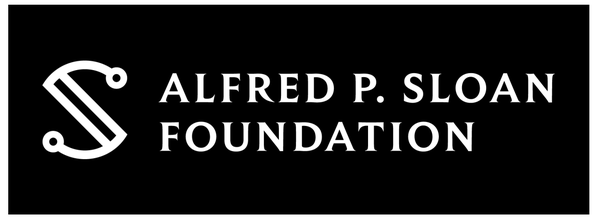
Towards Fabrication-as-Programming

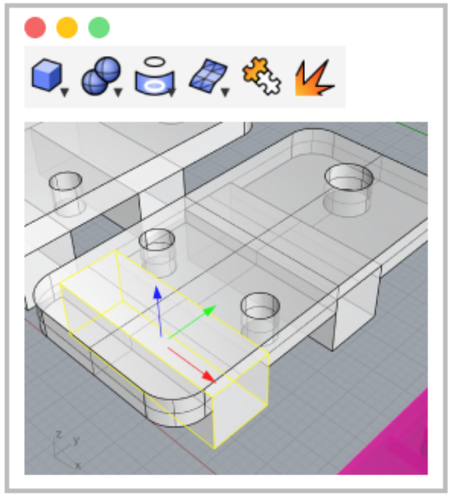
SCF 2022

Jasper Tran O'Leary, Eunice Jun, Nadya Peek

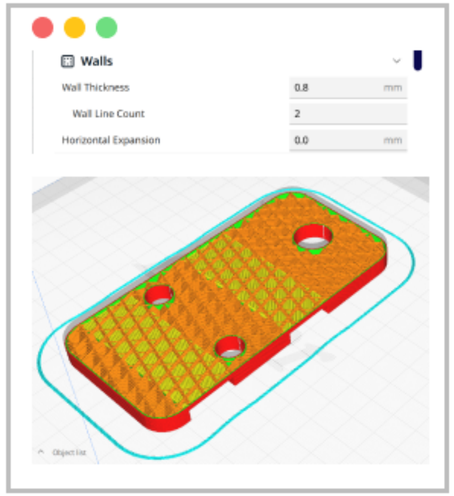
University of Washington



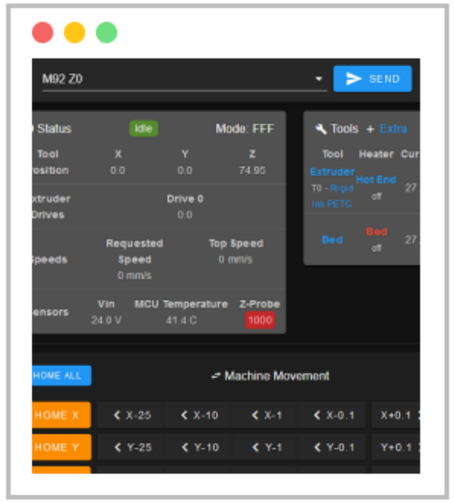
CAD



CAM



Toolpath Optimization Script

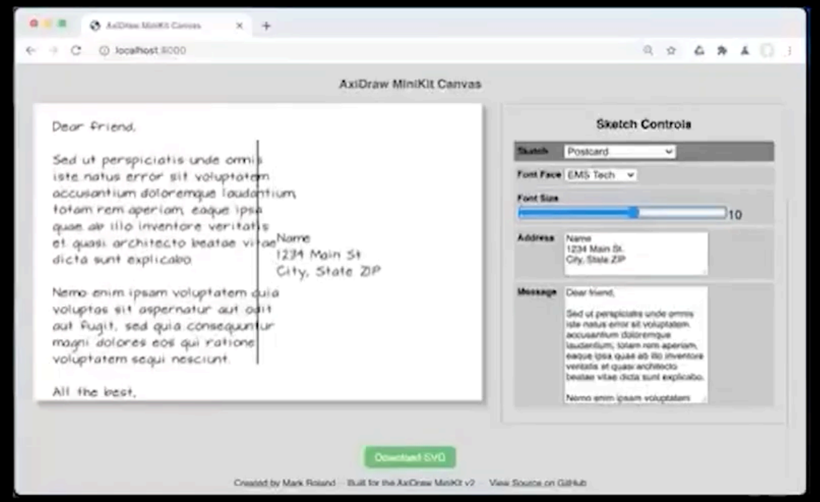


Post-Processing (sometimes)

Machine Control

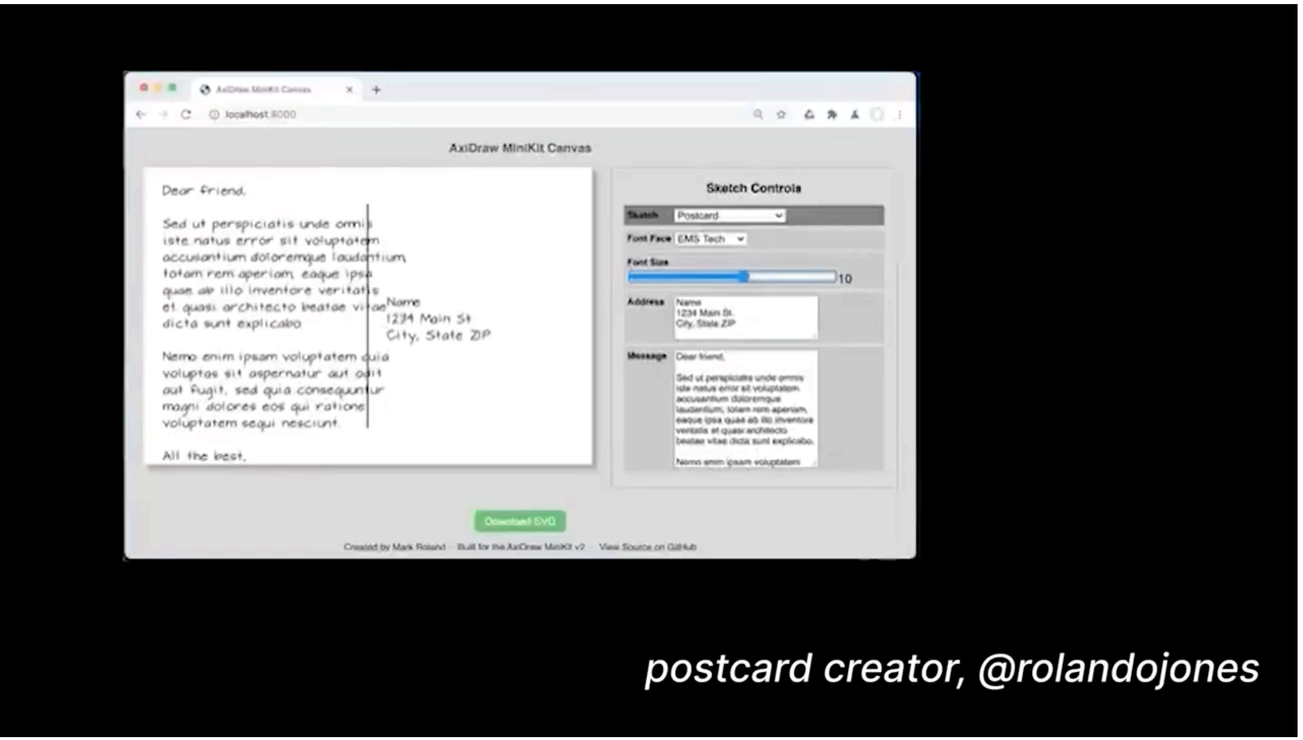
Exploratory digital fabrication

Exploratory digital fabrication



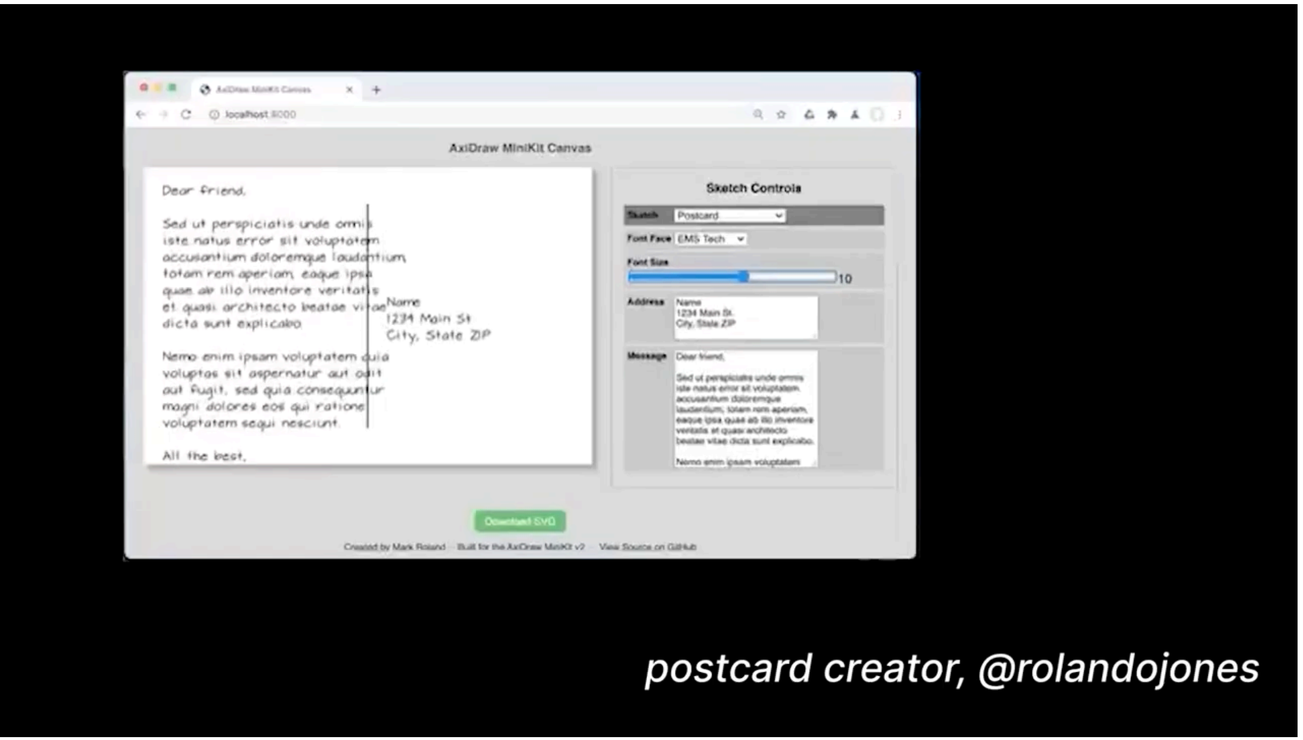
postcard creator, @rolandojones

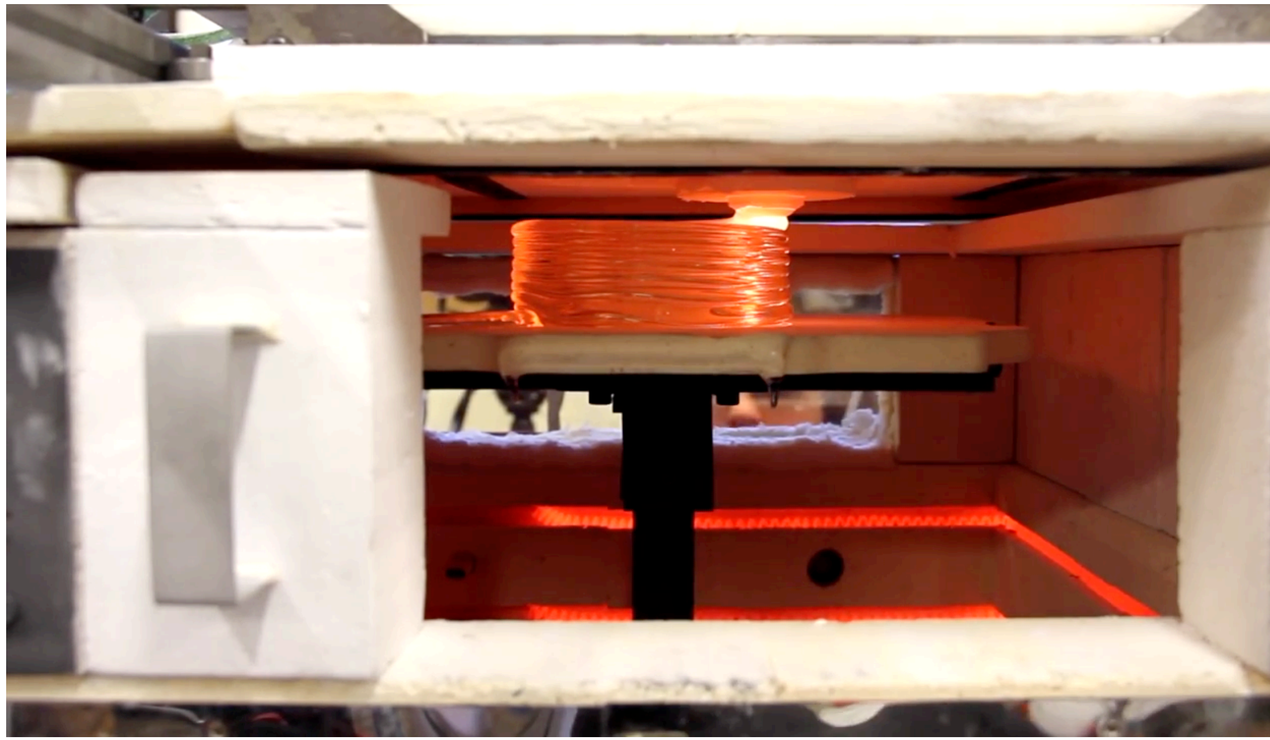
Exploratory digital fabrication



Twigg-Smith et al. Tools, Tricks, and Hacks. Investigating Novel Digital Fabrication Workflows on #PlotterTwitter. 2021.

Exploratory digital fabrication





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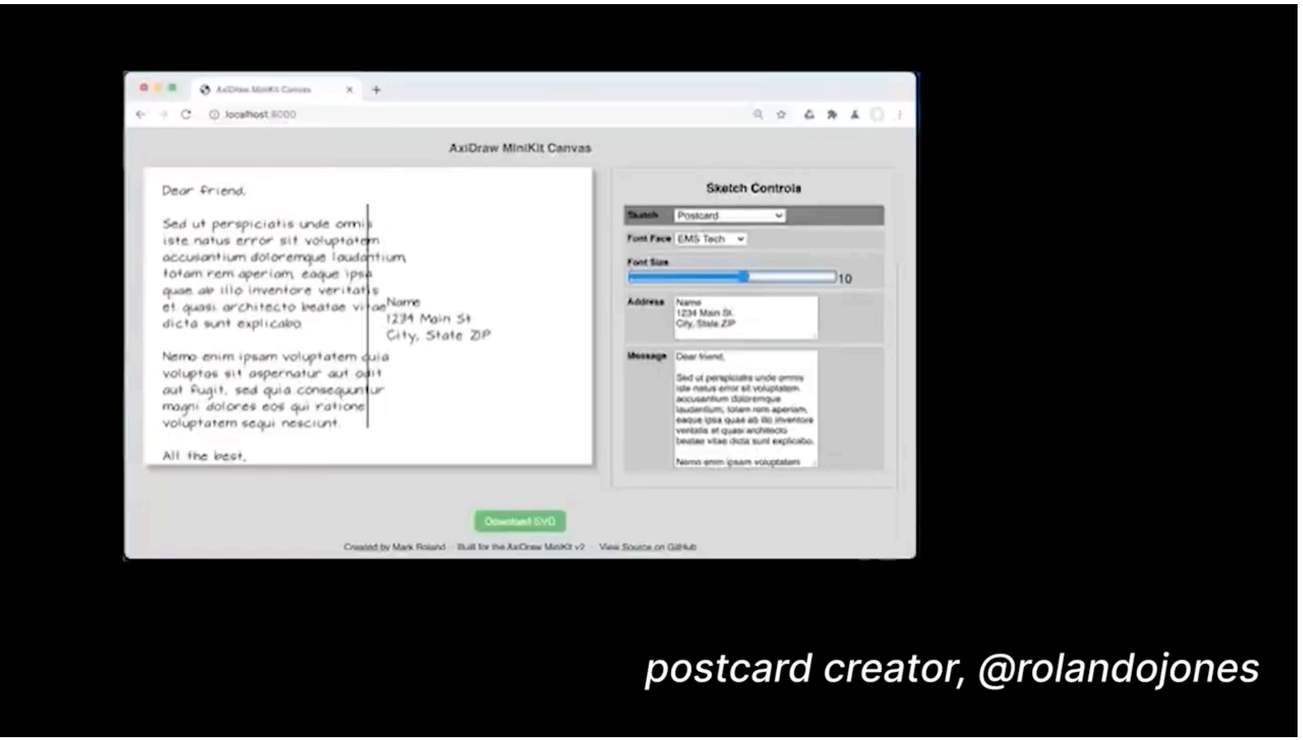

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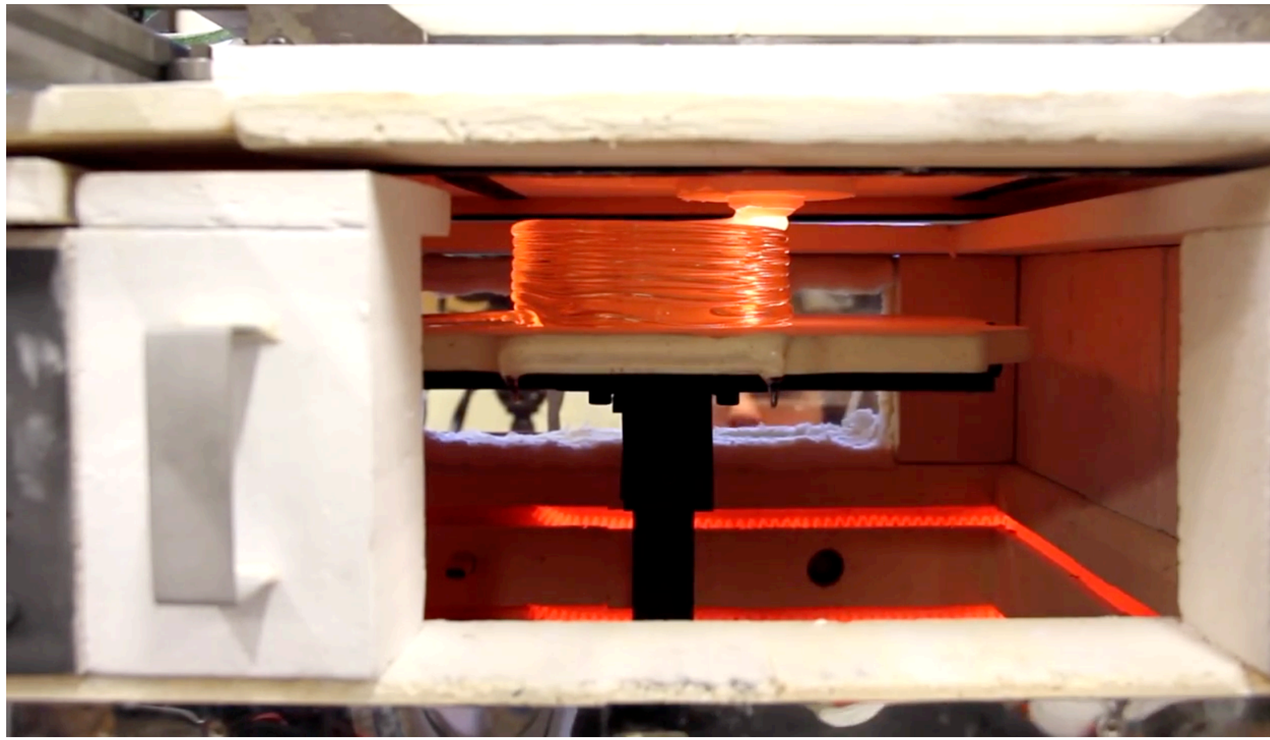

Klein et al. Additive Manufacturing of Optically Transparent Glass. 2015.

Programming for Exploratory Fab is Painful with Current Tools

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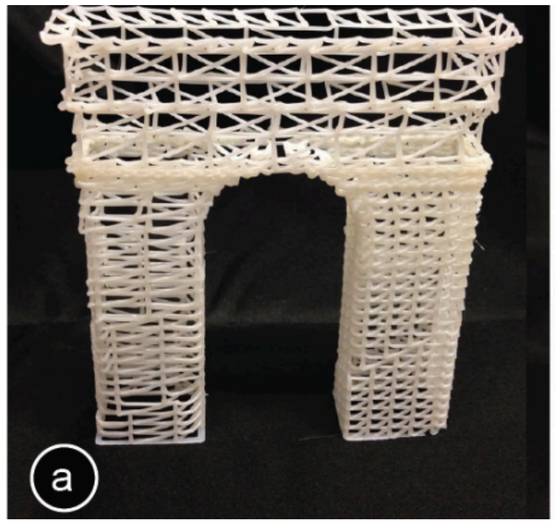
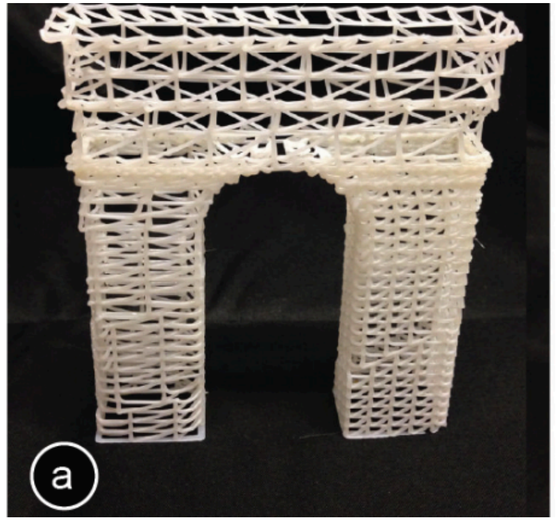


Mueller et al. Wireprint. 2014.

