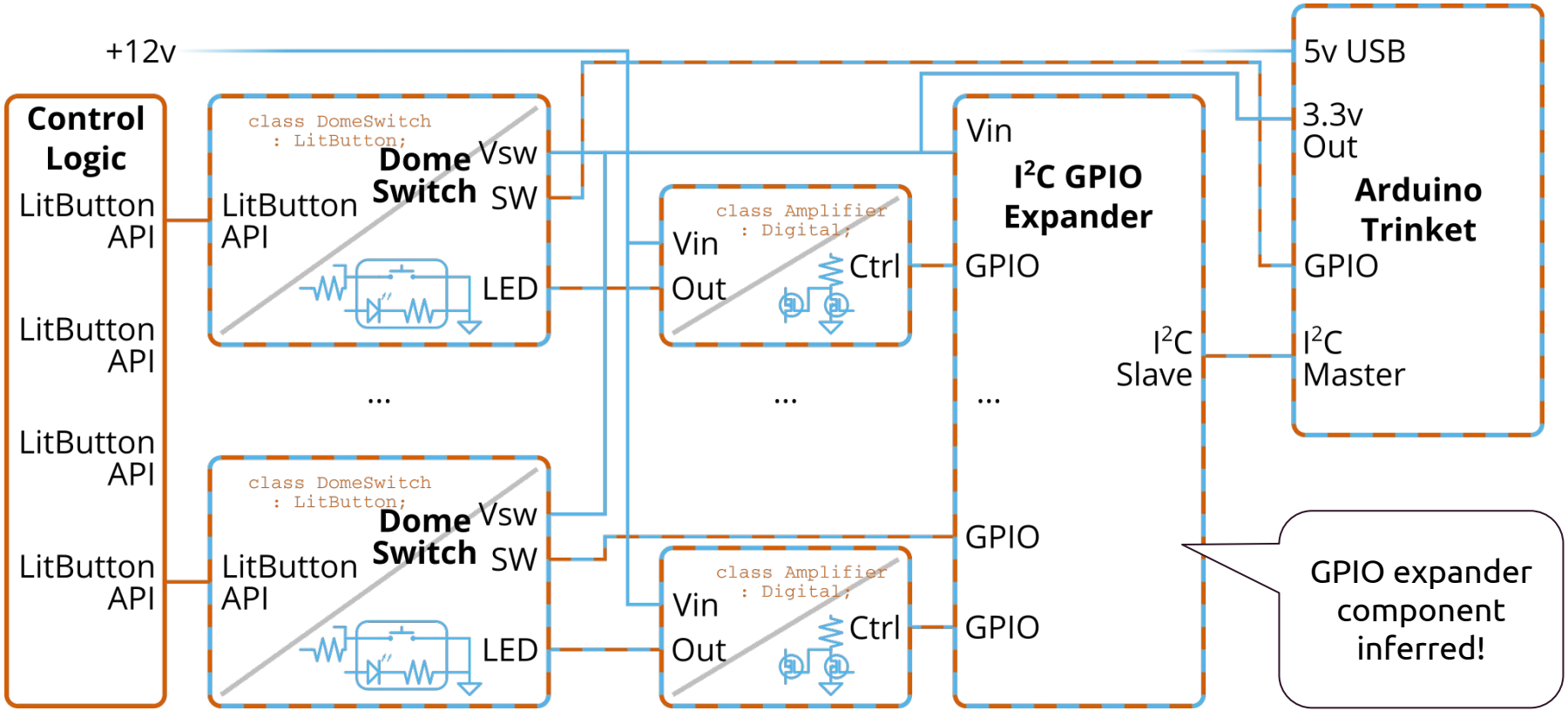
Does our system preserve functionality even when the library changes?

- 4 colored, light-up buttons
- Play a pattern, ask the user to press the buttons in the same order.