Programming for Exploratory Fab is Painful with Current Tools



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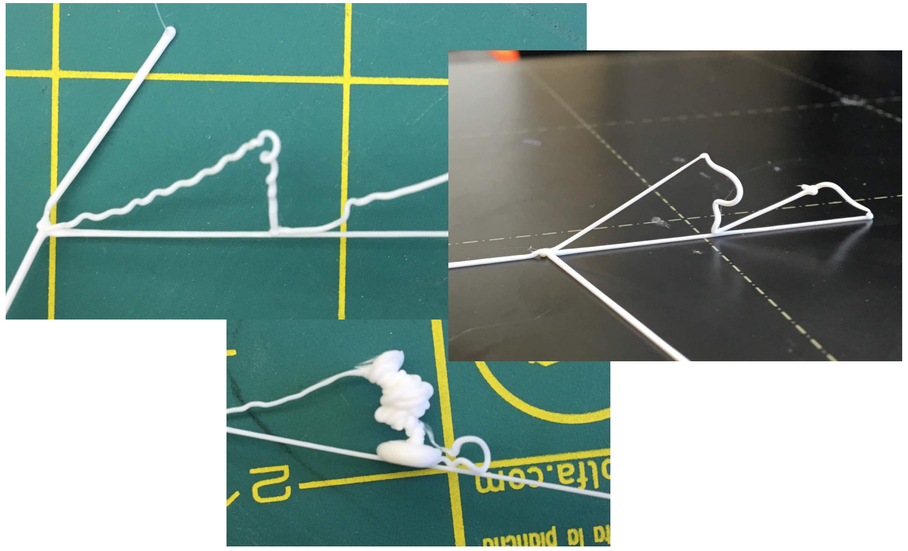

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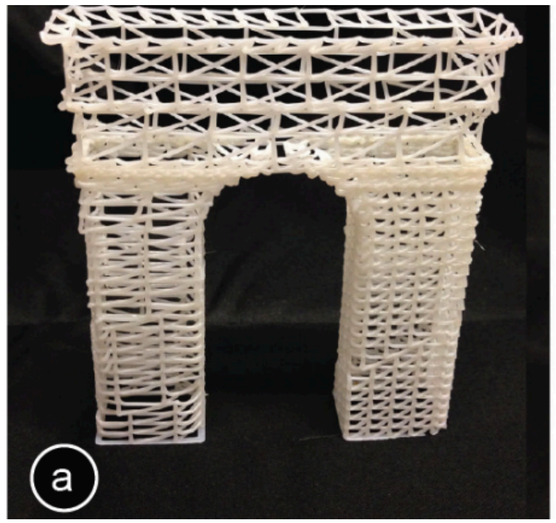

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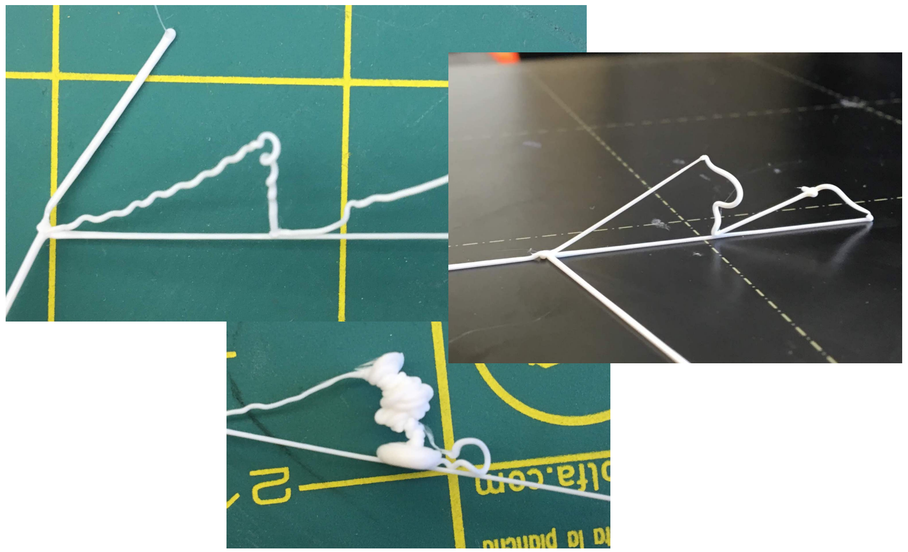

Max length vertical with rate

```
G1 Z20 E4.00 F50
```

Single fin v1

```
G1 X100 Y100 Z0 F2000
G1 X130 Y100 Z0 E4 F500 ; base
G1 Z20 E4.00 F50 ; vertical side
G1 X100 Y100 Z0 E4 F50 ; hypotenuse
```

Too big, try smaller fin

```
G1 X100 Y100 Z0 F2000
G1 X120 Y100 Z0 E2 F500 ; base
G1 Z10 E2.00 F50 ; vertical side
G1 X100 Y100 Z0 E0.5 F50 ; hypotenuse
```

This is doing well, but try to make hypotenuse thicker without buckling

```
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G1 Z10 E2.00 F50 ; vertical side
G1 E0.2 F500 ; preemptive extrude before hypotenuse
G1 X100 Y100 Z0.2 E2. F50 ; hypotenuse
```

Above worked okay at 205. Need to think about how to get hypotenuse less wiggly.

“While both GUIs and languages … [make] it easy to say common things, ***a language empowers users to say uncommon things too****.”*

—Chasins et al. “PL and HCI: better together.” Comm. ACM ’21.

We need more programming power than raw G-Code

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Visualization?

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Visualization?

Testing?

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Previewing in-situ?

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Functions?

Visualization?

Testing?

Previewing in-situ?

Interoperating with outside libraries?

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G1 X120 Y100 Z0.2 E2.5 F500 ; base
G1 Z10 E2.00 F50 ; vert
G1 E0.2 F500 ; preempti
G1 X100 Y100 Z0.2 E2. F
```

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Functions?

Visualization?

Testing?

Previewing in-situ?

Interoperating with outside libraries?

Adapting to different machines?

We need more programming power than raw G-Code

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```

Single fin v1

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G1 X130 Y100 Z0 E4 F500 ; ba
G1 Z20 E4.00 F50 ; vertical
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```

Too big, try smaller fin

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G1 X120 Y100 Z0 E2 F500 ;
G1 Z10 E2.00 F50 ; vertic
G1 X100 Y100 Z0 E0.5 F50 ; hypotenuse
```

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```
G1 X100 Y100 Z0.2 F20
G1 X120 Y100 Z0.2 E2.5 F500 ; base
G1 Z10 E2.00 F50 ; vert
G1 E0.2 F500 ; preempti
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Functions?

Visualization?

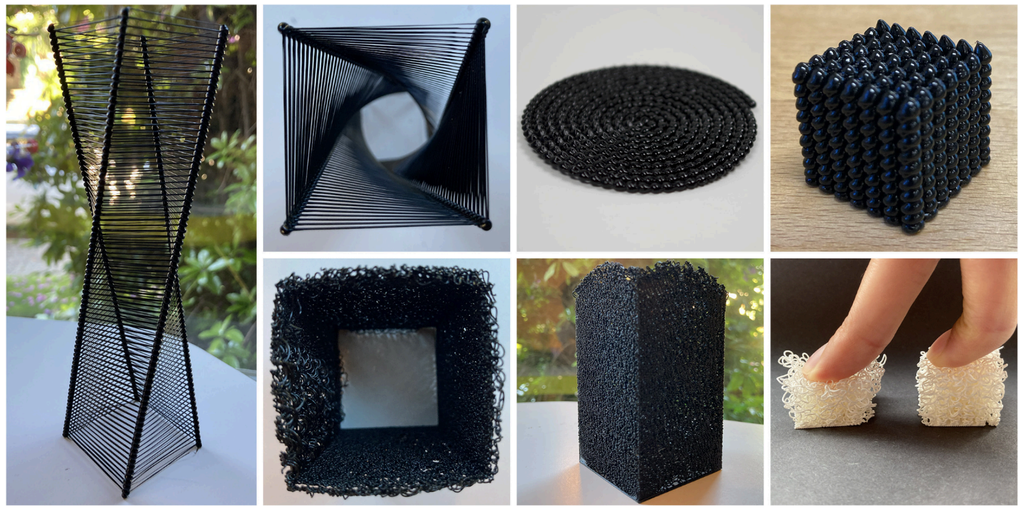
Testing?

Previewing in-situ?

Interoperating with outside libraries?

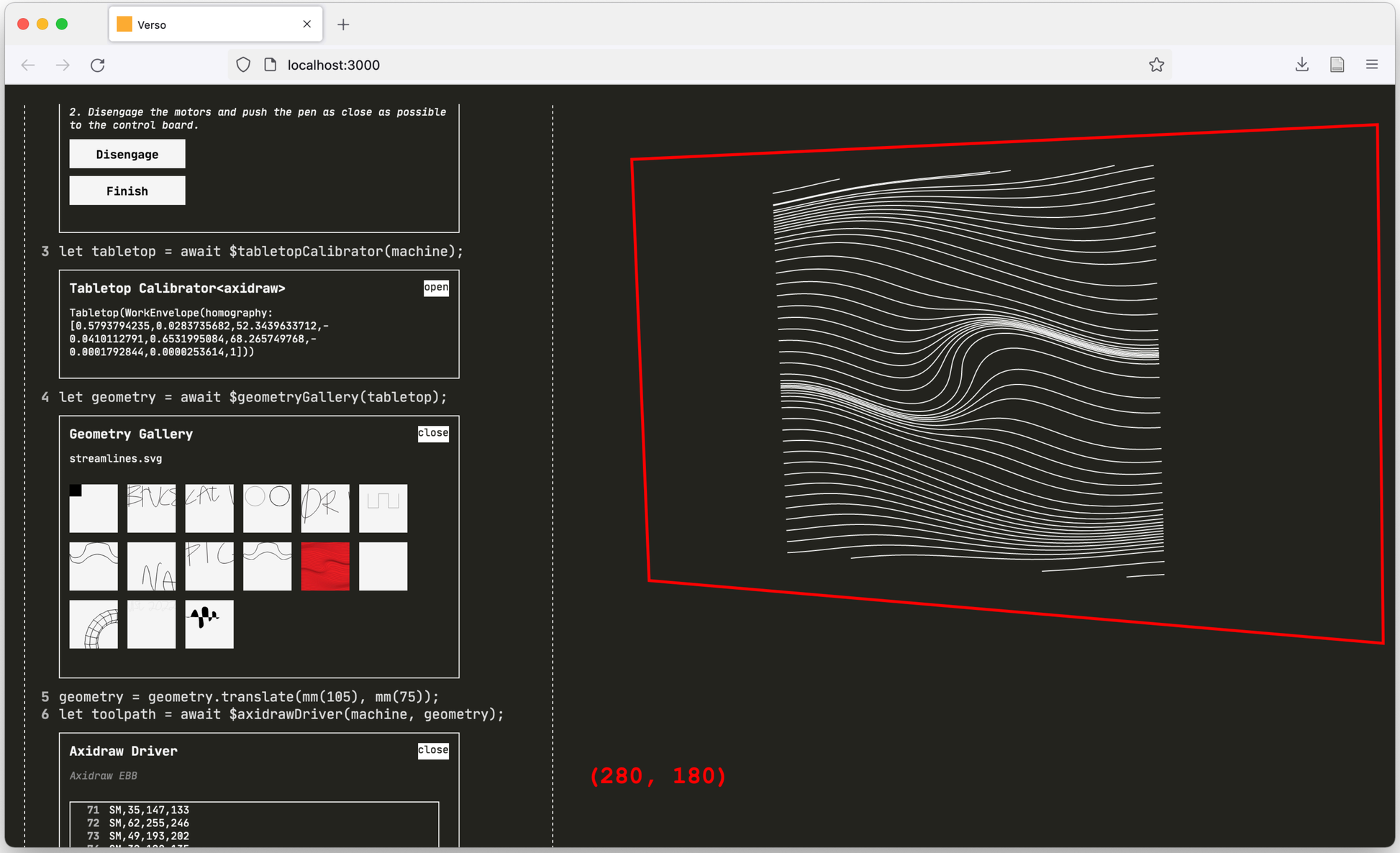
Adapting to different machines?

```
fab.moveExtrude(
  fab.maxX / 2 + x,
  fab.maxY / 2 + y,
  z
);
```



Subbaraman and Peek. p5.fab. 2022.

Verso is a tool for ***fabrication-as-programming***.



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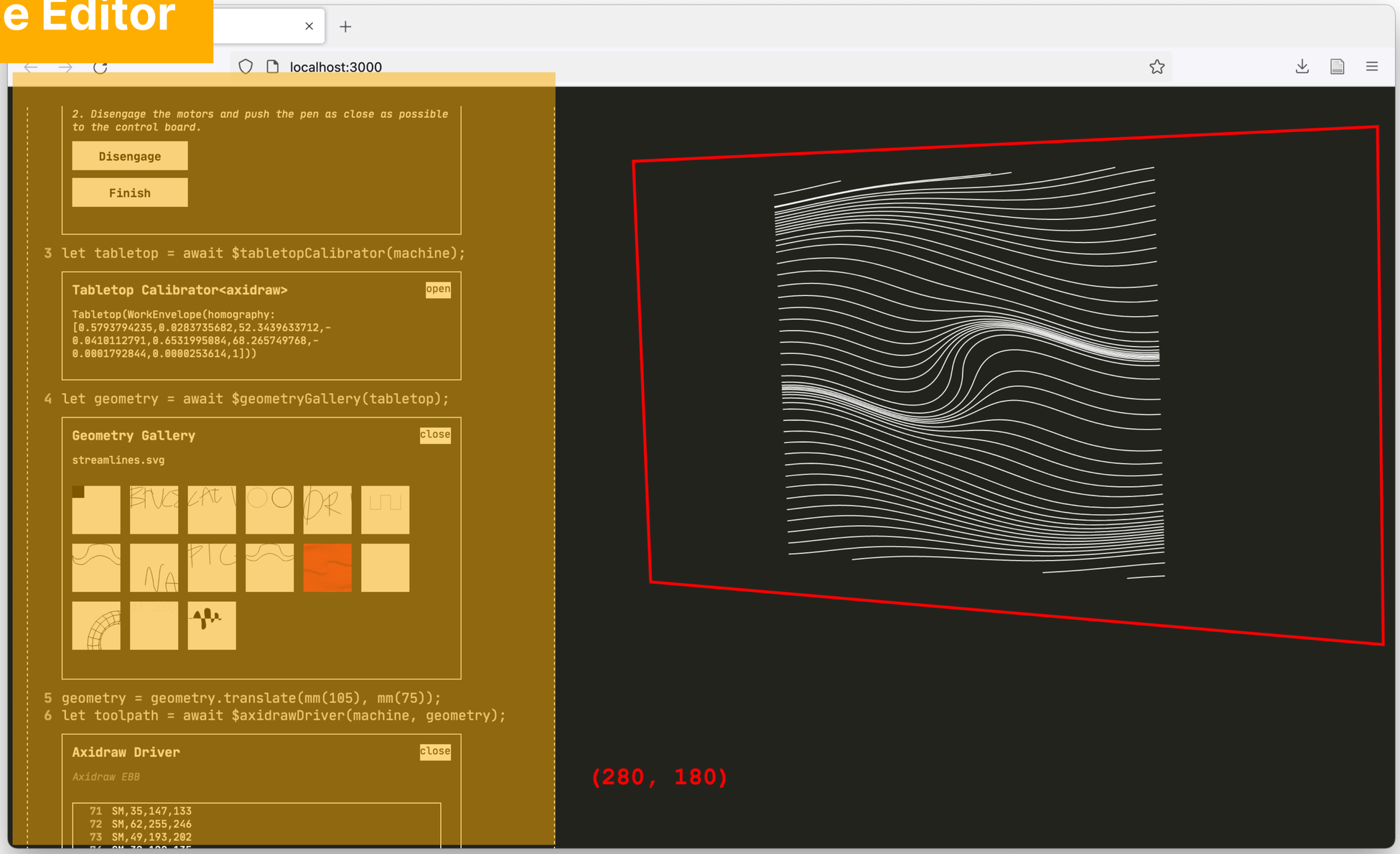
Code Editor



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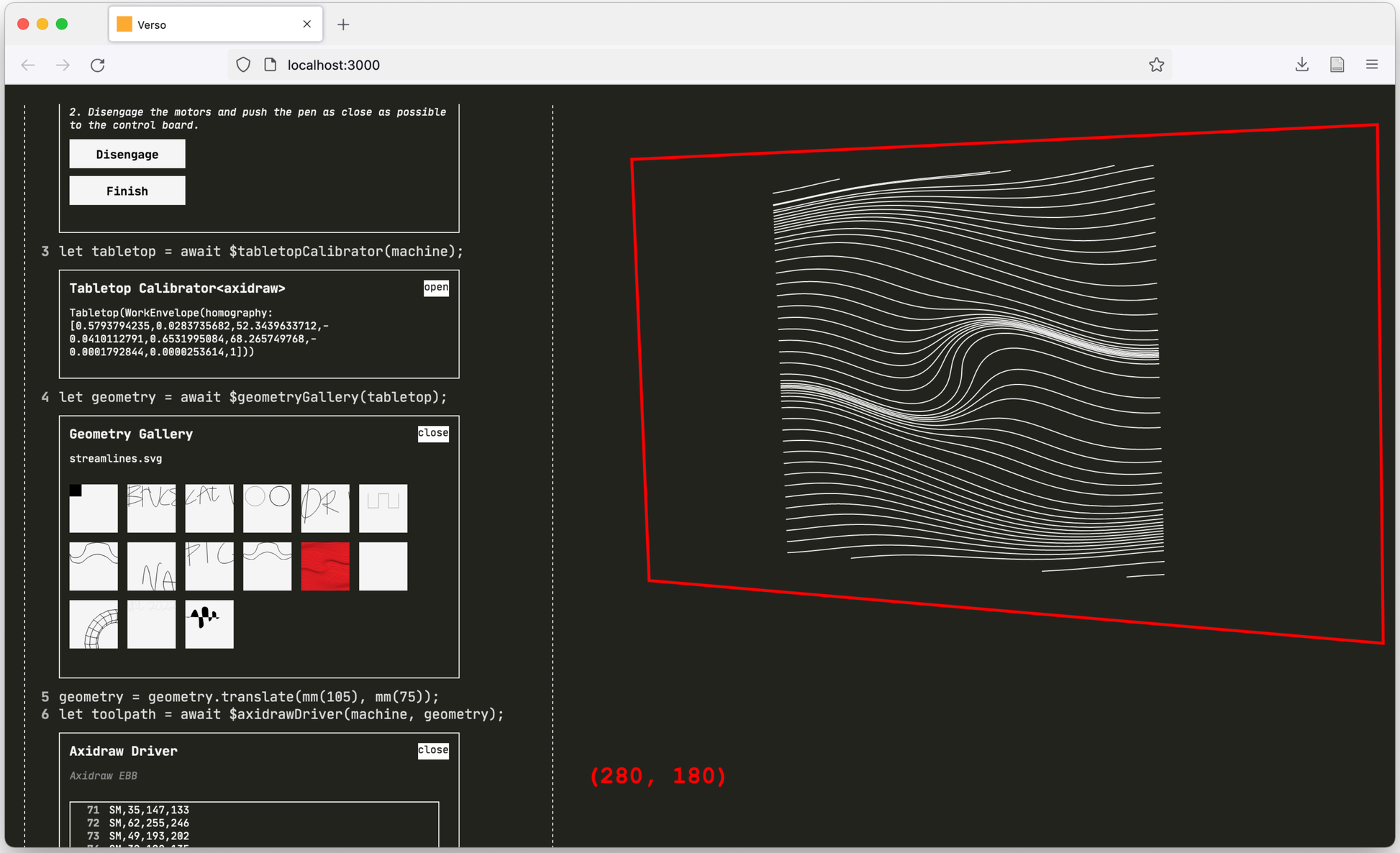


Verso is a tool for ***fabrication-as-programming***.

Verso

localhost:3000

Modules

2. Disengage the motors and push the pen as close as possible to the control board.

Disengage

Finish

```
3 let tabletop = await $tabletopCalibrator(machine);
```

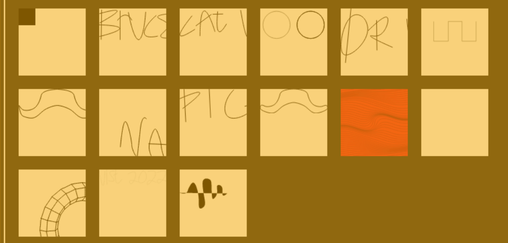
Tabletop Calibrator<axidraw> open

```
Tabletop(WorkEnvelope(homography:
[0.5793794235,0.0283735682,52.3439633712,-
0.0410112791,0.6531995084,68.265749768,-
0.0001792844,0.0000253614,1]))
```

```
4 let geometry = await $geometryGallery(tabletop);
```

Geometry Gallery close

streamlines.svg

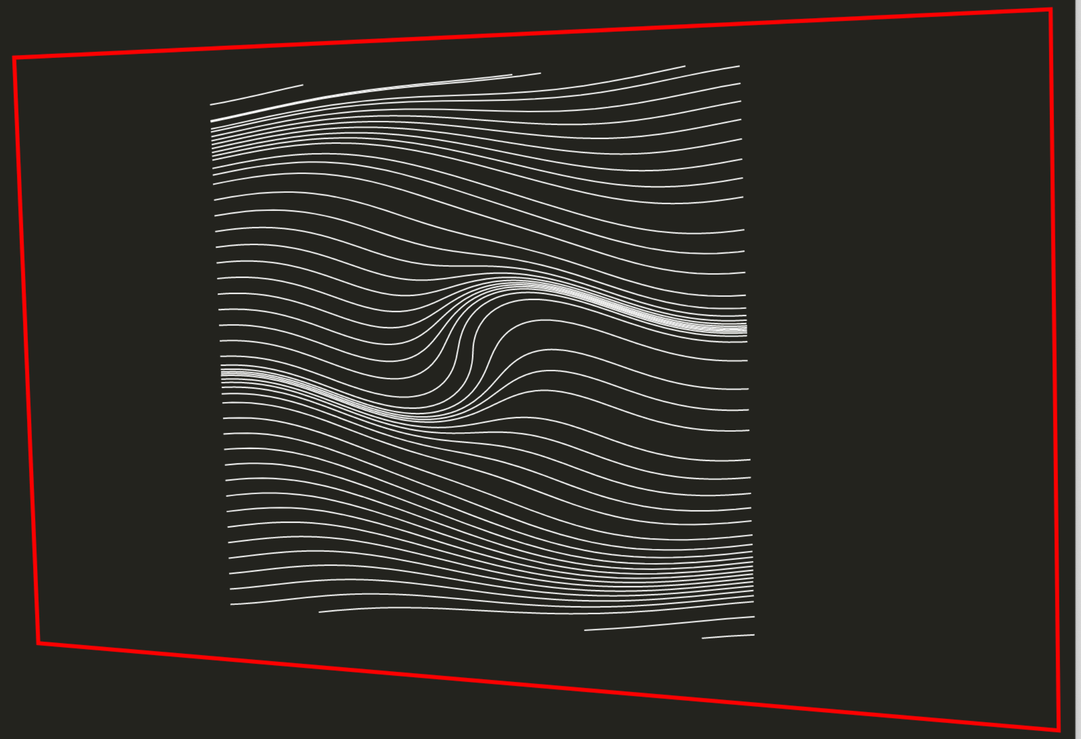


```
5 geometry = geometry.translate(mm(105), mm(75));
6 let toolpath = await $axidrawDriver(machine, geometry);
```

Axidraw Driver close

Axidraw EBB

```
71  SM,35,147,133
72  SM,62,255,246
73  SM,49,193,202
```



(280, 180)

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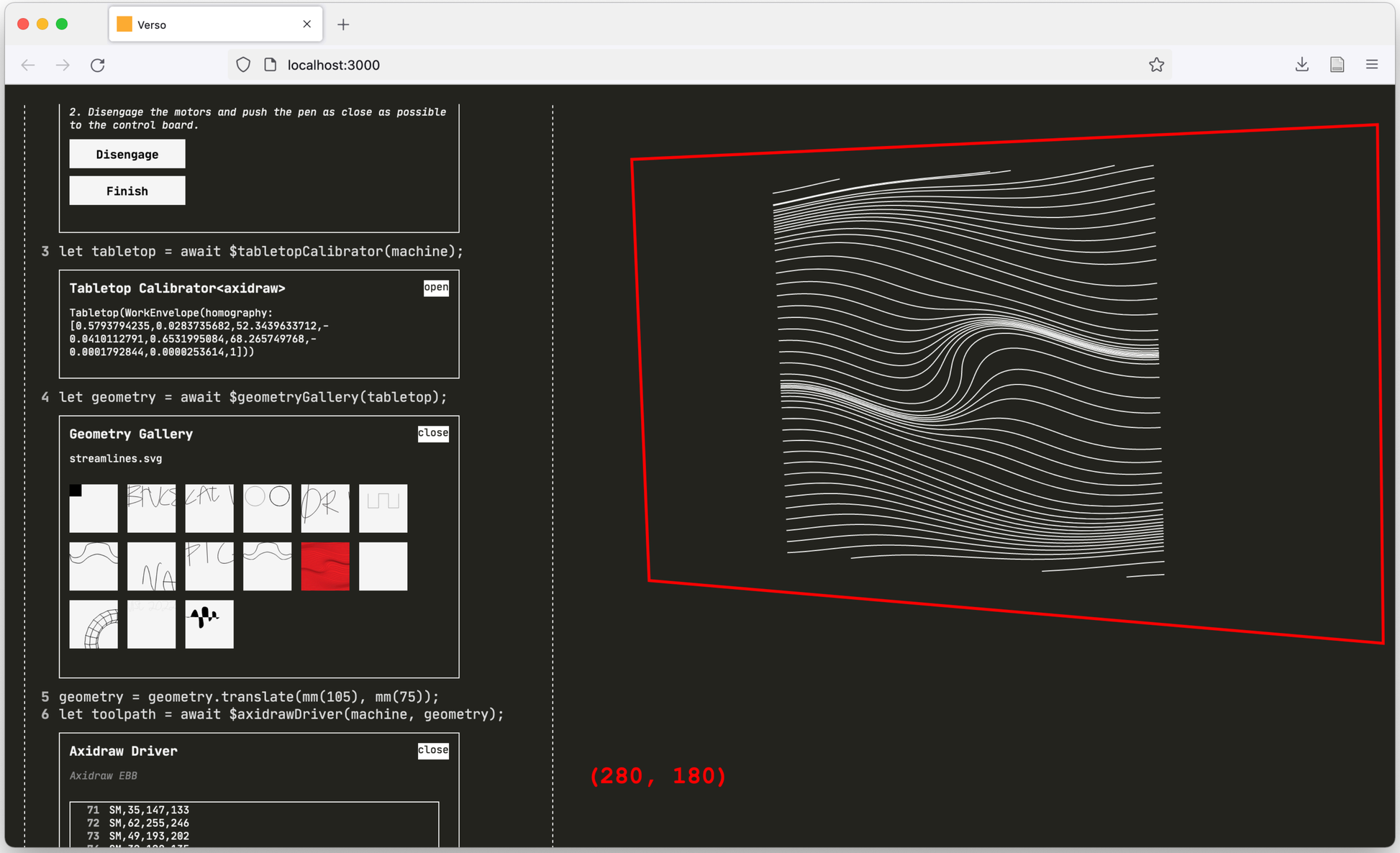

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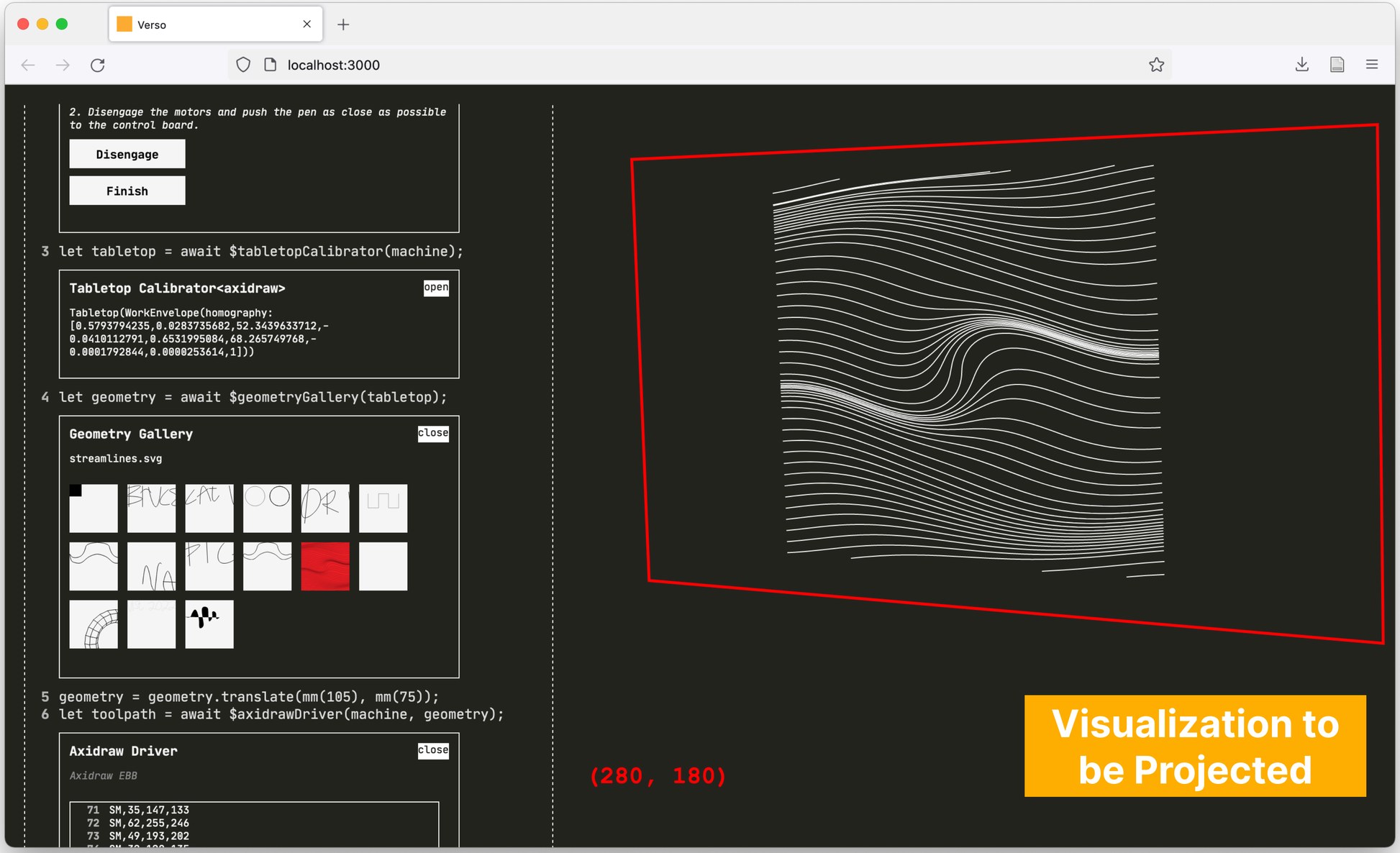

Fabrication-as-programming brings to digital fabrication:

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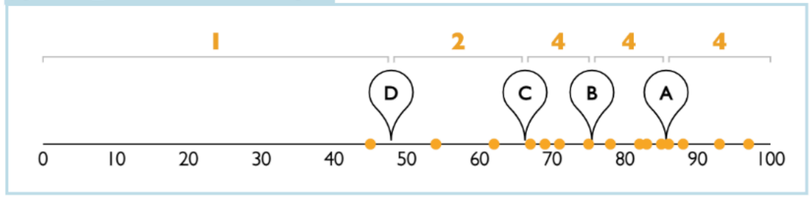
```
let q1_max = 36. in
let grades =
  $dataframe
```

= q1_max +. 24. +. $fslider 0. 40.

	"A1"	"A2"	"A3"	"Midterm"	"Final"
"Andrew"	80.	92.	83.5	95.	88.
"Cyrus"	61.	64.	98.	70.	85.
"David"	75.	81.	73.	82.	79.

```
in
let averages = compute_weighted_averages grades weights in
let cutoffs =
  $grade_cutoffs averages
```




```
in
format_for_university (assign_grades averages cutoffs)
```

Filling Typed Holes with Live GUIs. Omar et al. 2019.

Multimodal Programming

Fabrication-as-programming brings to digital fabrication:

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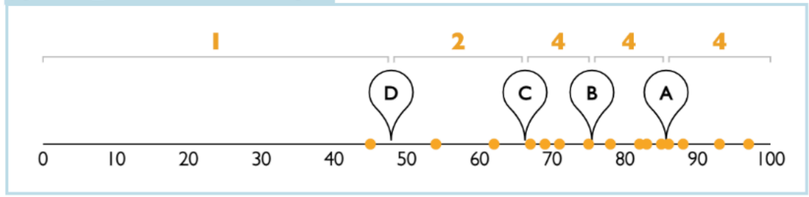


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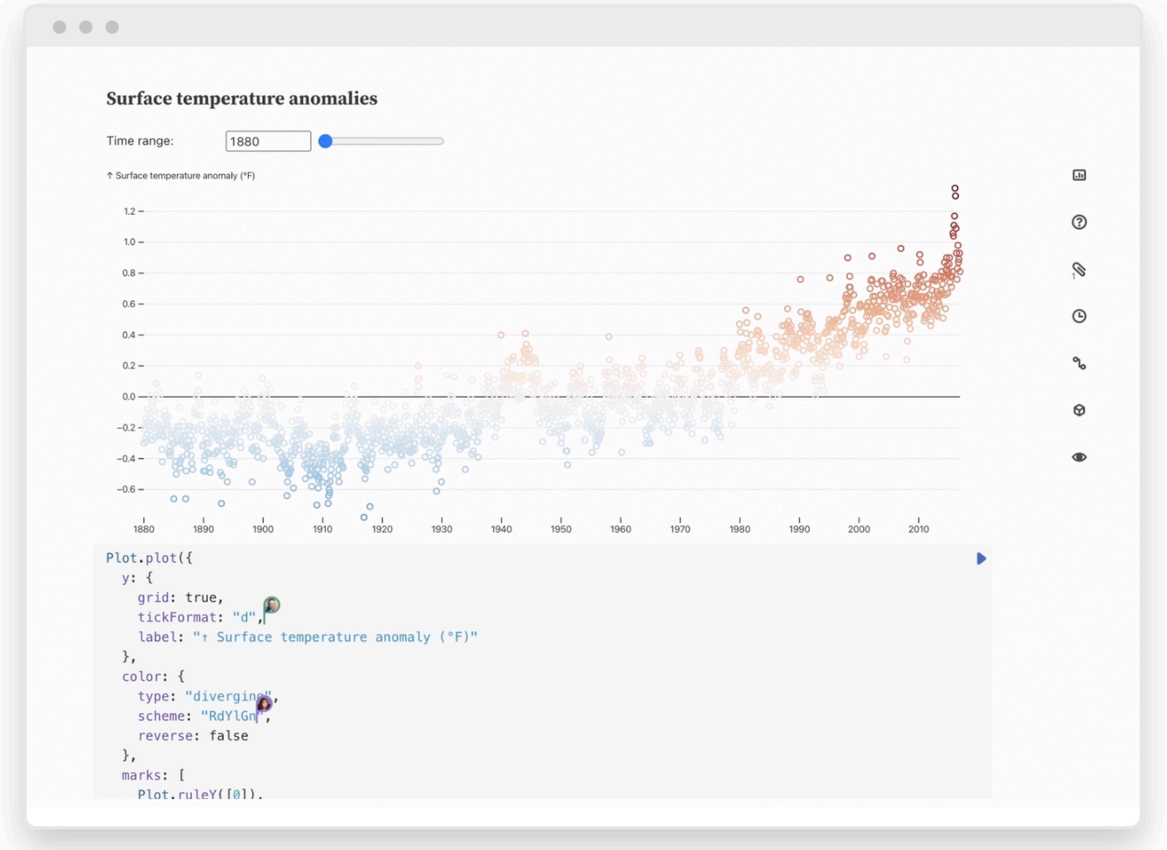
Multimodal Programming



D3.js and Observable Notebook.

Data visualization

Multimodal Programming

Modules: inline GUIs that accept and return values.

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```
$machineInitializer(myAxidraw)
```

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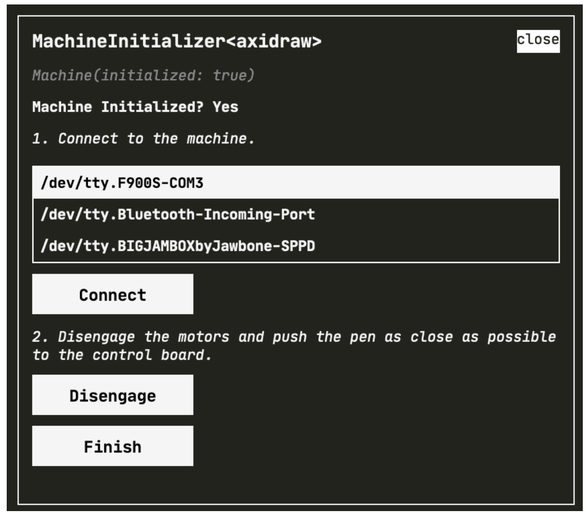
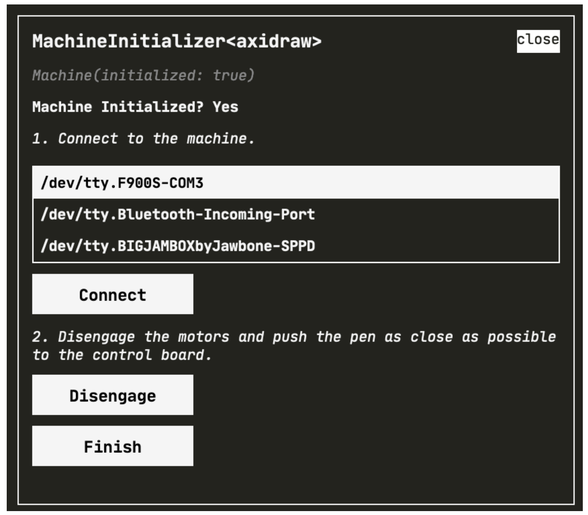


Multimodal Programming

Modules: inline GUIs that accept and return values.

```
Machine {
  type: “axidraw”,
  initialized: false
}
```



Multimodal Programming

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→ `$machineInitializer(myAxidraw)` →

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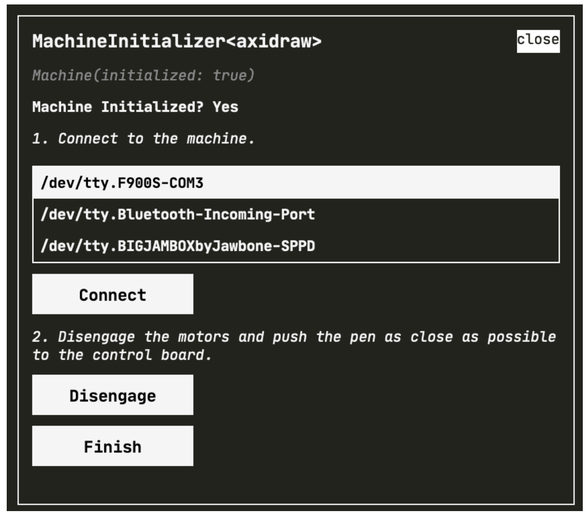
Machine {
  type: “axidraw”,
  initialized: true
}
```



Multimodal Programming

Modules: inline GUIs that accept and return values.