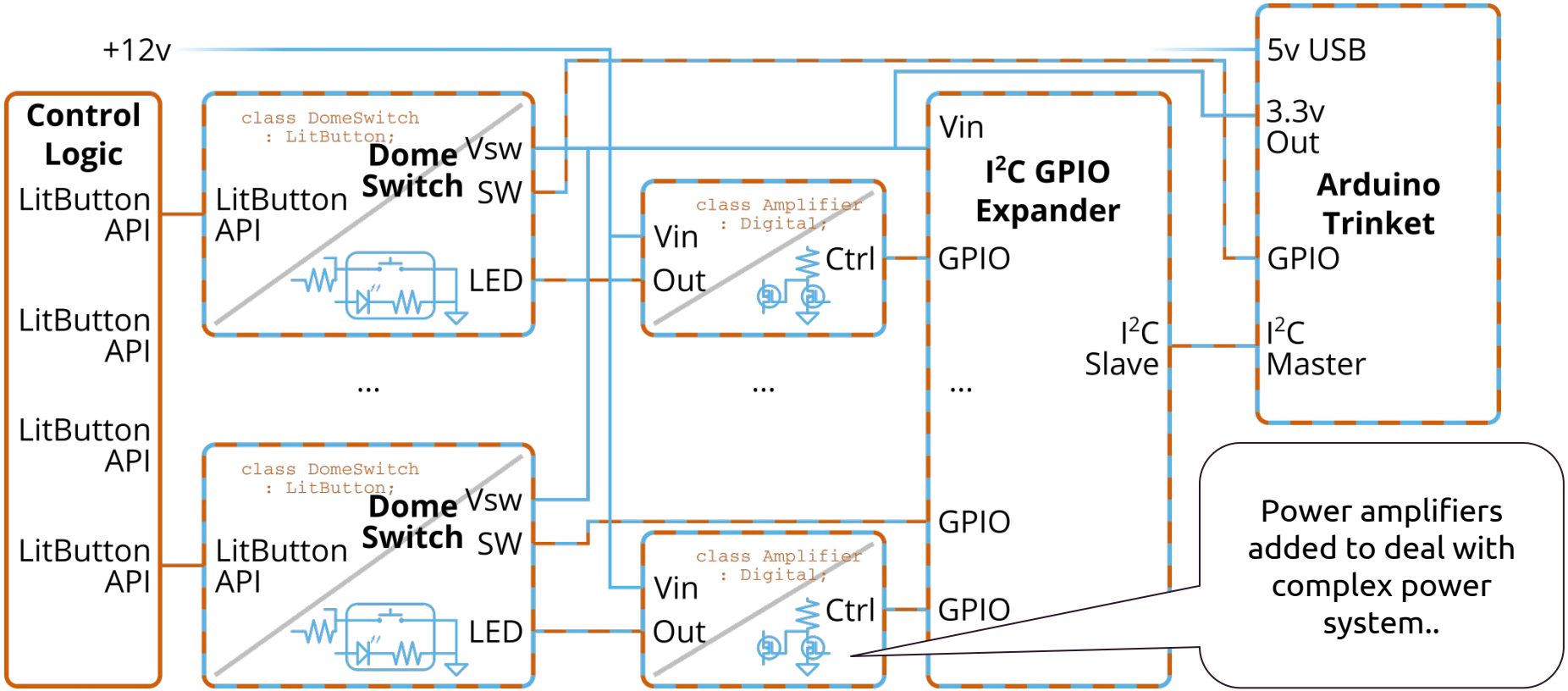
Does our system preserve functionality even when the library changes?



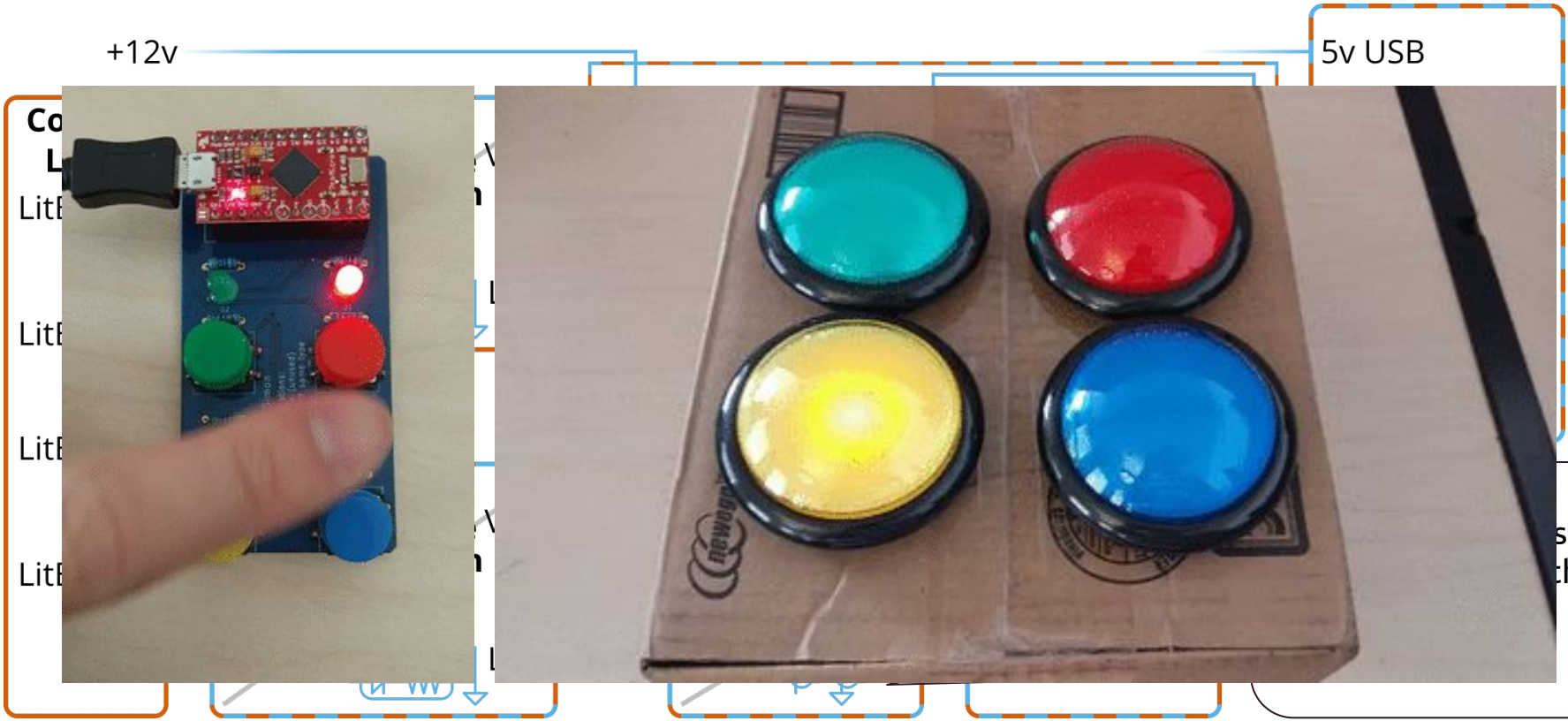
Does our system preserve functionality even when the library changes?



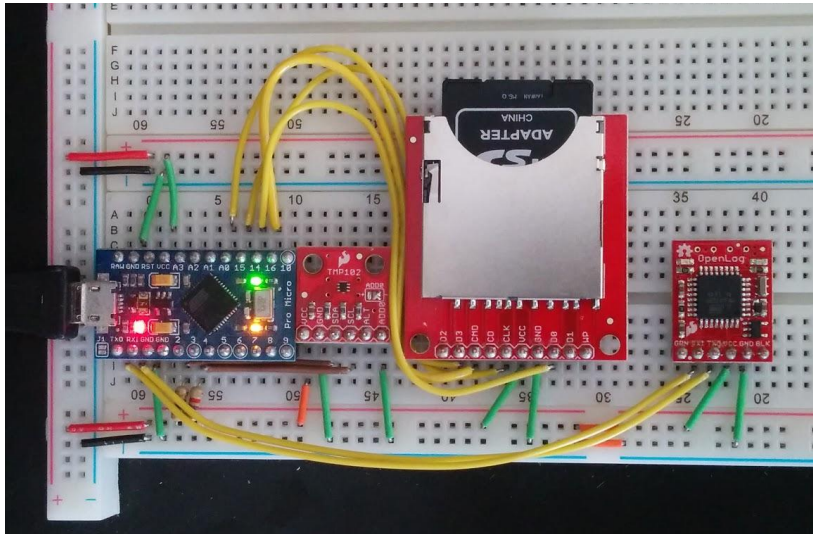
Does our system preserve functionality even when the library changes?