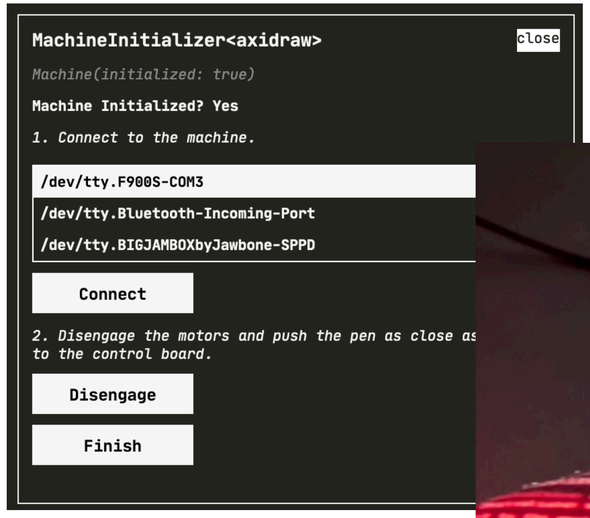
```
Machine {
  type: “axidraw”,
  initialized: false
}
```

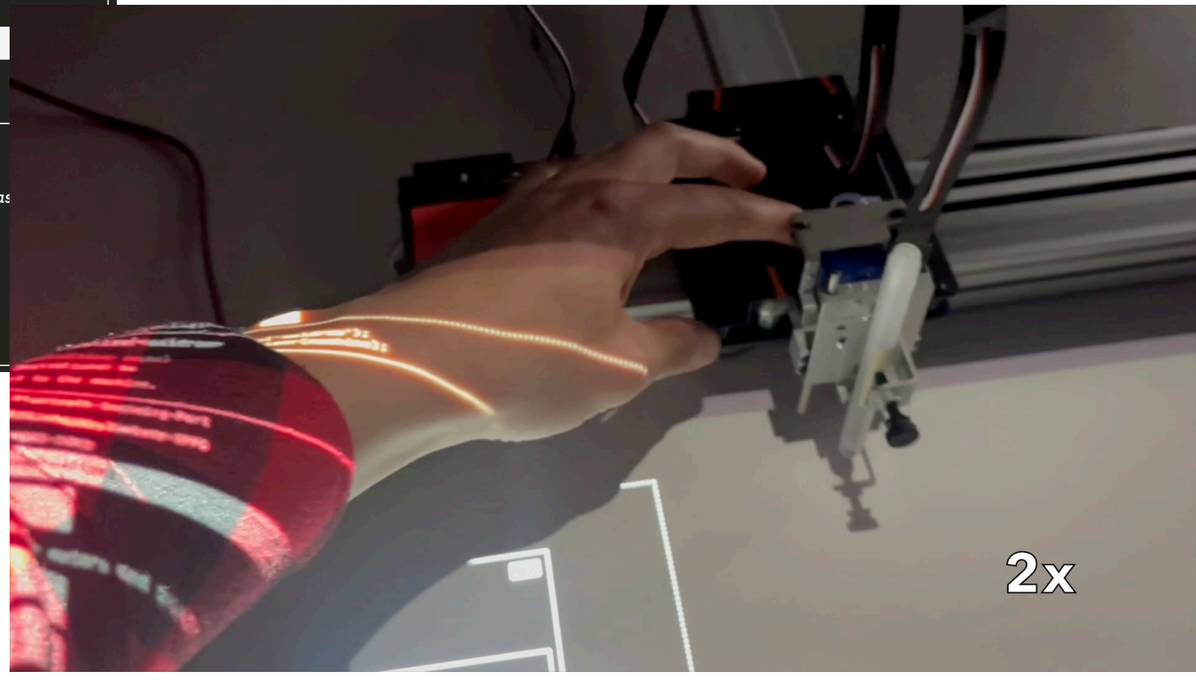
→

```
$machineInitializer(myAxidraw)
```

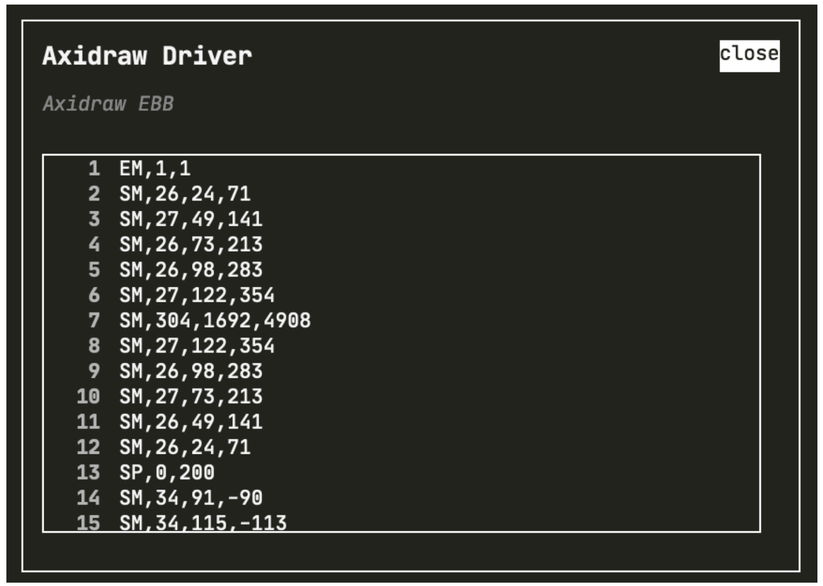
→

```
Machine {
  type: “axidraw”,
  initialized: true
}
```





Interoperate with existing tools



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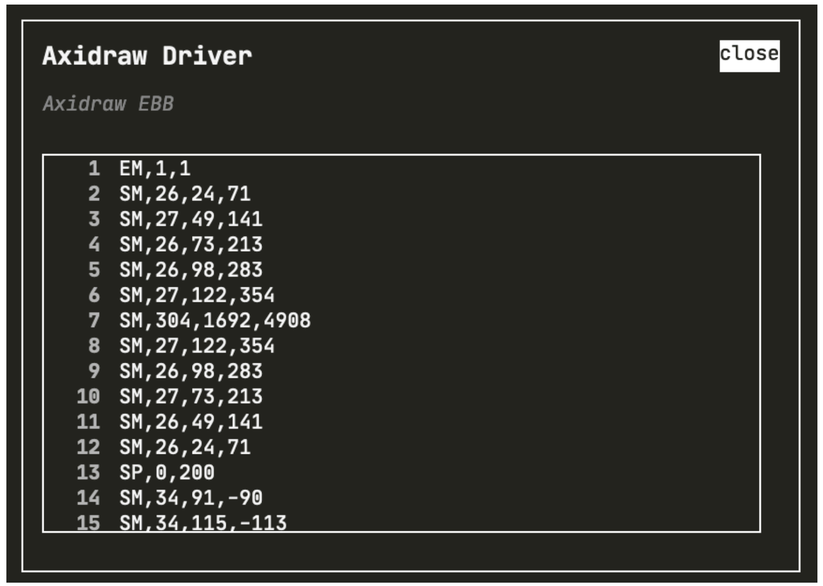
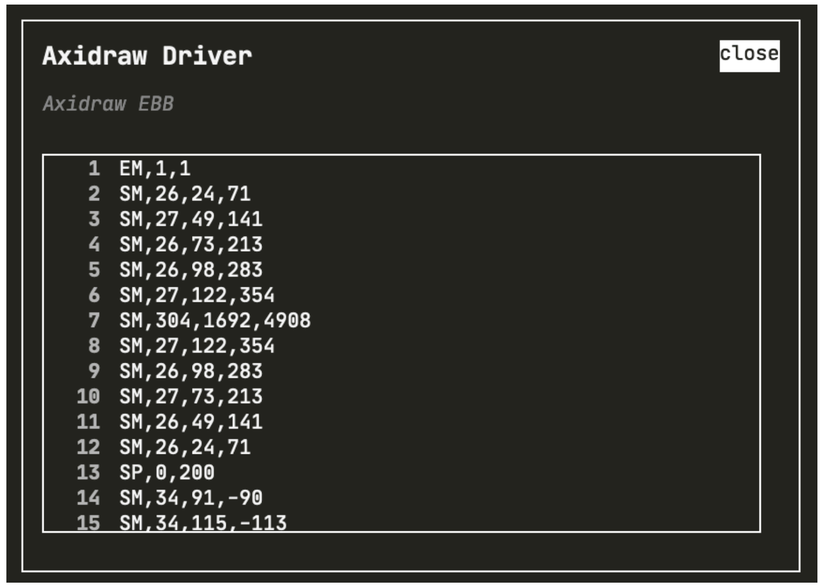


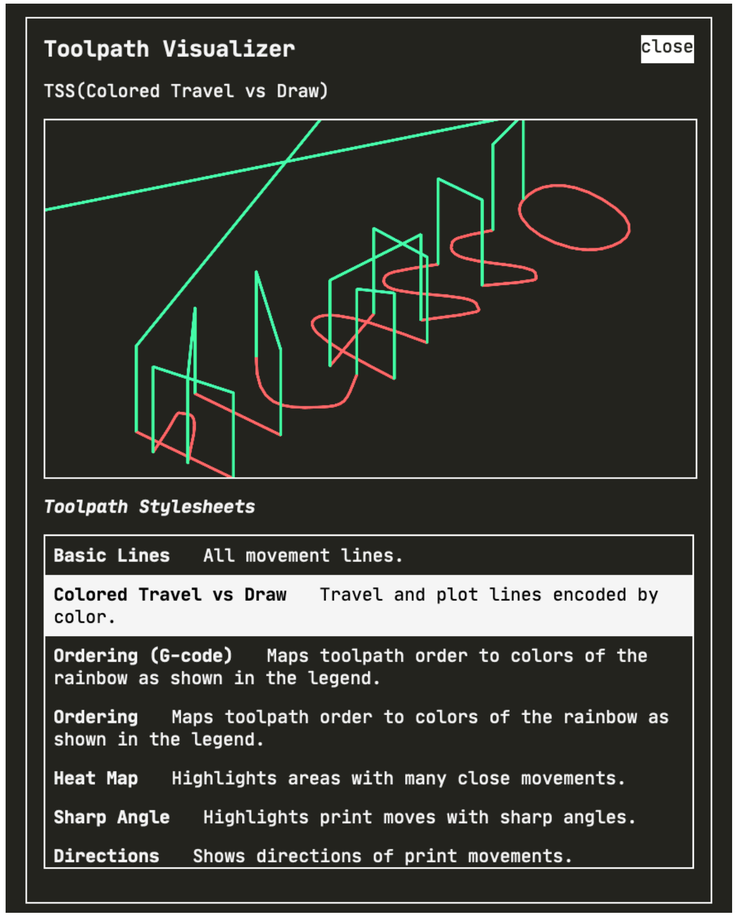
Selectively deploy parts of a toolpath

Interoperate with existing tools



Selectively deploy parts of a toolpath

Visualize machine behavior



Data Visualization

Toolpath stylesheets (TSS): generate task-specific views of a given toolpath.

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Pen markings

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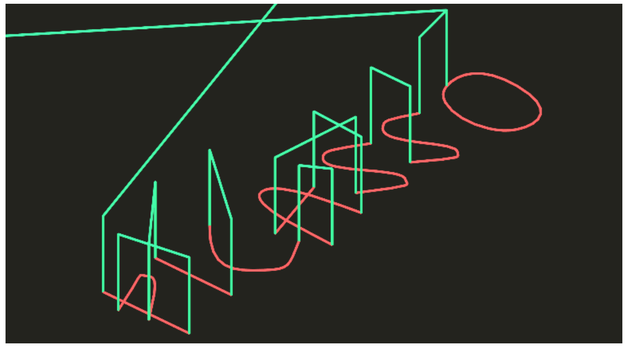

Markings vs. travel

Data Visualization

Toolpath stylesheets (TSS): generate task-specific views of a given toolpath.

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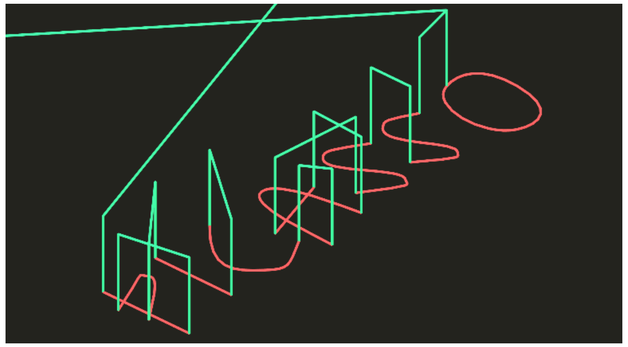

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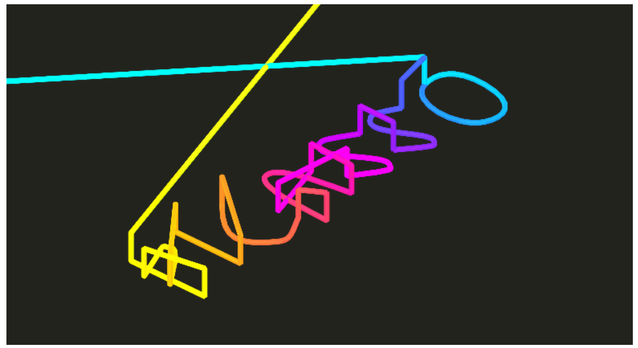

Move order

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Toolpath stylesheets (TSS): generate task-specific views of a given toolpath.

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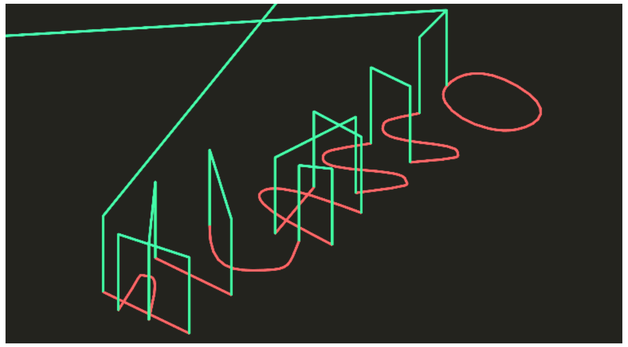

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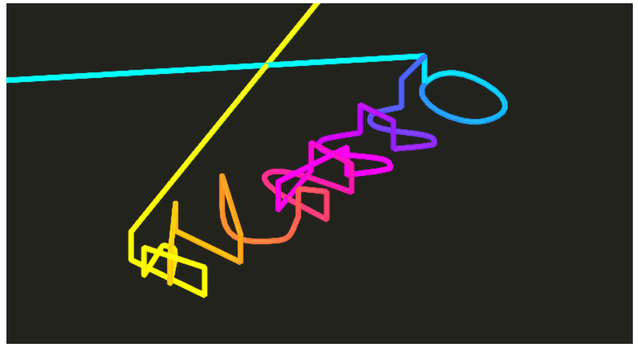

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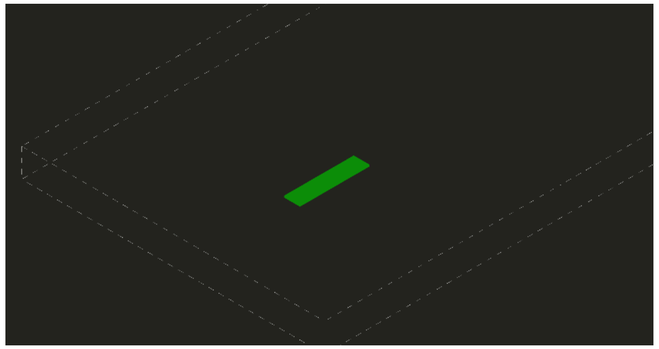

Scale w.r.t. work envelope

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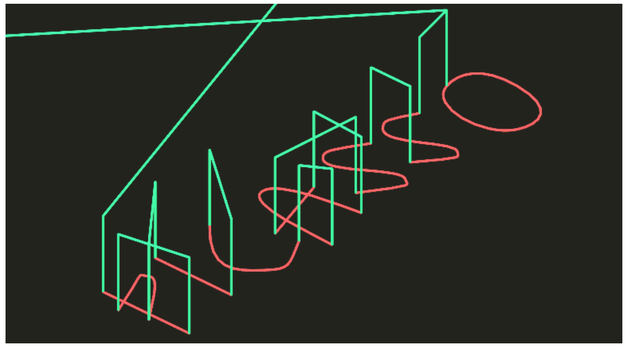

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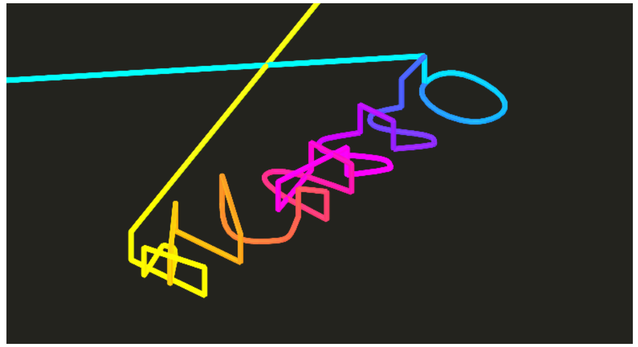

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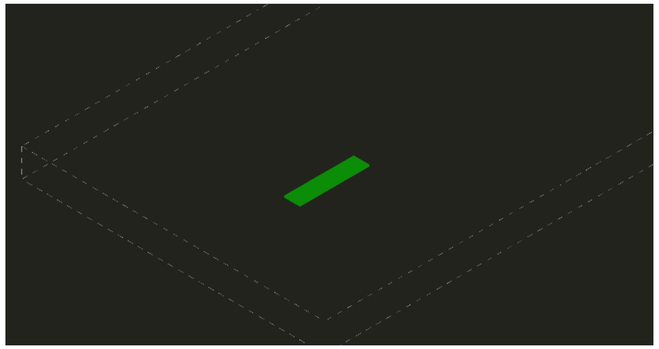

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Vinyl cutter sharp angles

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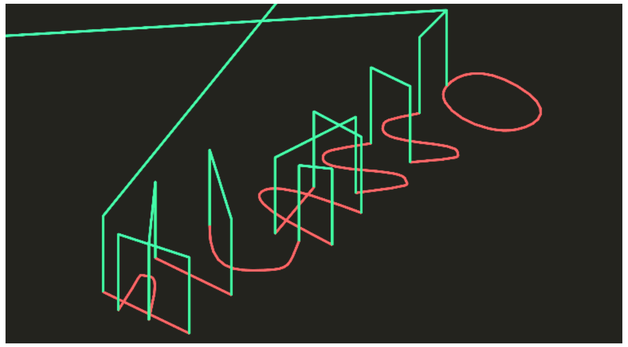

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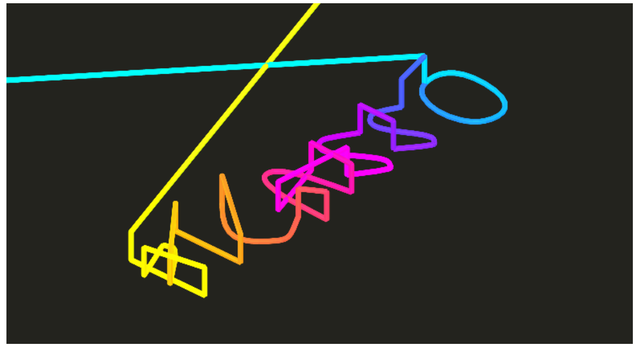

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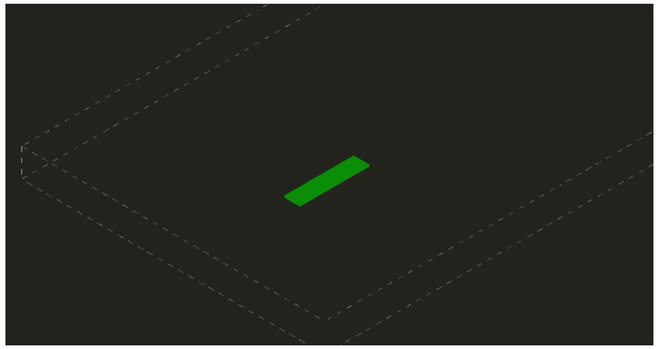

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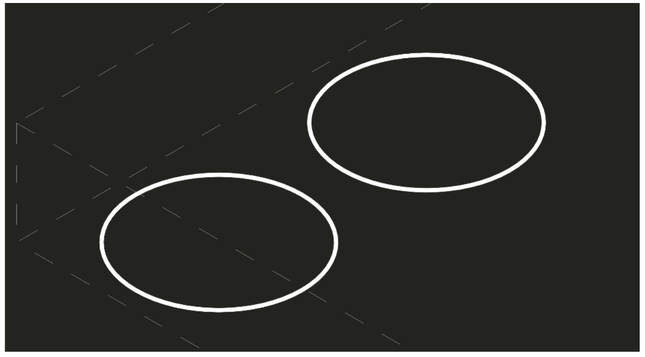

Laser cut geometries

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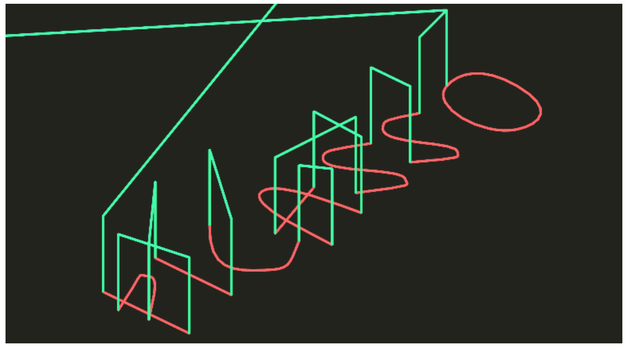

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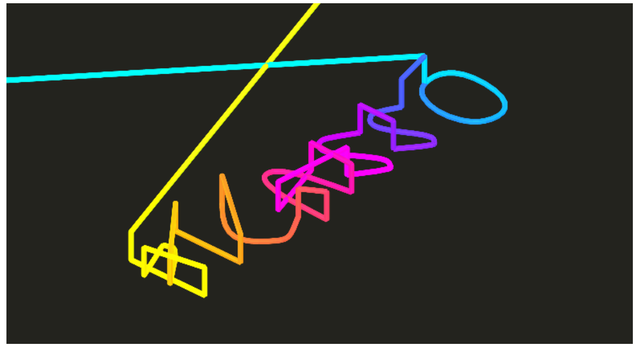

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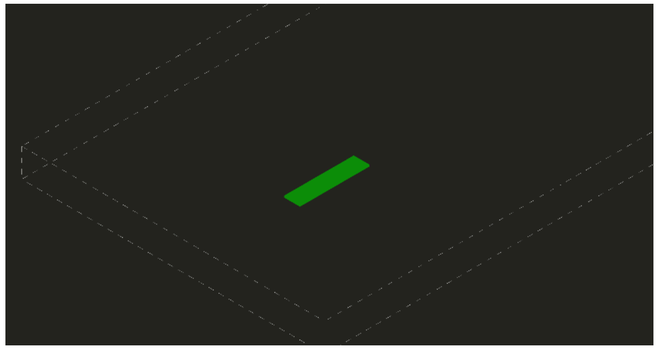