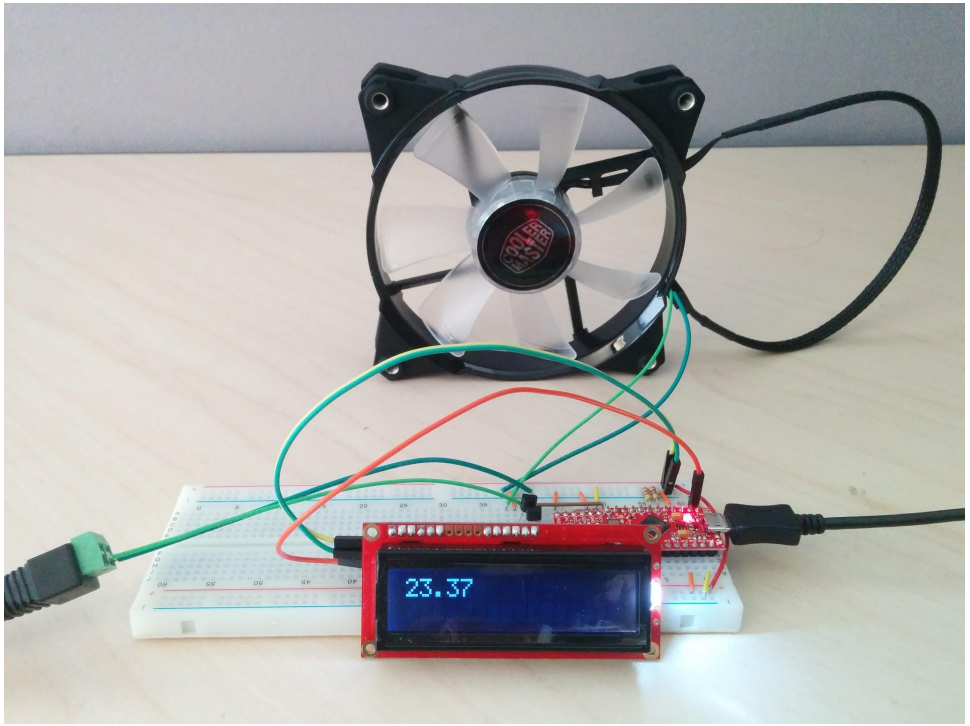


Does our system preserve functionality even when the library changes? Yes

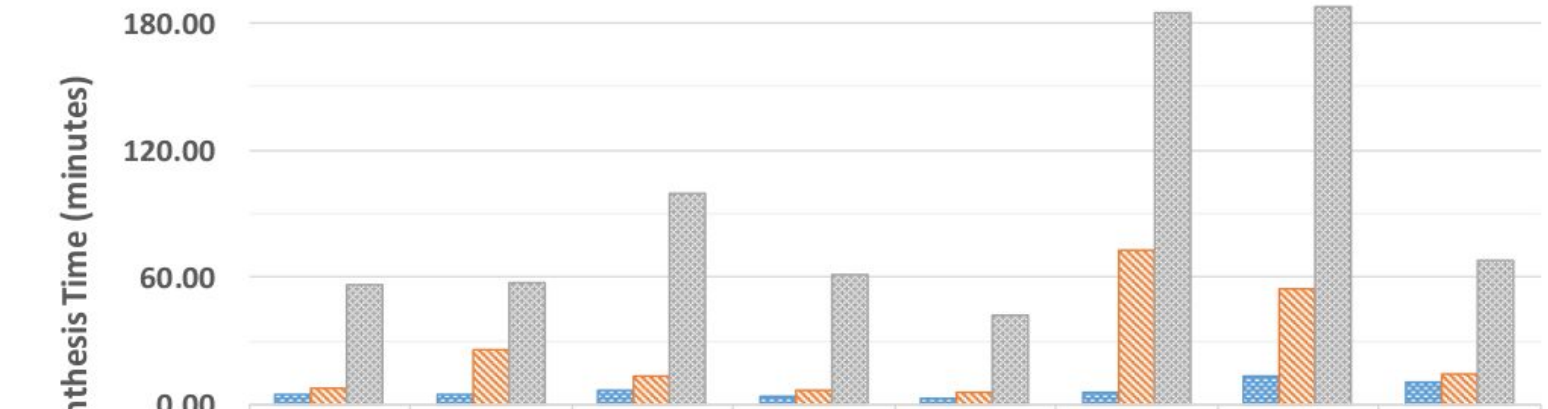


We also built other designs, including a datalogger and control system.





Performance is decent for small problem sizes.



	Blinky (10)	Feedback Fan (20)	Robot (24)	Datalogger (14)	w/ FAT* (18)	Simon (39)	w/ Trinket* (45)	w/ Dome* (41)
Minimal Lib	4.79	4.69	6.99	3.75	3.07	5.53	13.61	10.48
Intermediate Lib	7.38	26.08	13.42	6.81	5.70	72.33	54.59	14.16
Full Lib	56.30	57.10	99.95	61.58	42.40	184.62	187.88	67.65

For simple designs, our tool has taken around 3 hours in the most realistic tests. Mind, that's still time you could be doing something else.

Discussion and Future Work

There are many things that need further research.

- Performance scales exponentially, and will never be a lower complexity class.
  - But there’s still immense room for optimization. Including library pruning, and more efficient encoding of constraints.

There are many things that need further research.

- Performance scales exponentially, and will never be a lower complexity class.
  - But there's still immense room for optimization. Including library pruning, and more efficient encoding of constraints.

- We need some way for the user to figure out what their specifications actually mean, especially for large classes of wildly different parts.

There are many things that need further research.

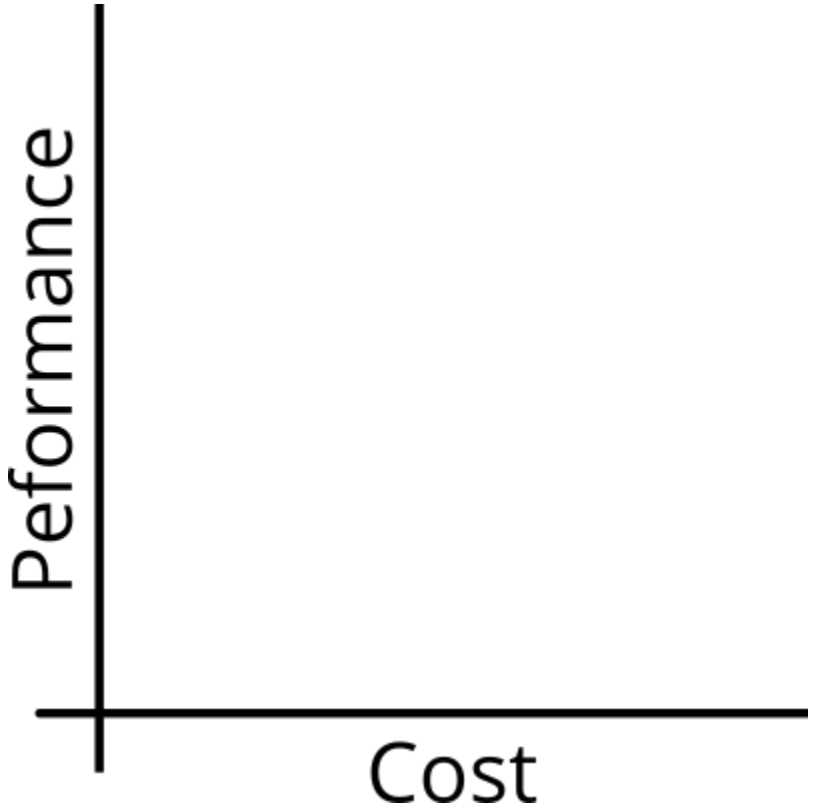
- Performance scales exponentially, and will never be a lower complexity class.
  - But there's still immense room for optimization. Including library pruning, and more efficient encoding of constraints.

- We need some way for the user to figure out what their specifications actually mean, especially for large classes of wildly different parts.