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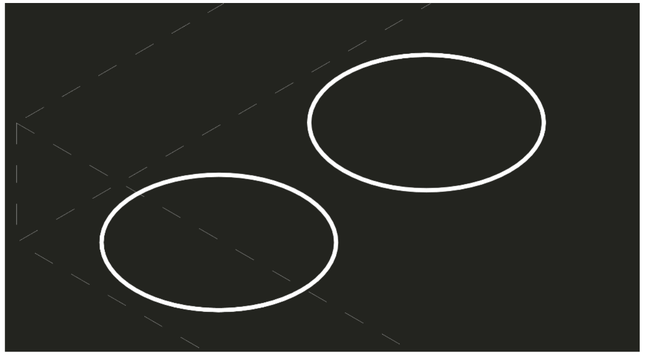
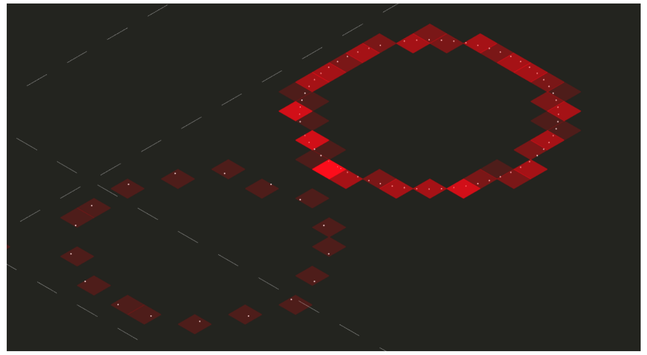


Laser cut geometries



Laser heat map

Data Visualization

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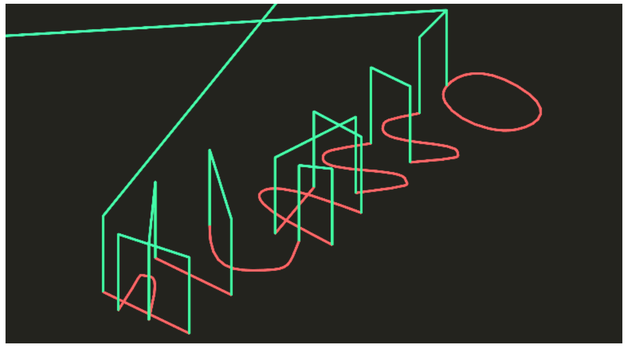
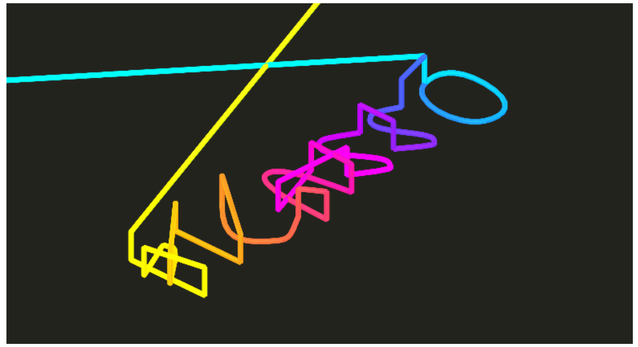
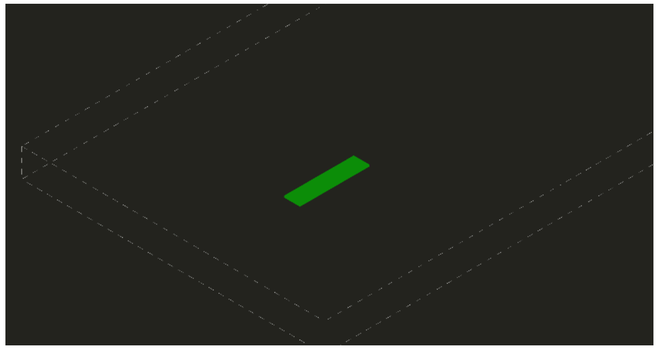
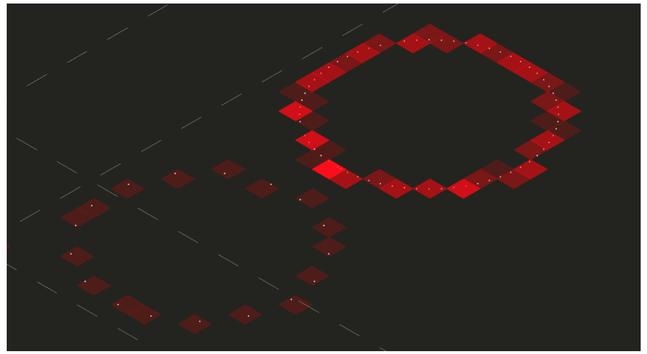






Pen marking **order** **Scale w.r.t. work envelope**



Vinyl **Laser heat map**

Knowing exactly where the toolpath will go in physical space is crucial in many EDF applications.

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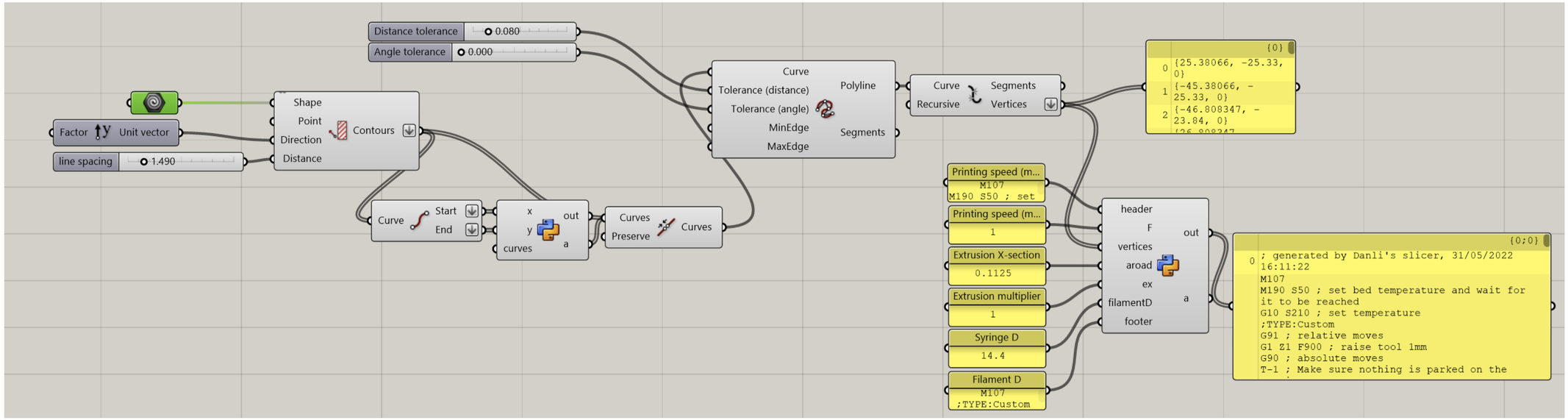

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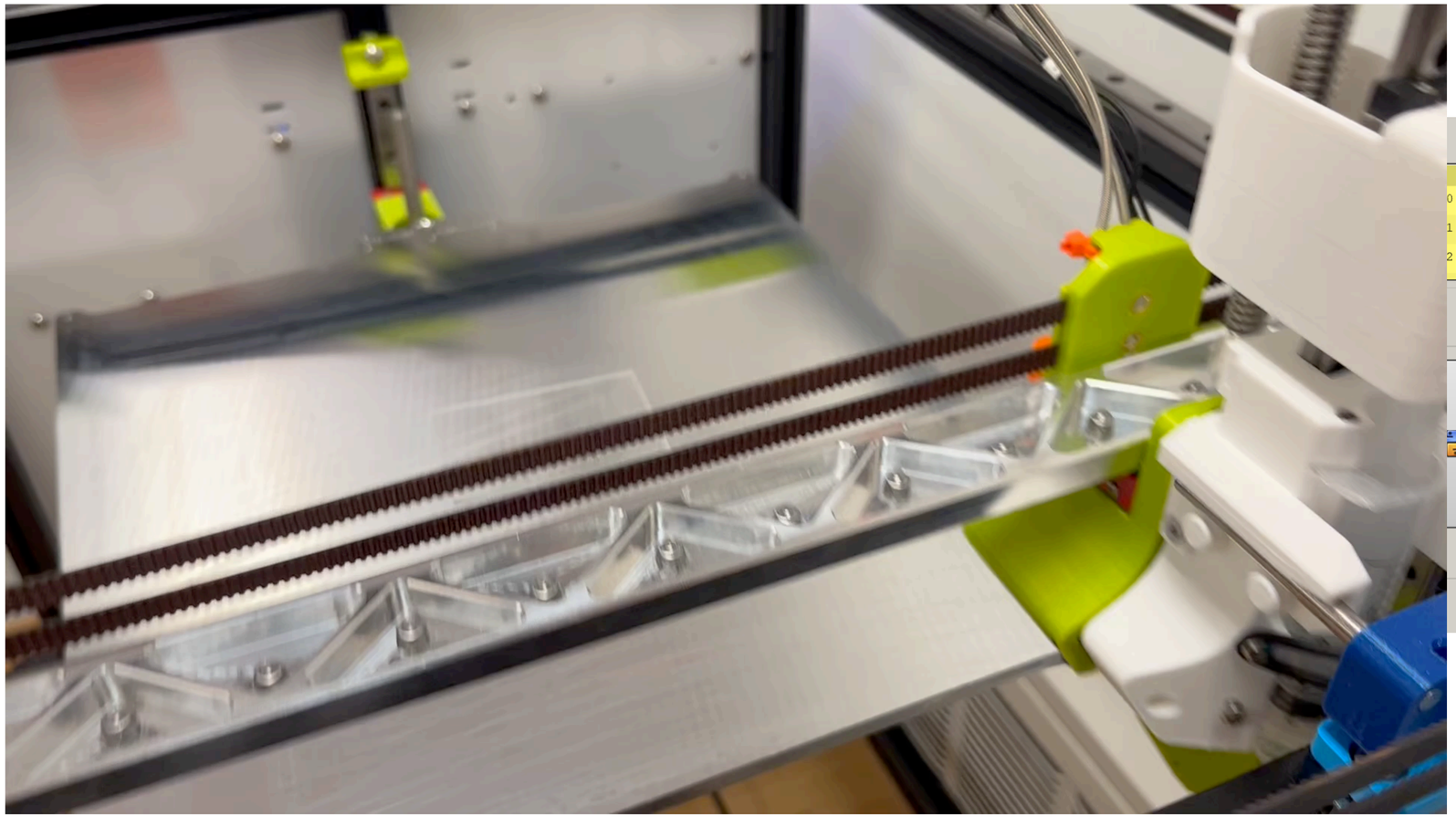

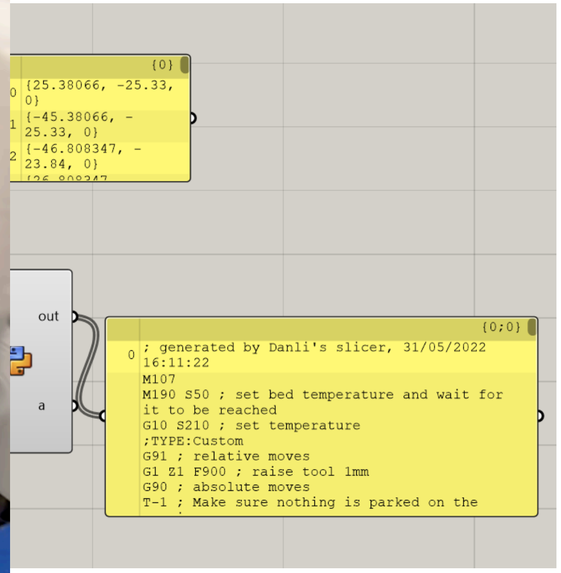

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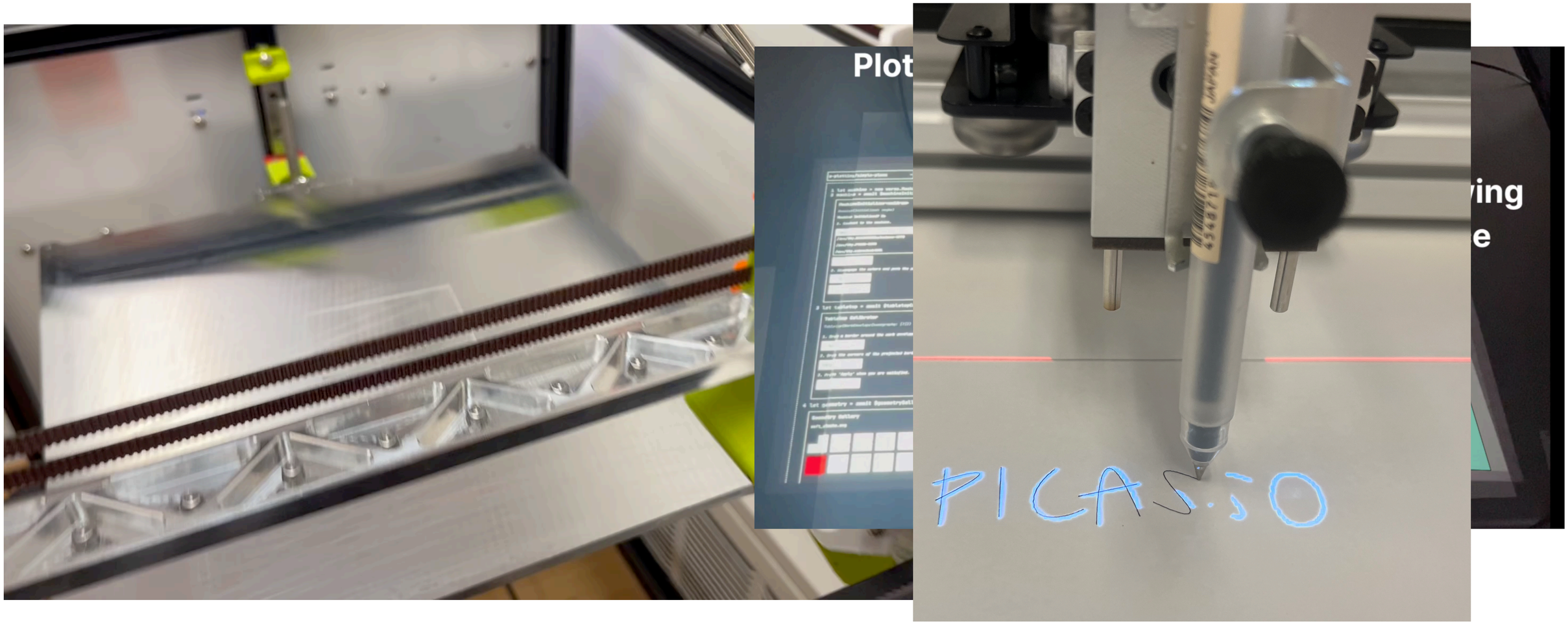
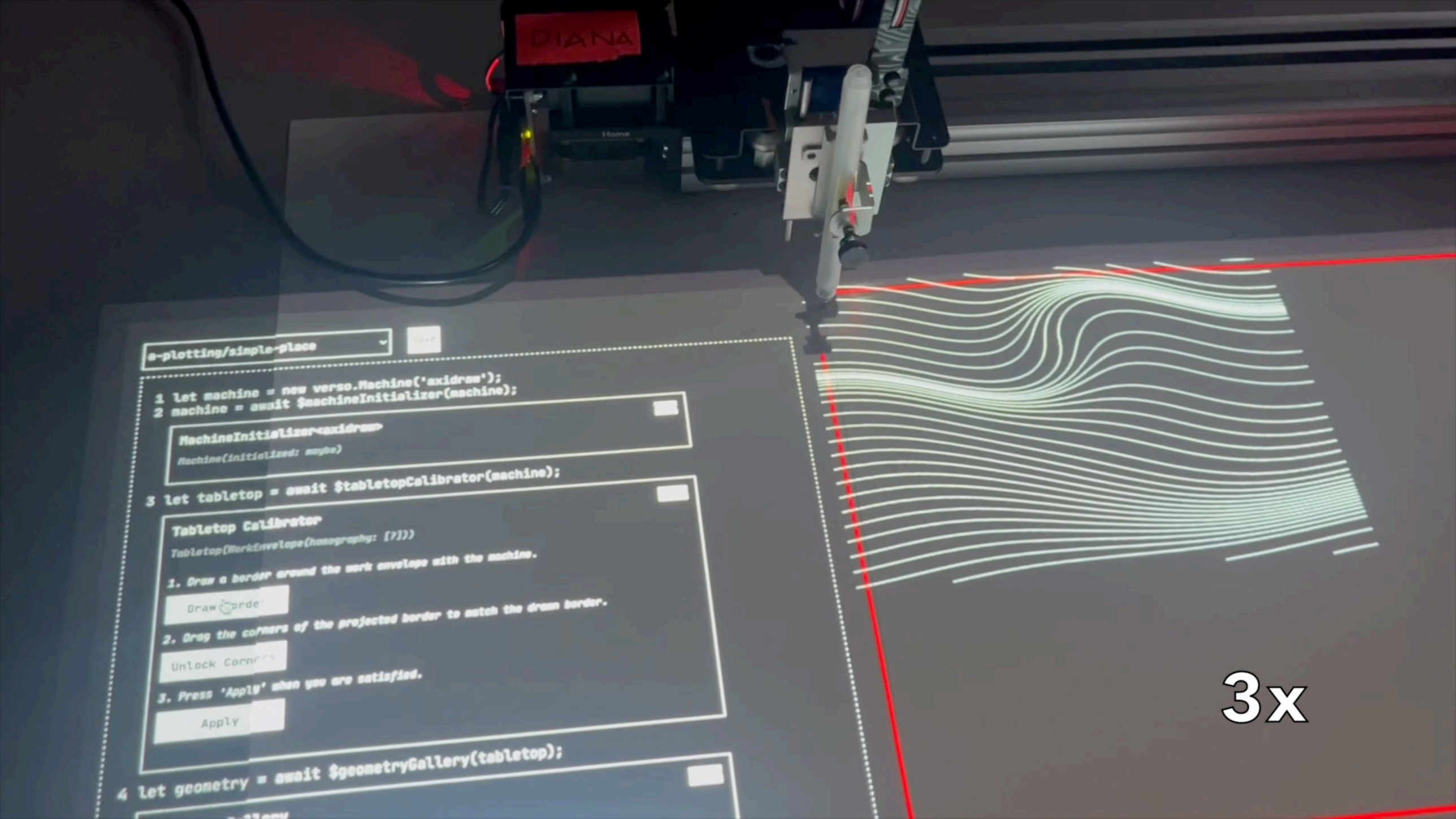
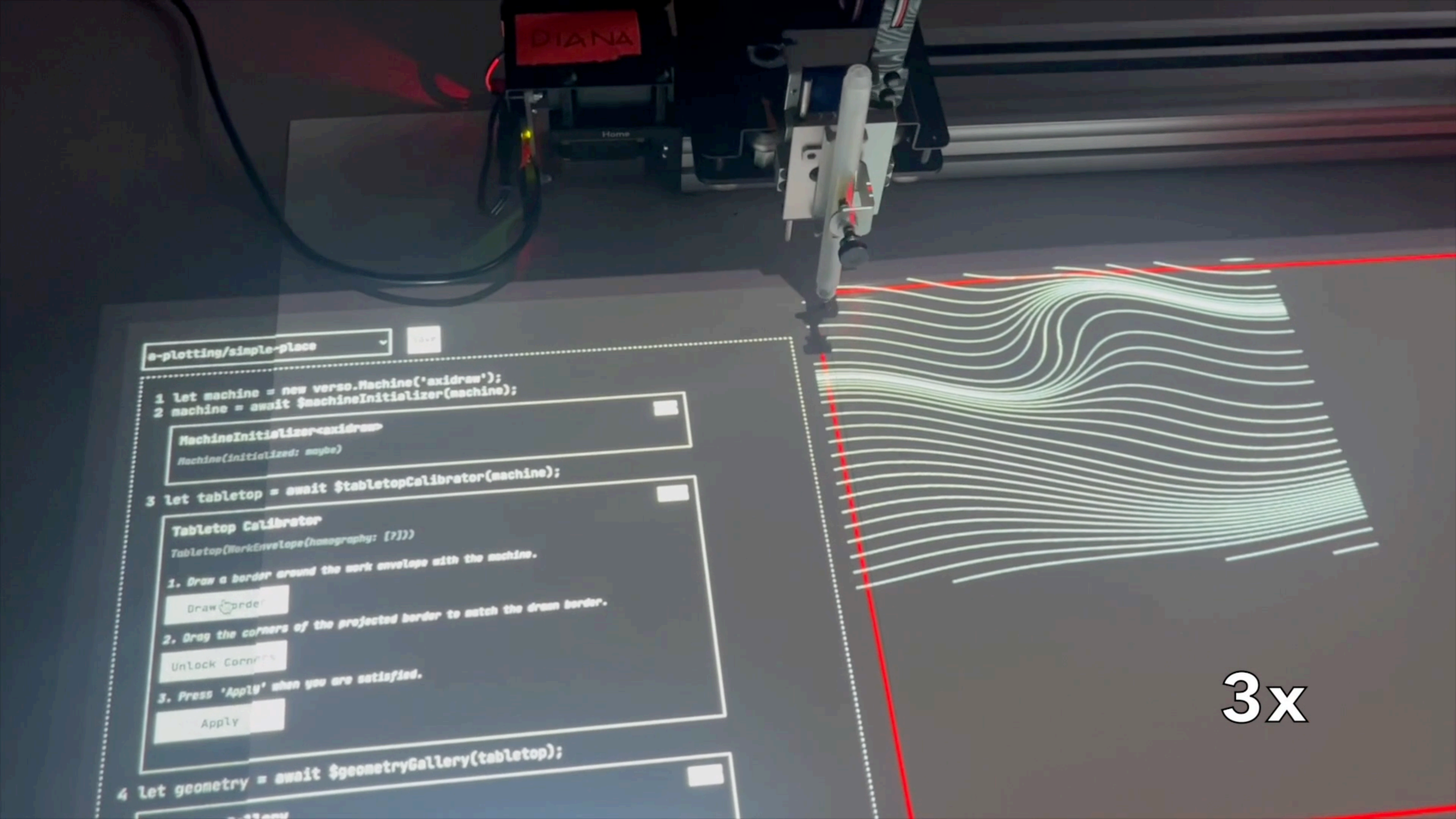



DIANA
Home
a-plotting/simple-place
1 let machine = new verso.Machine('axidraw');
2 machine = await $machineInitializer(machine);
MachineInitializer<axidraw>
Machine(initialized: maybe)
3 let tabletop = await $tabletopCalibrator(machine);
Tabletop Calibrator
Tabletop(WorkEnvelope(homography: [?]))
1. Draw a border around the work envelope with the machine.
Draw Border
2. Drag the corners of the projected border to match the drawn border.
Unlock Corners
3. Press 'Apply' when you are satisfied.
Apply
4 let geometry = await $geometryGallery(tabletop);
3x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9 await $dispatcher(machine, {toolpath});

Dispatcher

Machine(initialized: maybe)

Machine status: free

; Enter G-code to adjust the tool prior to dispatch.

Send Snippet

Toolpath 0

Dispatch

Pause

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Next steps for fabrication-as-programming

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More visualizations with toolpath stylesheets

Next steps for fabrication-as-programming

More visualizations with toolpath stylesheets

More modules for emerging human-machine interactions

Next steps for fabrication-as-programming

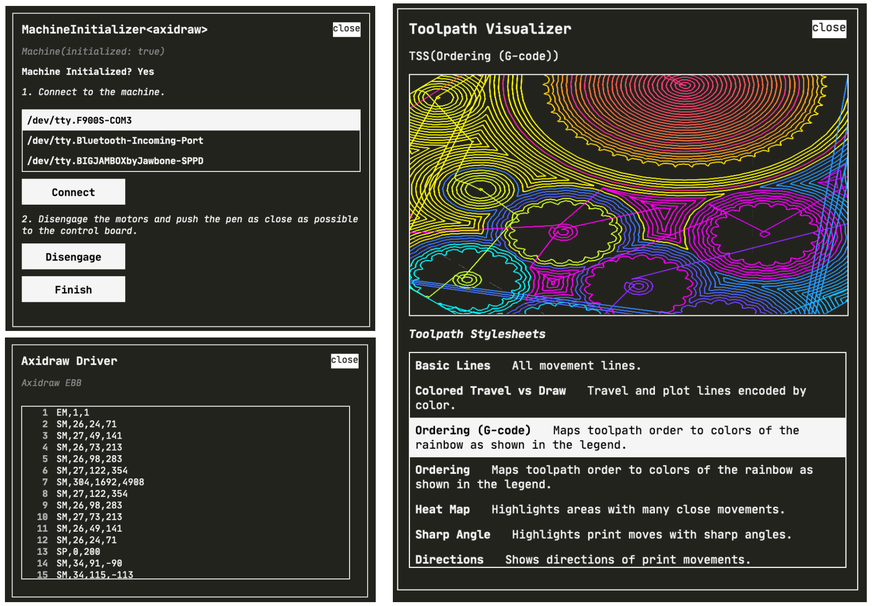
More visualizations with toolpath stylesheets

More modules for emerging human-machine interactions

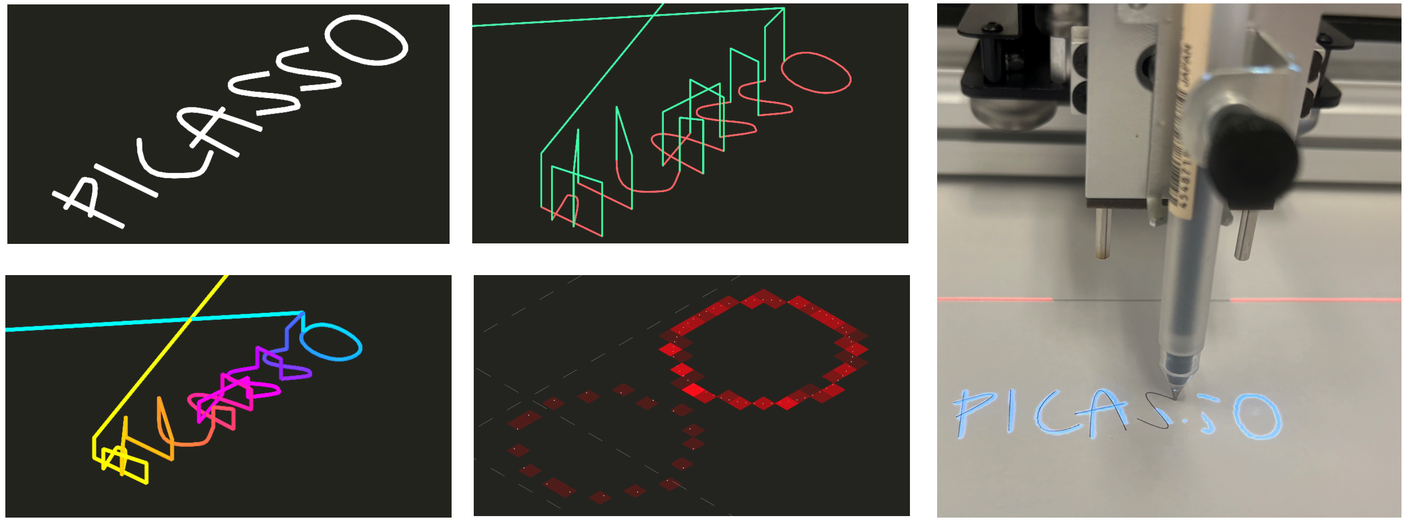
More sharing of exploratory workflows

Verso: Towards Fabrication-as-Programming

Multimodal Programming



Toolpath Stylesheets



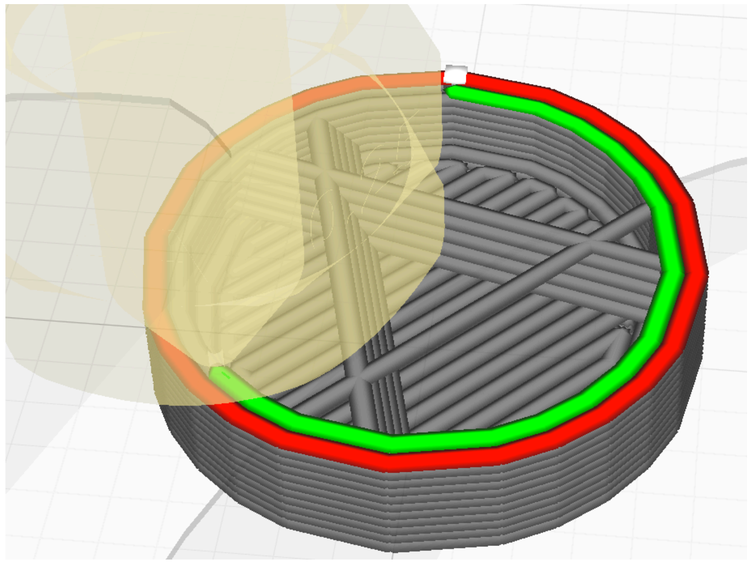
Jasper Tran O'Leary, Eunice Jun, Nadya Peek

University of Washington

PAUL G. ALLEN SCHOOL

ALFRED P. SLOAN FOUNDATION

“Can’t Cura/Fusion360/etc… already visualize toolpaths?”



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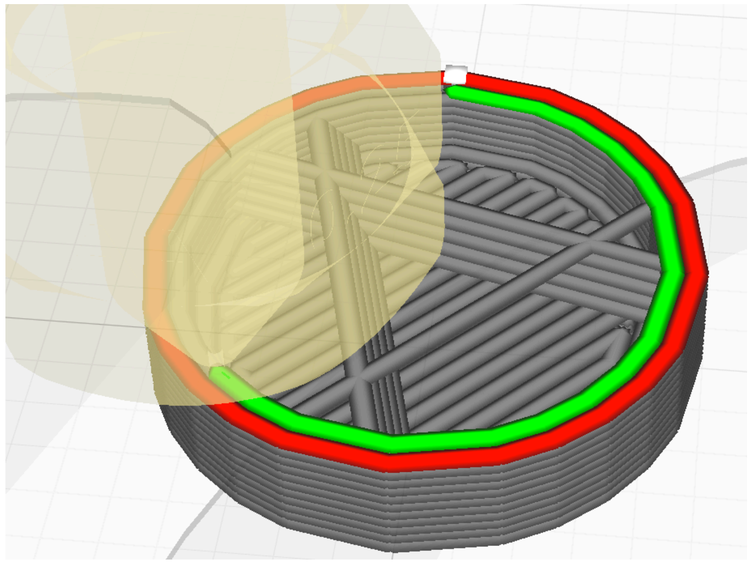

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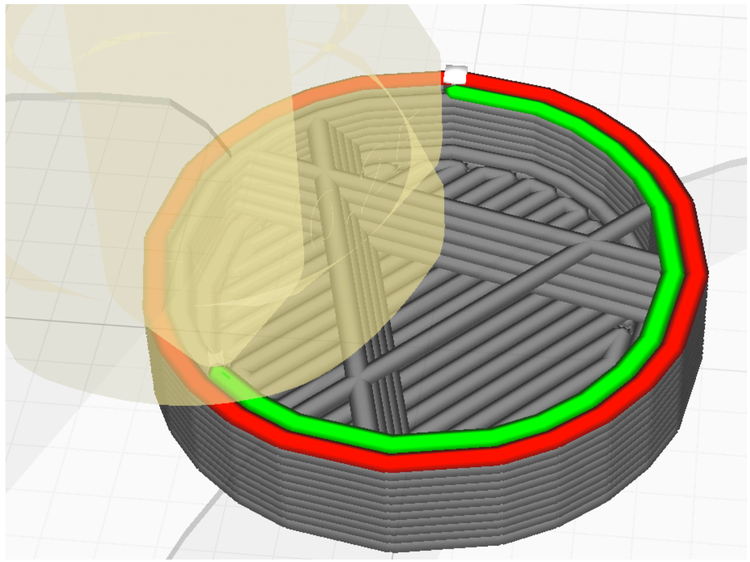

Yes, and they typically provide great common-case visualization.

However we’re focused on uncommon tasks which may require specialized visualizations.

TSS are extensible.

A TSS is an interpreter that provides a ***visual semantics*** for a given set of instructions.

```
G55
M8
G0 X73.332 Y62.712
G0 Z15.
G0 Z5.
G0 Z-3.498
G1 Z-4.498 F400.
G1 X73.331 Y62.704 Z-4.618
G1 X73.325 Y62.683 Z-4.737
G1 X73.316 Y62.649 Z-4.852
G1 X73.304 Y62.601 Z-4.962
G1 X73.288 Y62.54 Z-5.066
G1 X73.144 Y61.975 Z-5.469
G1 X73.114 Y61.86 Z-5.49
G1 X73.084 Y61.743 Z-5.498
G3 X72.693 Y59.021 R12.765
G1 Y58.871 F800.
```

Algorithm 1 Ordering TSS (G-Code Instruction Set)