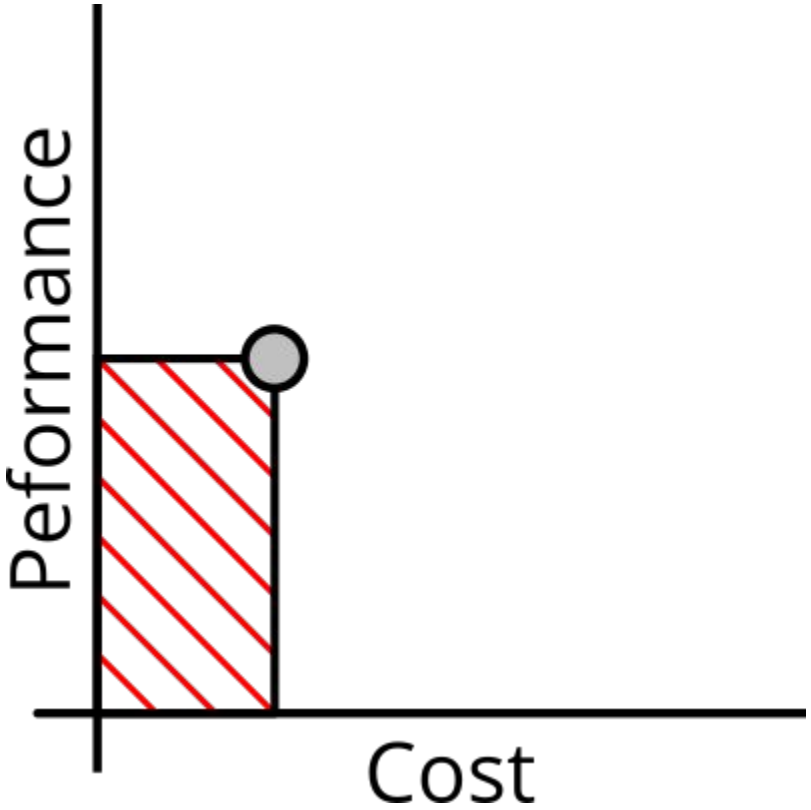
- We need to do research on making our system more expressive, as of now it cannot handle things like timing requirements or isolated power domains.