Require: *instructions*

```
points ← [ ]
for instruction in instructions do
    opcode ← parseOpcode(instruction)
    match opcode do
        case "G0" or "G1"
            X, Y, Z, F, E ← parseArgs(instruction)
            push(points, Vector3(X, Y, Z))
```

```
G55
M8
G0 X73.332 Y62.712
G0 Z15.
G0 Z5.
G0 Z-3.498
G1 Z-4.498 F400.
G1 X73.331 Y62.704 Z-4.618
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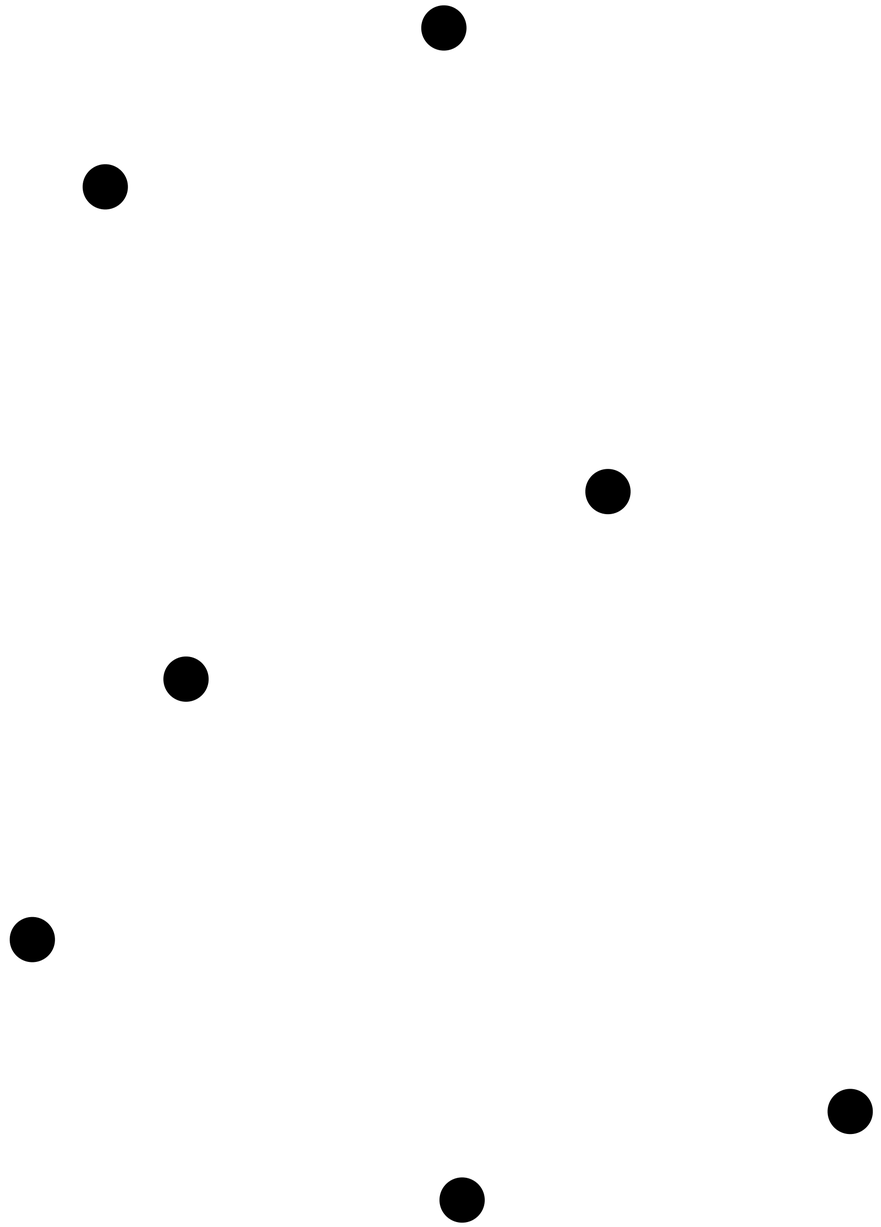
case "G0" **or** "G1"

$X, Y, Z, F, E \leftarrow parseArgs(instruction)$

$push(points, Vector3(X, Y, Z))$



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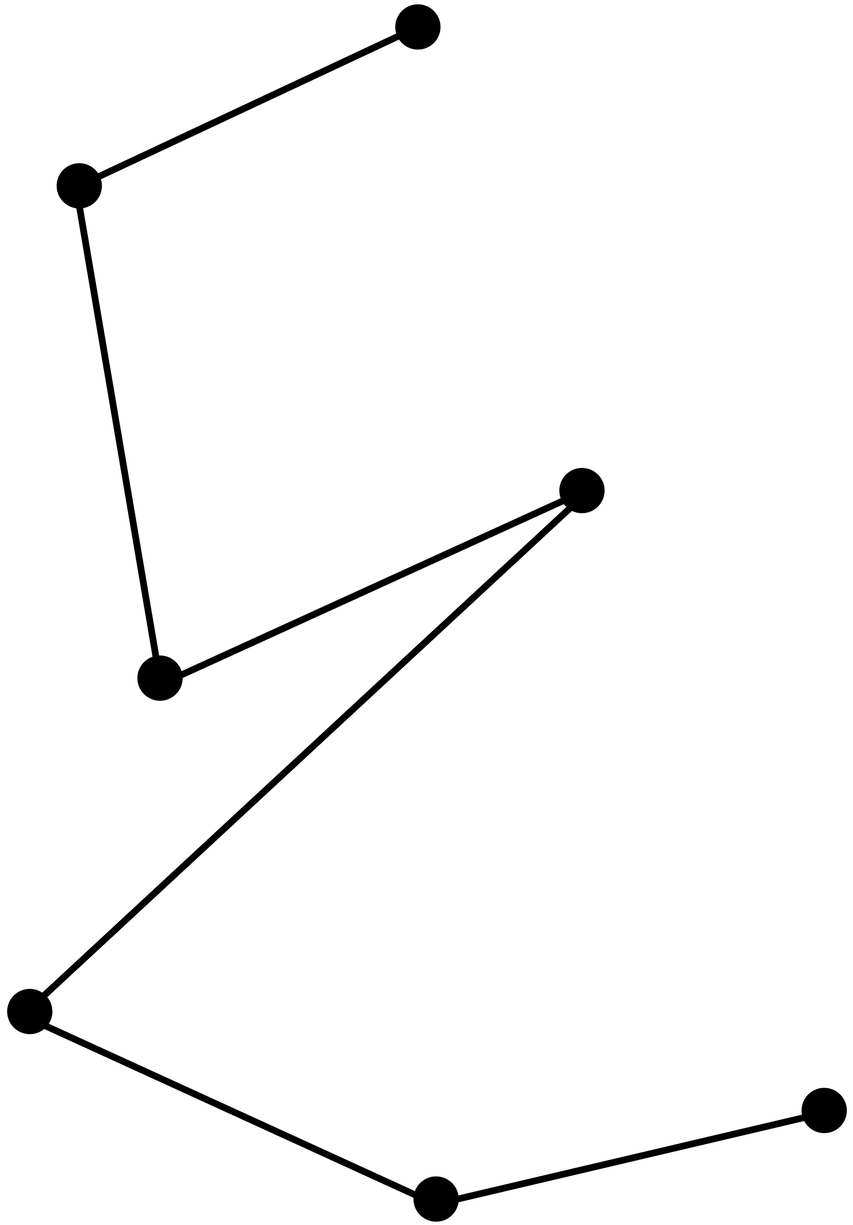
        $X, Y, Z, F, E \leftarrow parseArgs(instruction)$
        $push(points, Vector3(X, Y, Z))$
  end for
  $curve \leftarrow interpolate(points)$



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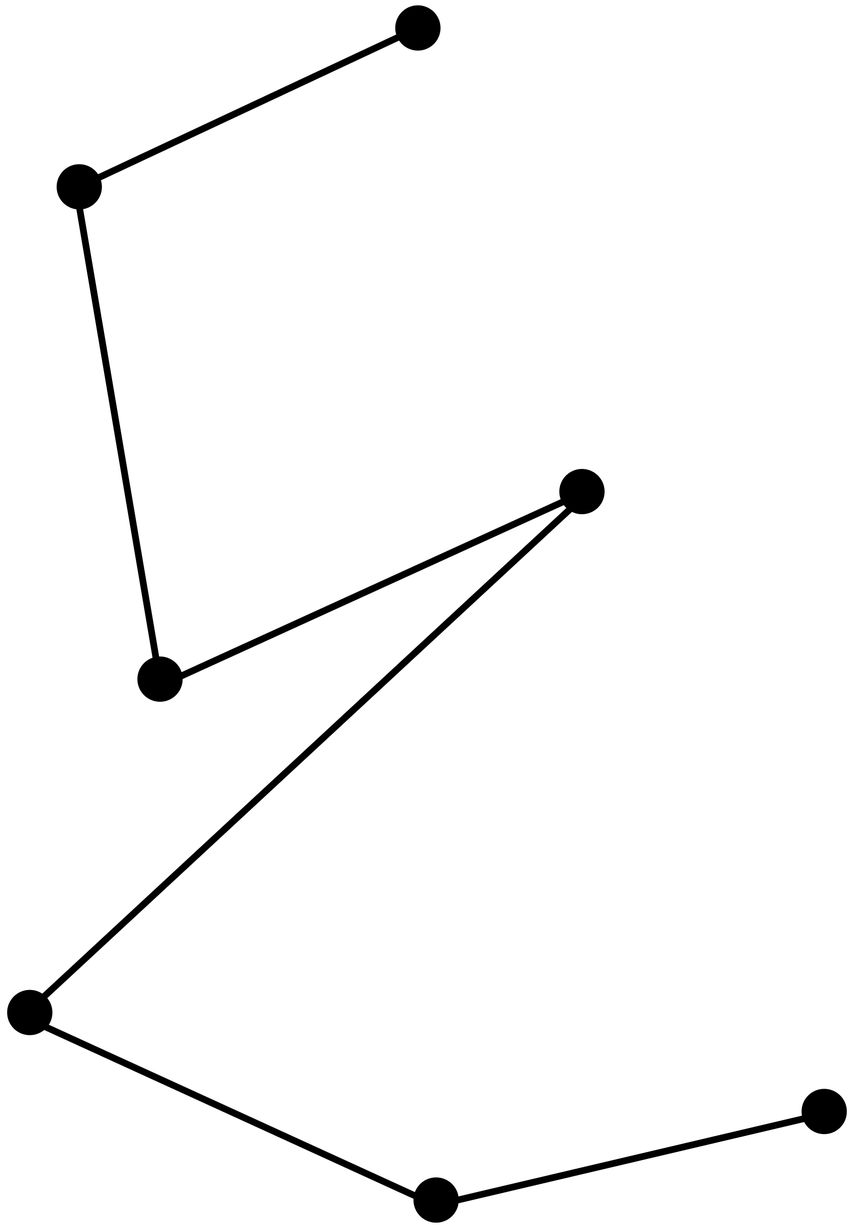
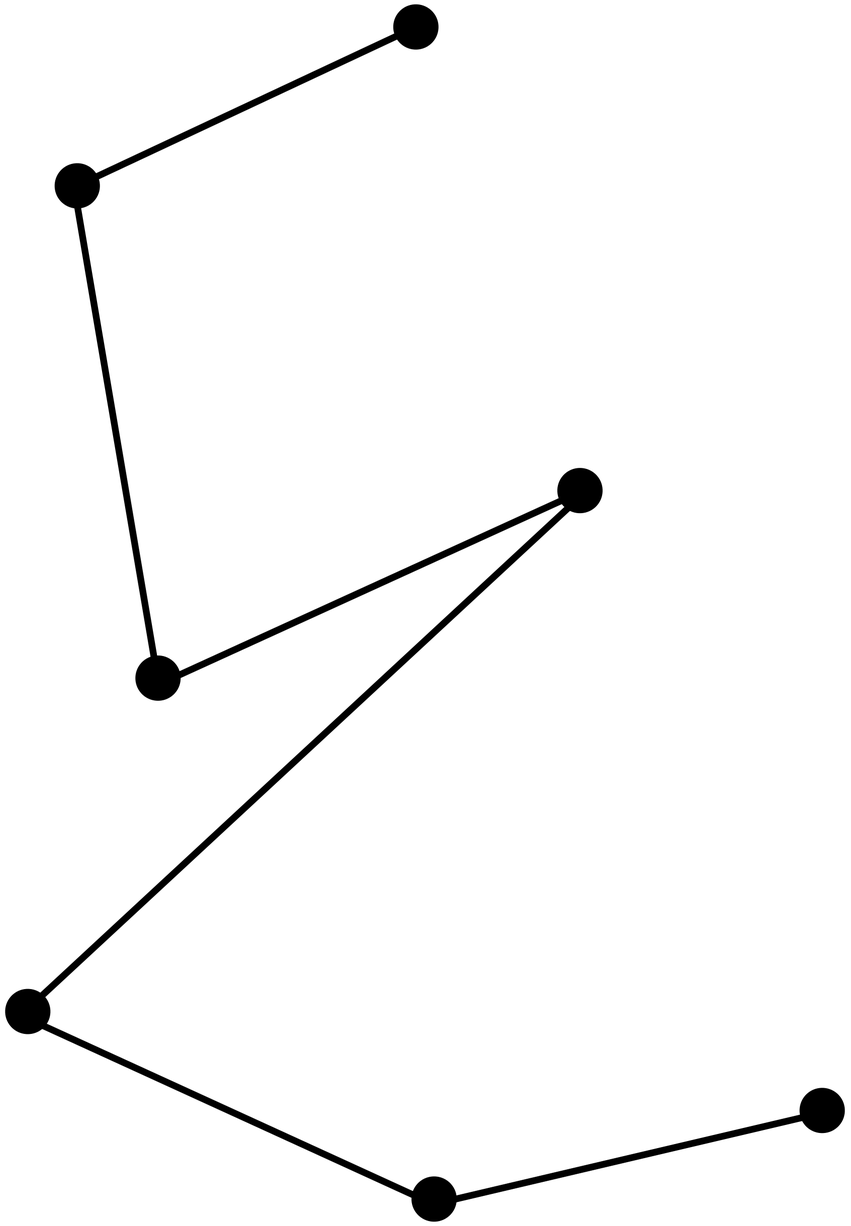
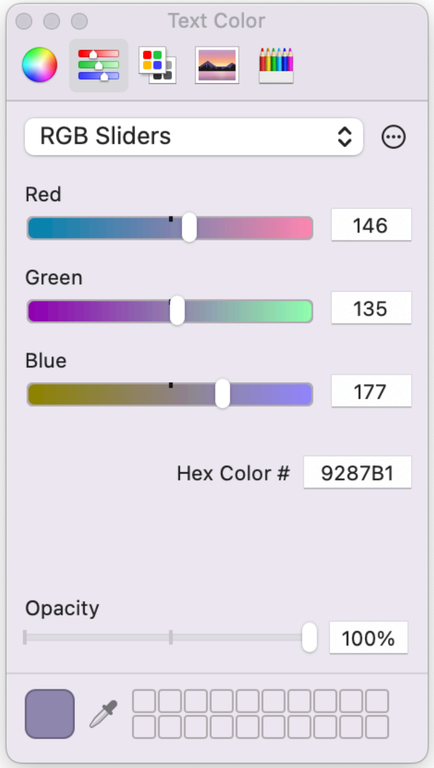
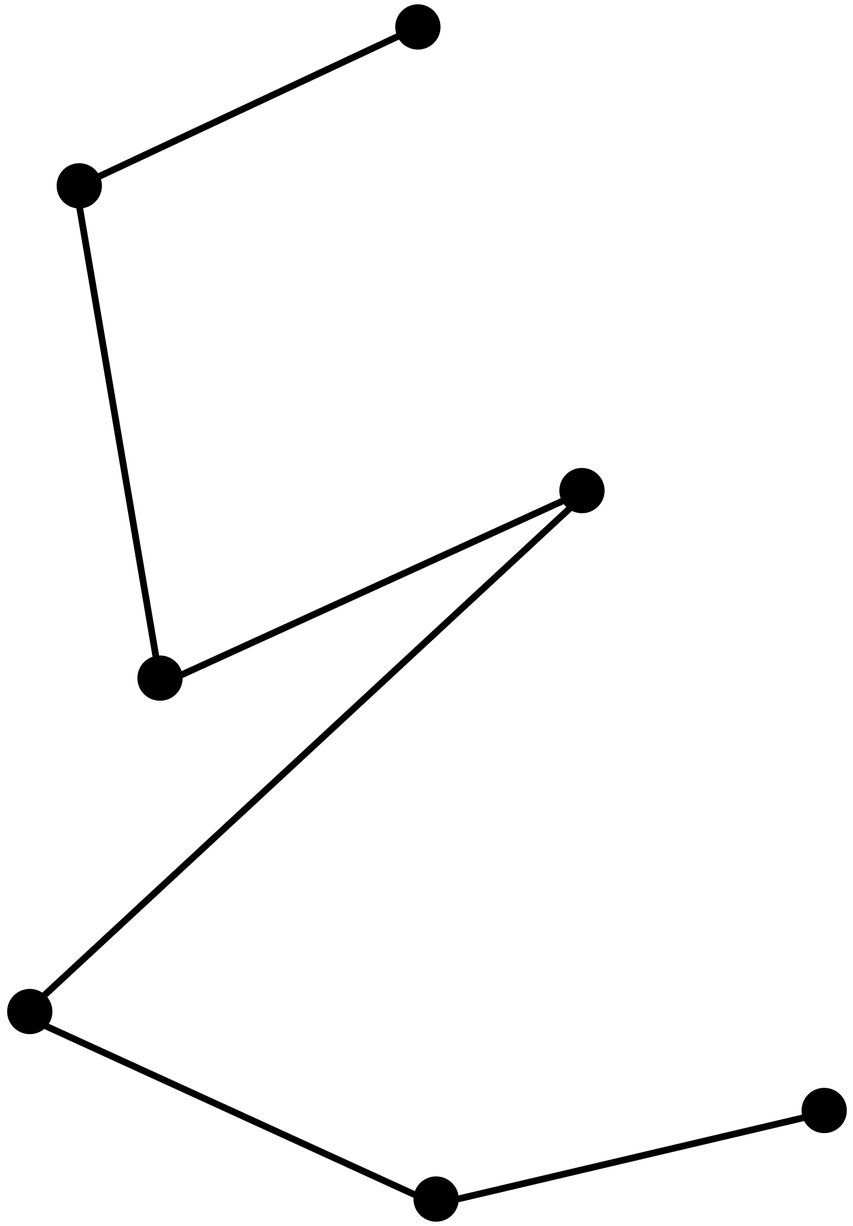


$colors \leftarrow [\quad]$
$f \leftarrow \ldots$ ▷ Choose a constant frequency for cycling colors.
$\phi_r, \phi_g, \phi_b \leftarrow \ldots$ ▷ Choose a constant phase offset per channel.
for $(\_, index)$ in $curve$ **do**
    $red \leftarrow sin(f \times index + \phi_r)$
    $green \leftarrow sin(f \times index + \phi_g)$
    $blue \leftarrow sin(f \times index + \phi_b)$
    $push(colors, Color(red, blue, green))$
end for



$colors \leftarrow [\ \ ]$
$f \leftarrow \ldots$ ▷ Choose a constant frequency for cycling colors.
$\phi_r, \phi_g, \phi_b \leftarrow \ldots$ ▷ Choose a constant phase offset per channel.
for $(\_, index)$ in $curve$ **do**
    $red \leftarrow sin(f \times index + \phi_r)$
    $green \leftarrow sin(f \times index + \phi_g)$
    $blue \leftarrow sin(f \times index + \phi_b)$
    $push(colors, Color(red, blue, green))$
end for





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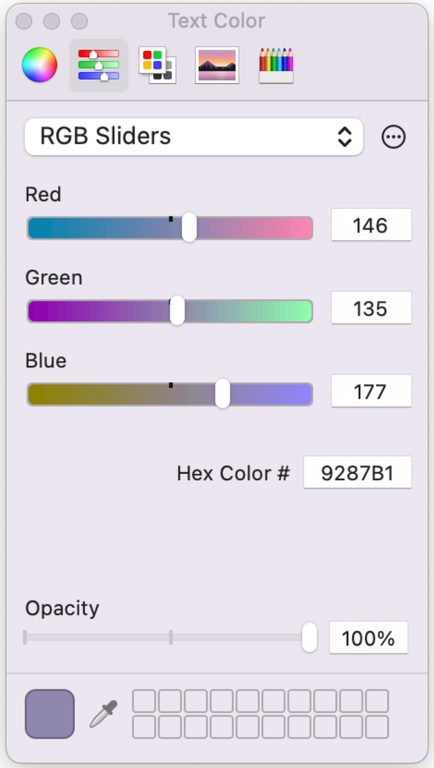
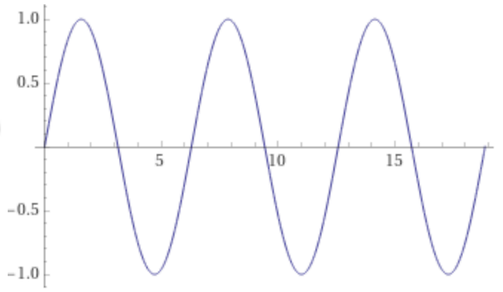
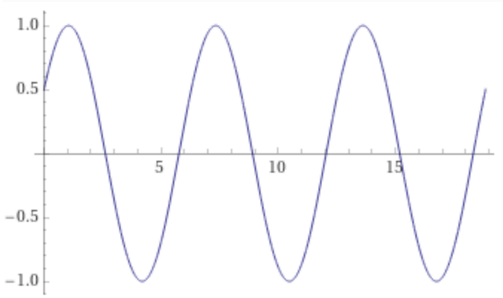
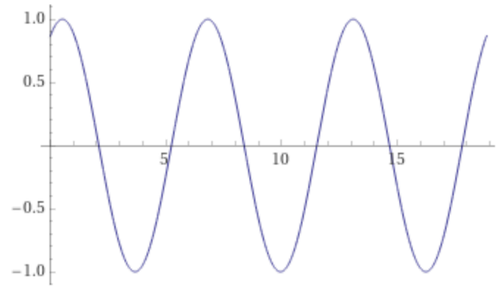
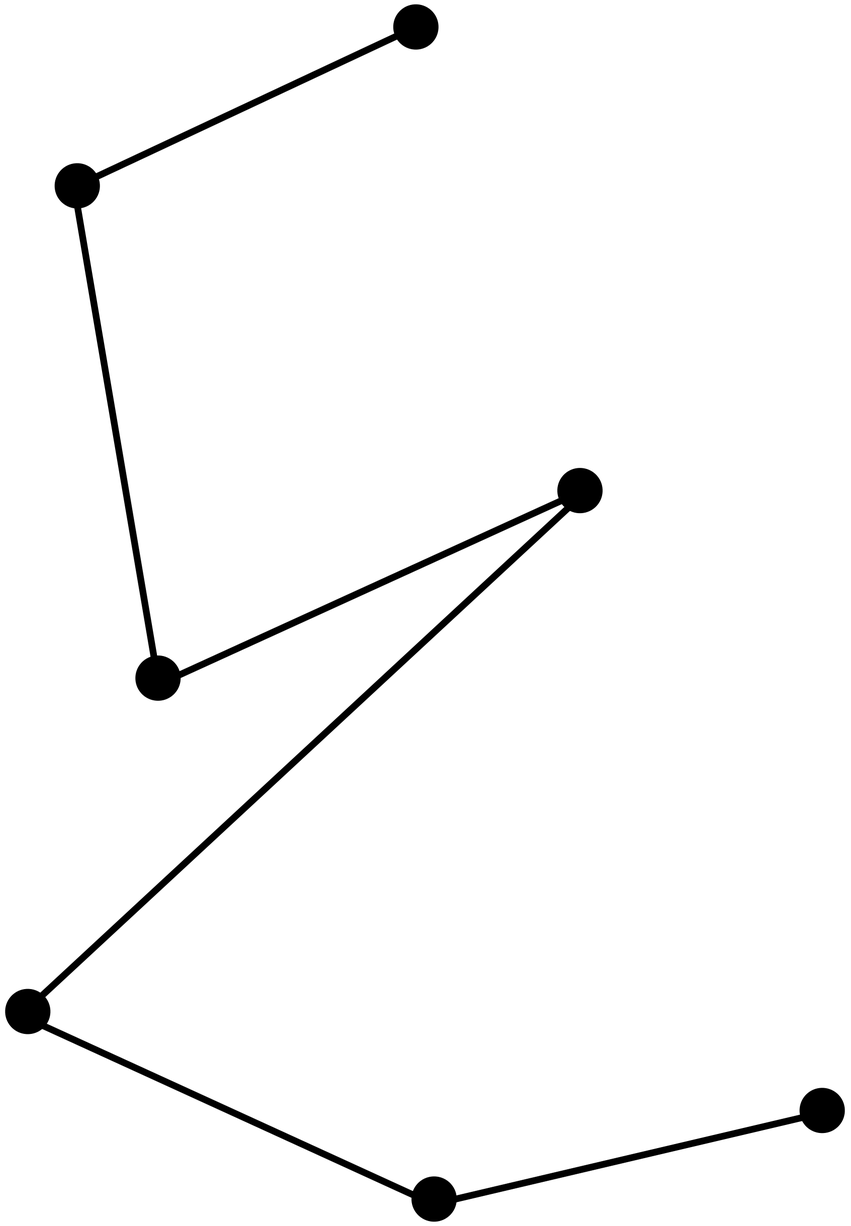
    $green \leftarrow sin(f \times index + \phi_g)$
    $blue \leftarrow sin(f \times index + \phi_b)$
    $push(colors, Color(red, blue, green))$
end for



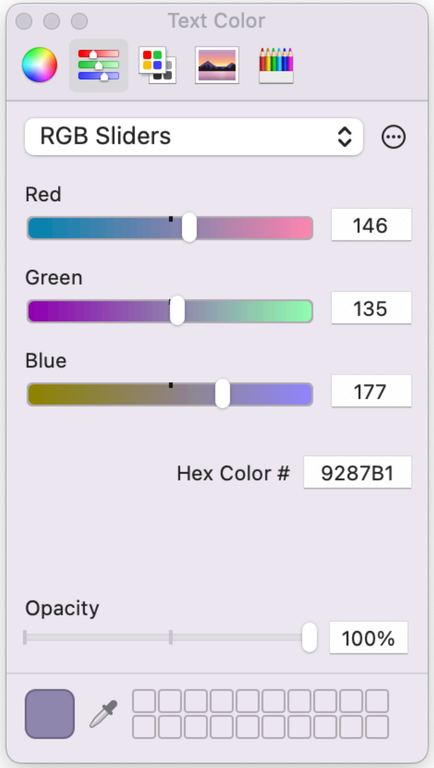


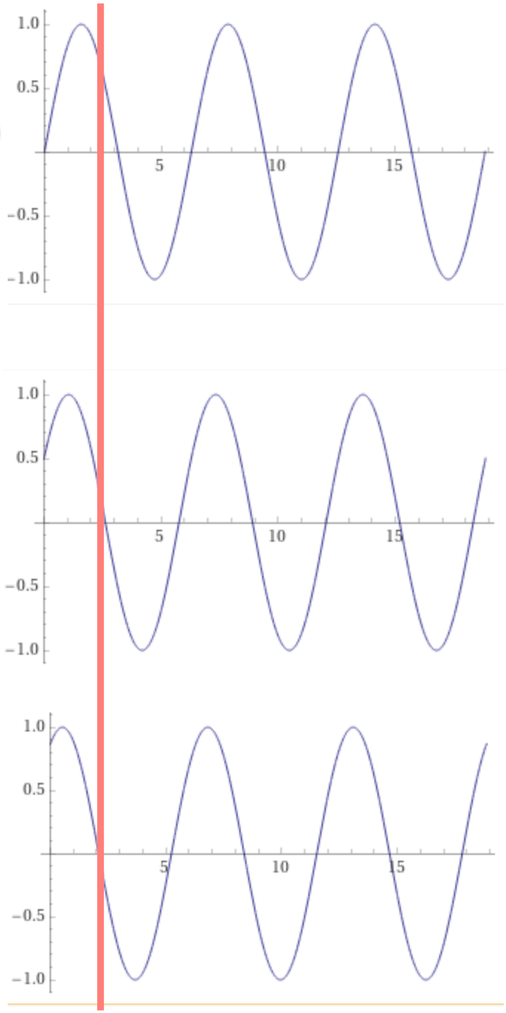


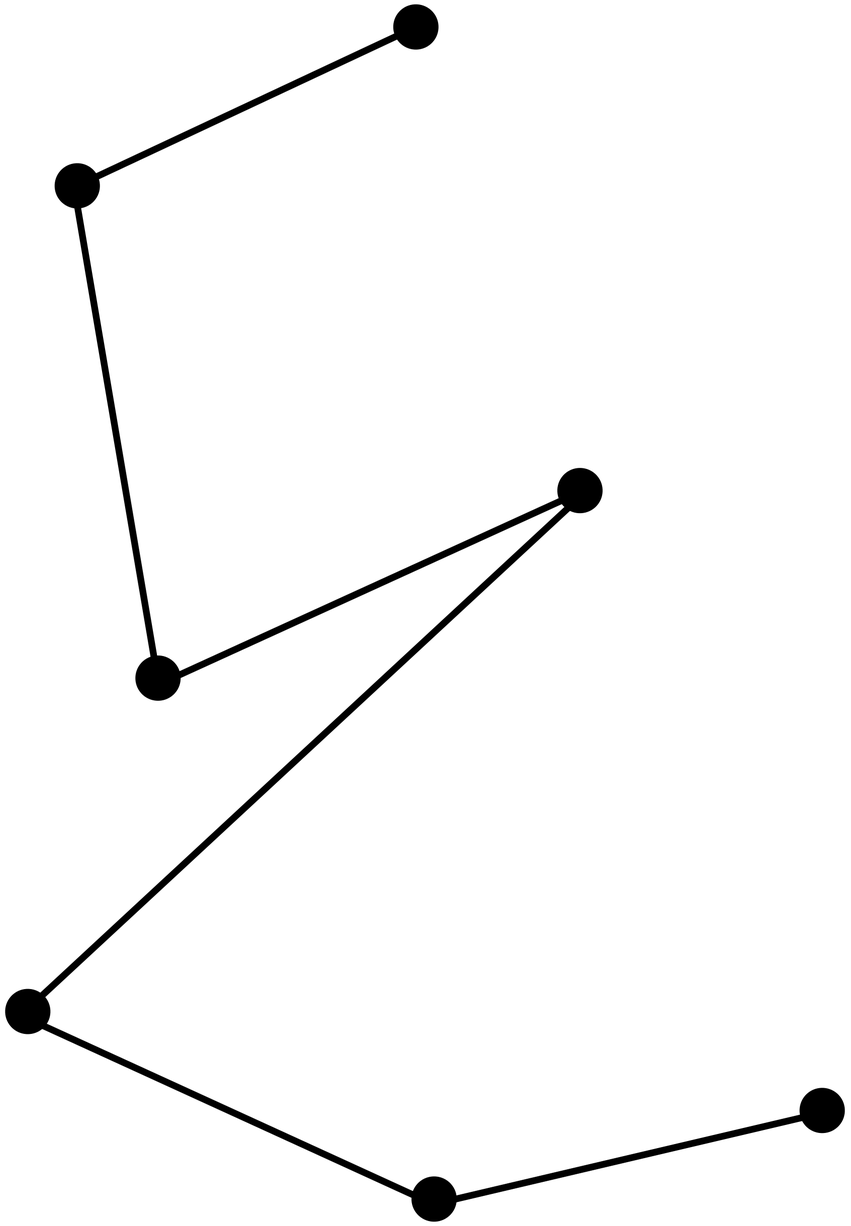




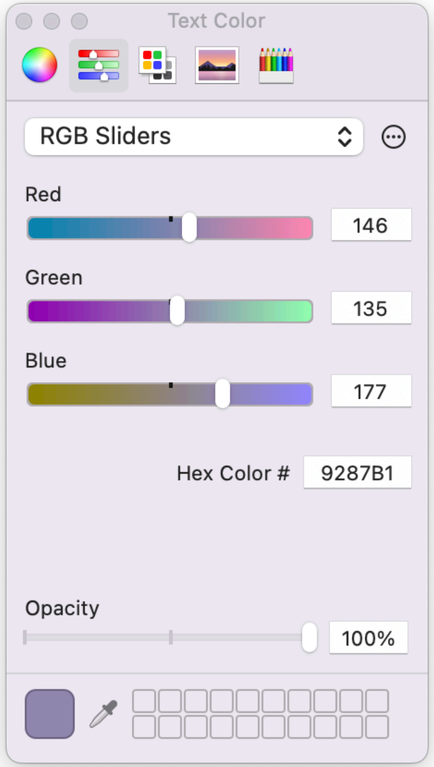
$colors \leftarrow [\ \ ]$
$f \leftarrow \ldots$ ▷ Choose a constant frequency for cycling colors.
$\phi_r, \phi_g, \phi_b \leftarrow \ldots$ ▷ Choose a constant phase offset per channel.
for $(\_, index)$ in $curve$ **do**
    $red \leftarrow sin(f \times index + \phi_r)$
    $green \leftarrow sin(f \times index + \phi_g)$
    $blue \leftarrow sin(f \times index + \phi_b)$
    $push(colors, Color(red, blue, green))$
end for

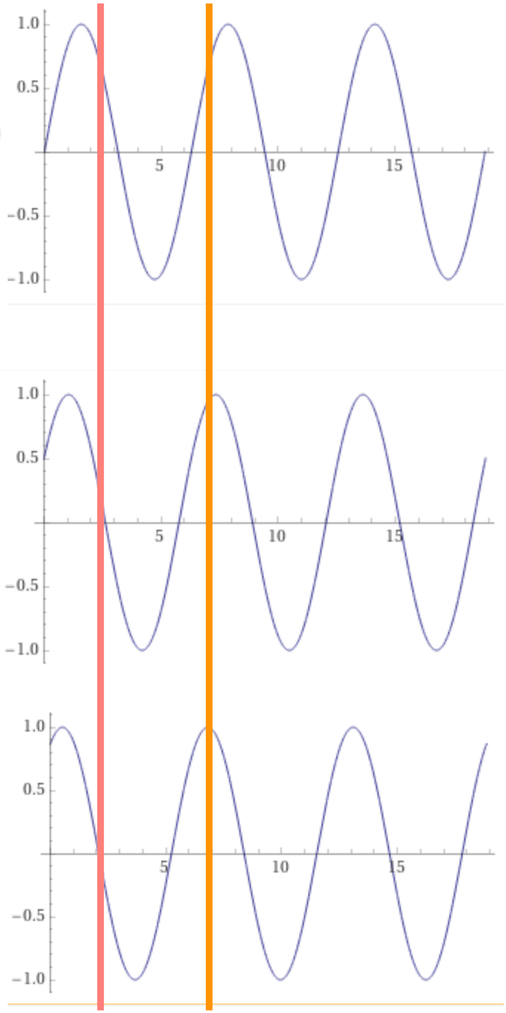


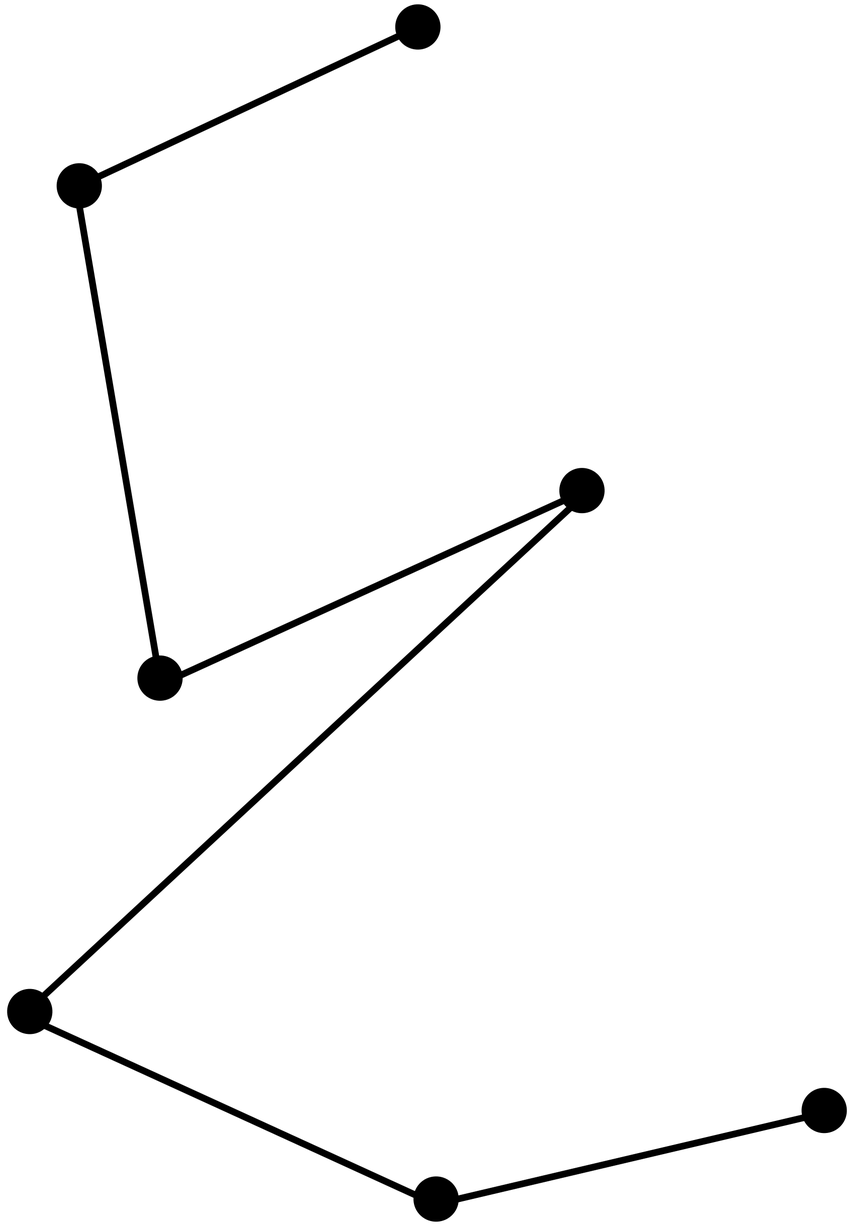




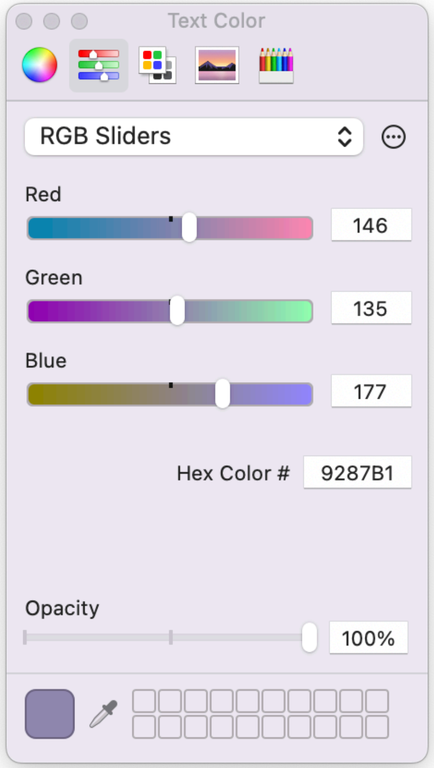
$colors \leftarrow [\ \ ]$
$f \leftarrow \ldots$ ▷ Choose a constant frequency for cycling colors.
$\phi_r, \phi_g, \phi_b \leftarrow \ldots$ ▷ Choose a constant phase offset per channel.
for $(\_, index)$ in $curve$ **do**
    $red \leftarrow sin(f \times index + \phi_r)$
    $green \leftarrow sin(f \times index + \phi_g)$
    $blue \leftarrow sin(f \times index + \phi_b)$
    $push(colors, Color(red, blue, green))$
end for

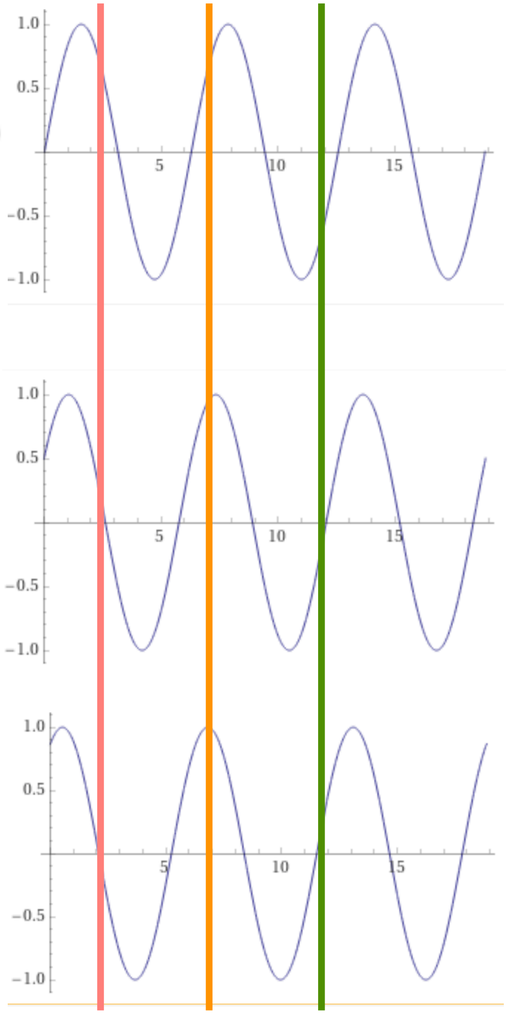


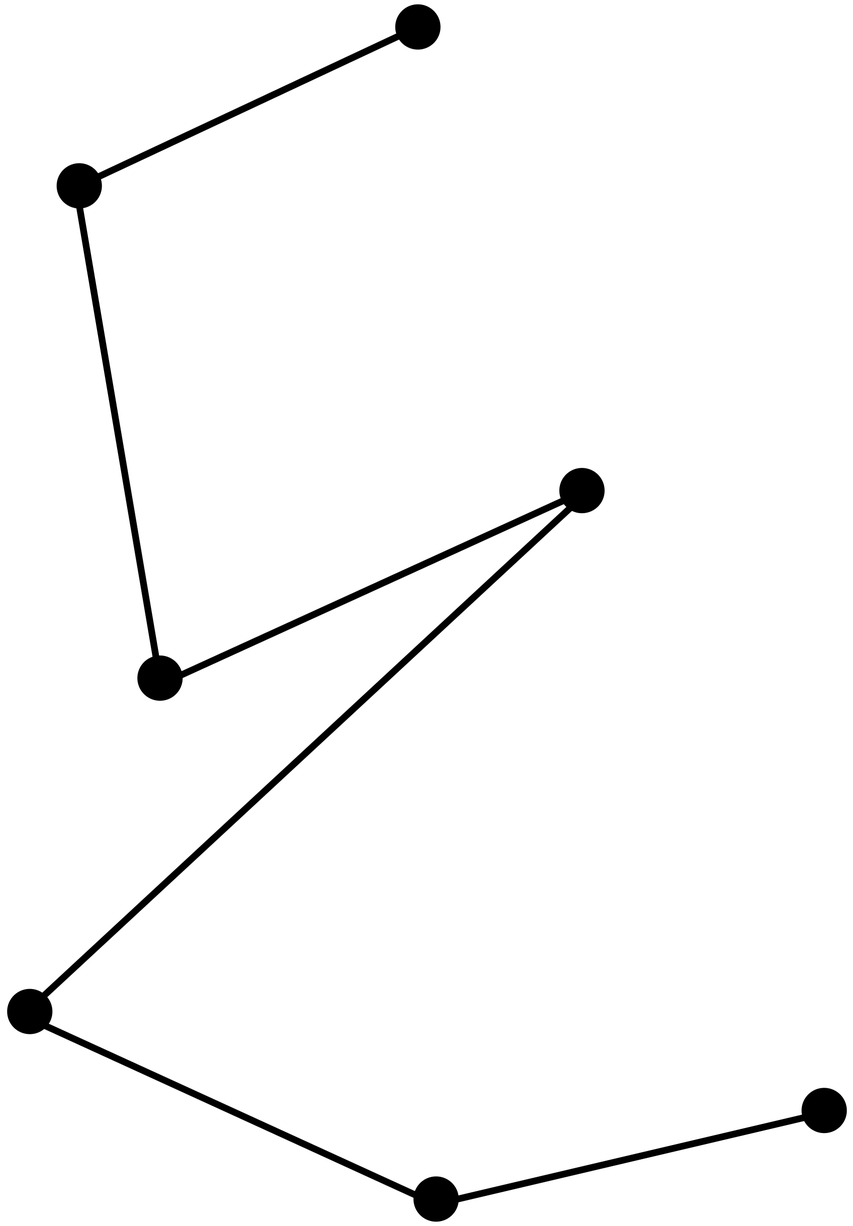




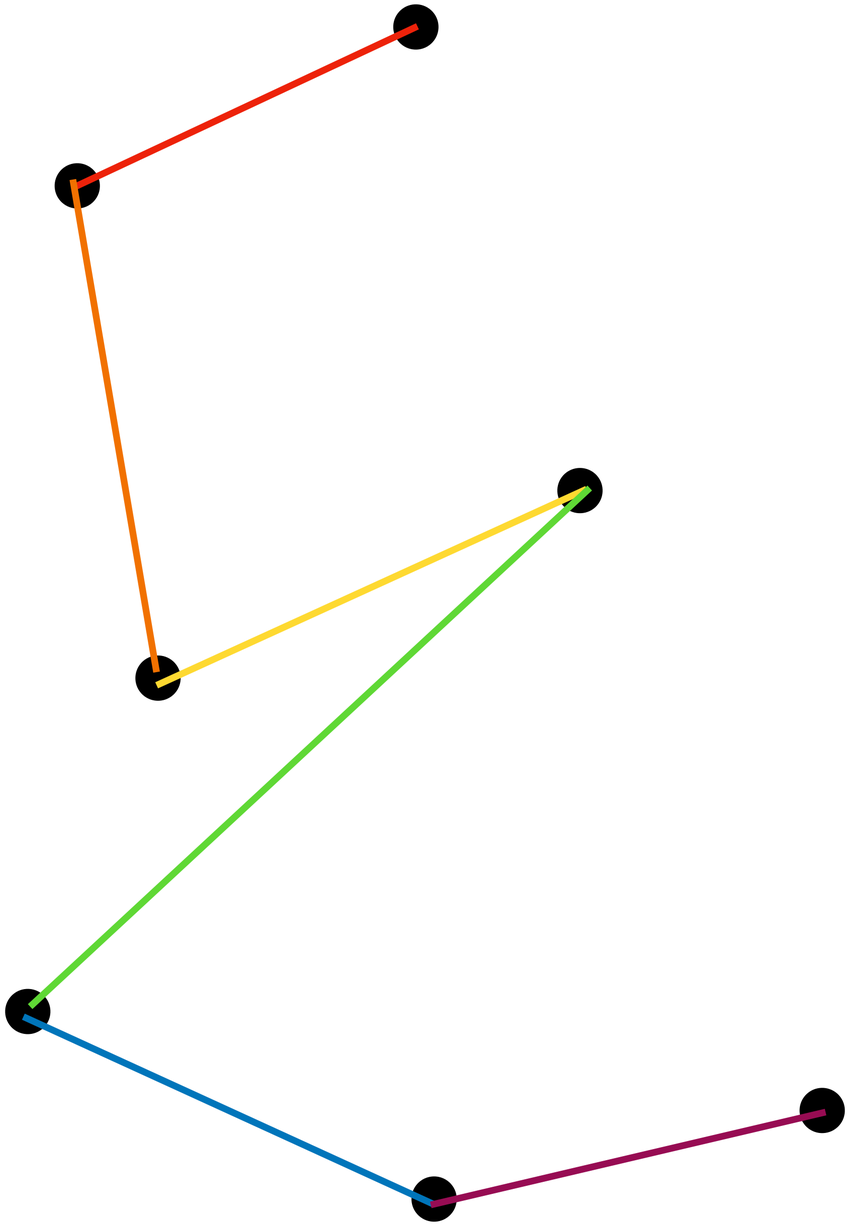
$colors \leftarrow [\ \ ]$
$f \leftarrow \ldots$ ▷ Choose a constant frequency for cycling colors.
$\phi_r, \phi_g, \phi_b \leftarrow \ldots$ ▷ Choose a constant phase offset per channel.
for $(\_, index)$ in $curve$ **do**
    $red \leftarrow sin(f \times index + \phi_r)$
    $green \leftarrow sin(f \times index + \phi_g)$
    $blue \leftarrow sin(f \times index + \phi_b)$
    $push(colors, Color(red, blue, green))$
end for



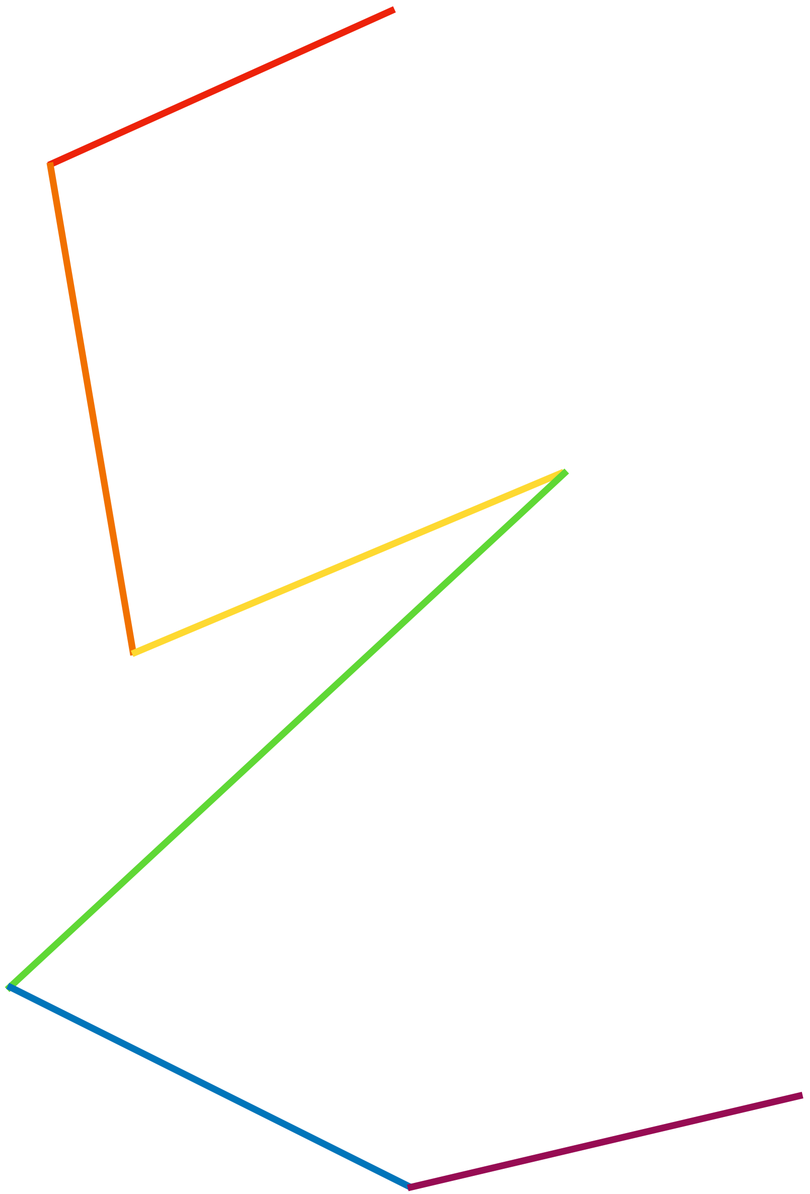




```
colors ← [ ]
f ← ...                ▷ Choose a constant frequency for cycling colors.
φ_r, φ_g, φ_b ← ...    ▷ Choose a constant phase offset per channel.
for (_, index) in curve do
    red ← sin(f × index + φ_r)
    green ← sin(f × index + φ_g)
    blue ← sin(f × index + φ_b)
    push(colors, Color(red, blue, green))
end for
```



```
meshes ← [ ]
for (segment, index) in curves do
    color ← colors[index]
    mesh ← Mesh(curve, color)
    push(meshes, mesh)
end for
return meshes
```



```
meshes ← [ ]
for (segment, index) in curves do
    color ← colors[index]
    mesh ← Mesh(curve, color)
    push(meshes, mesh)
end for
return meshes
```