EDG can help automate optimization

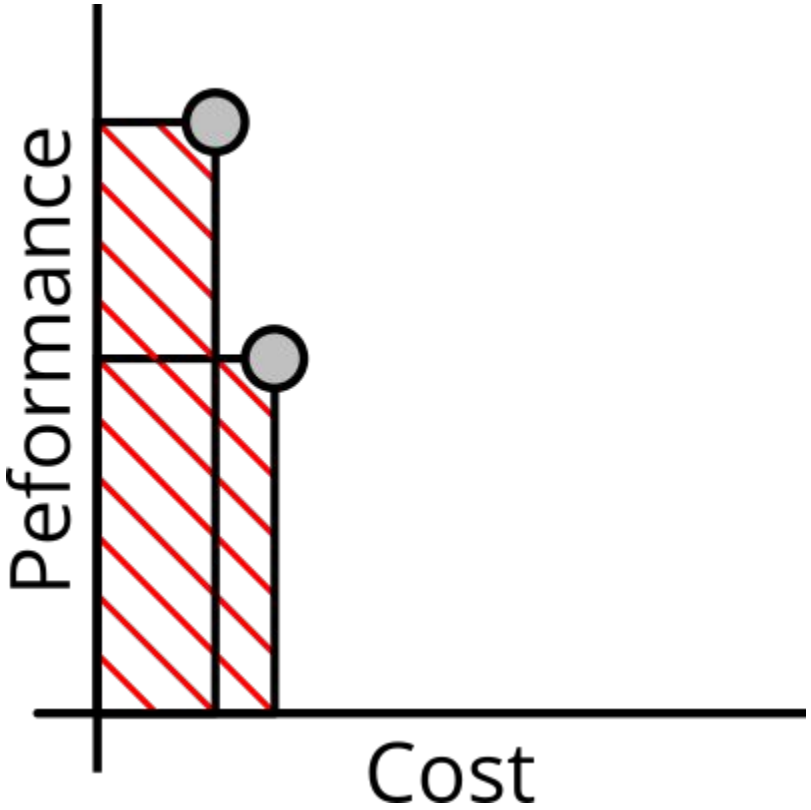
EDG can help automate optimization



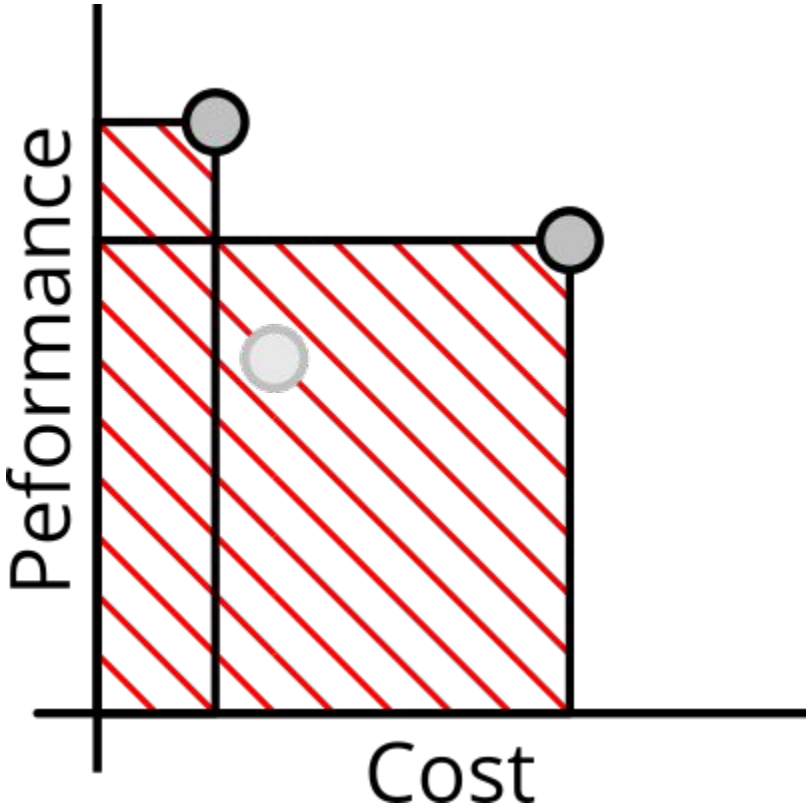
EDG can help automate optimization



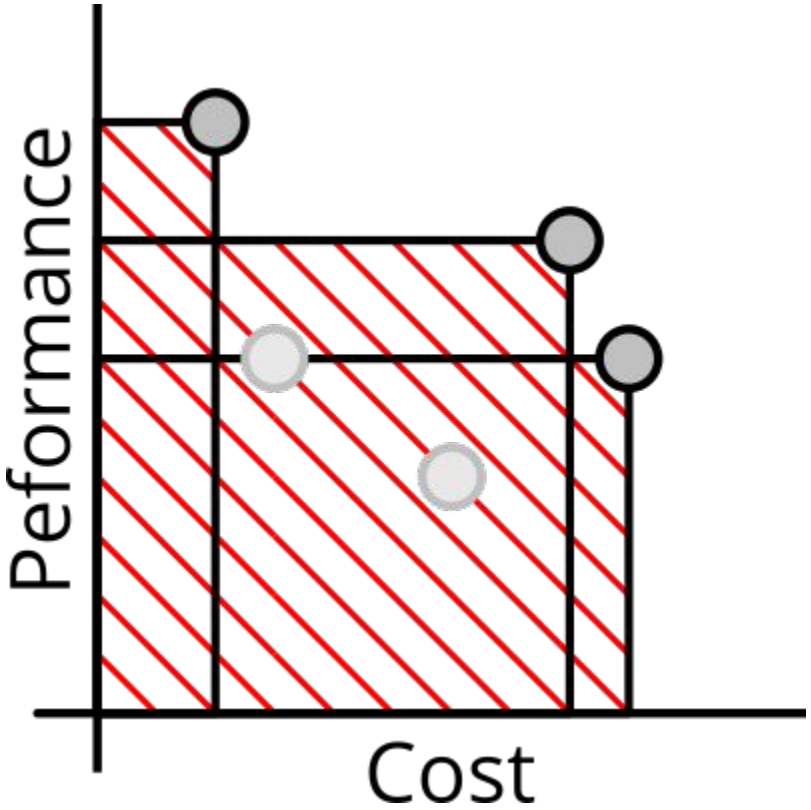
EDG can help automate optimization



EDG can help automate optimization



EDG can help automate optimization



Questions?