PhD Dissertation Defense
05/13/2020

Dynamic Shape Construction and Transformation with Collective Elements

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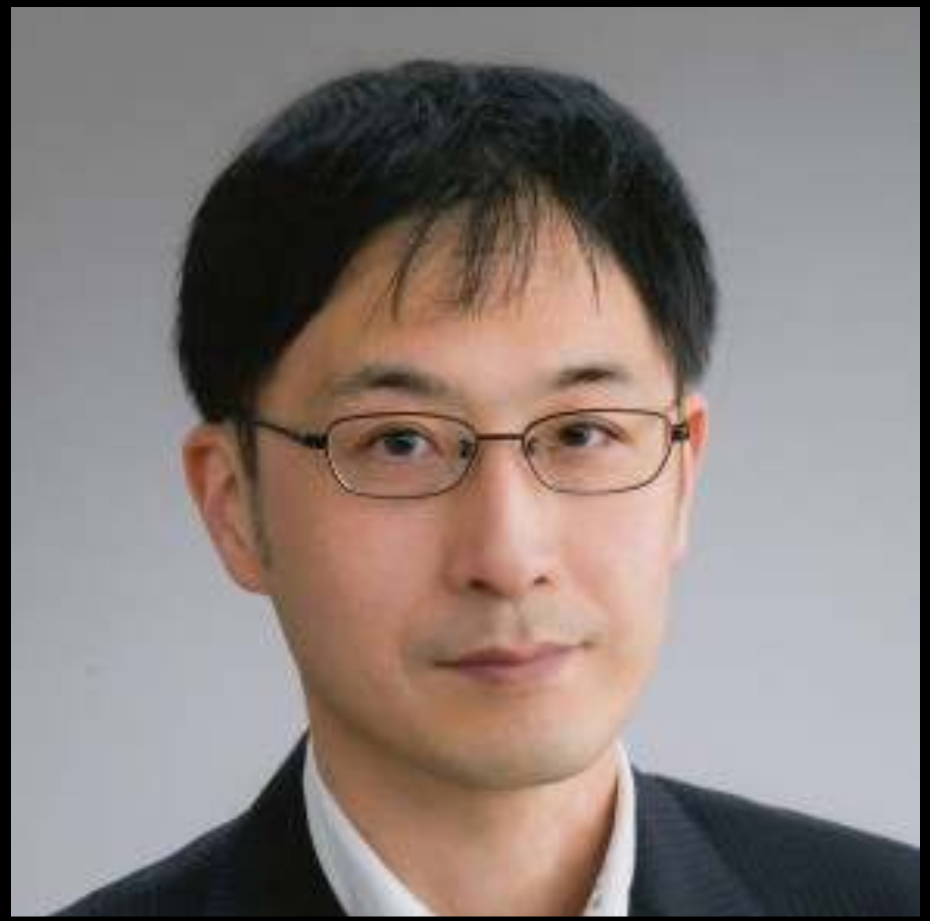

Takeo Igarashi
UTokyo

This thesis is about an exploration of ways to dynamically **physicalize** digital information from a computer screen, in the real world.

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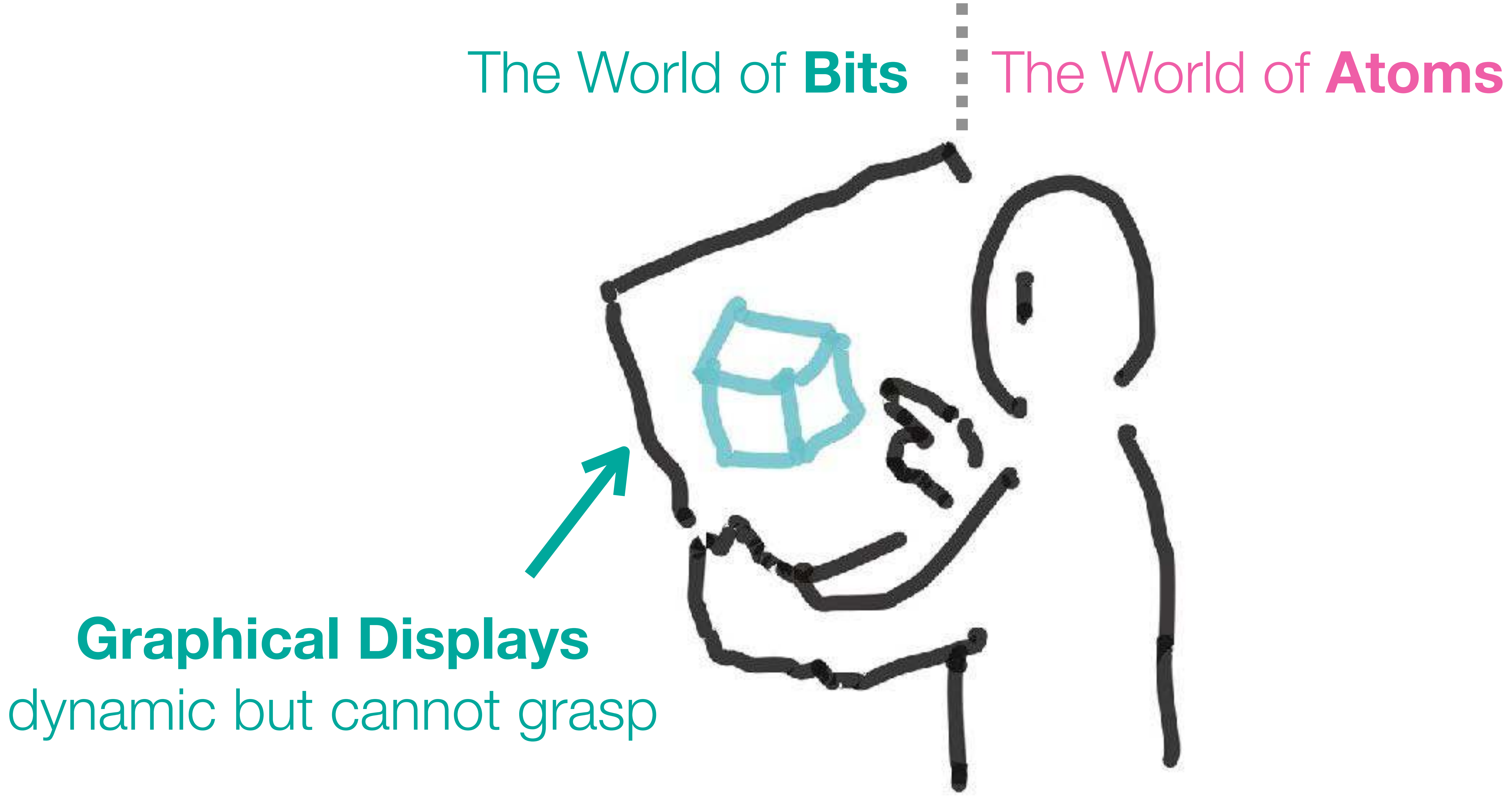
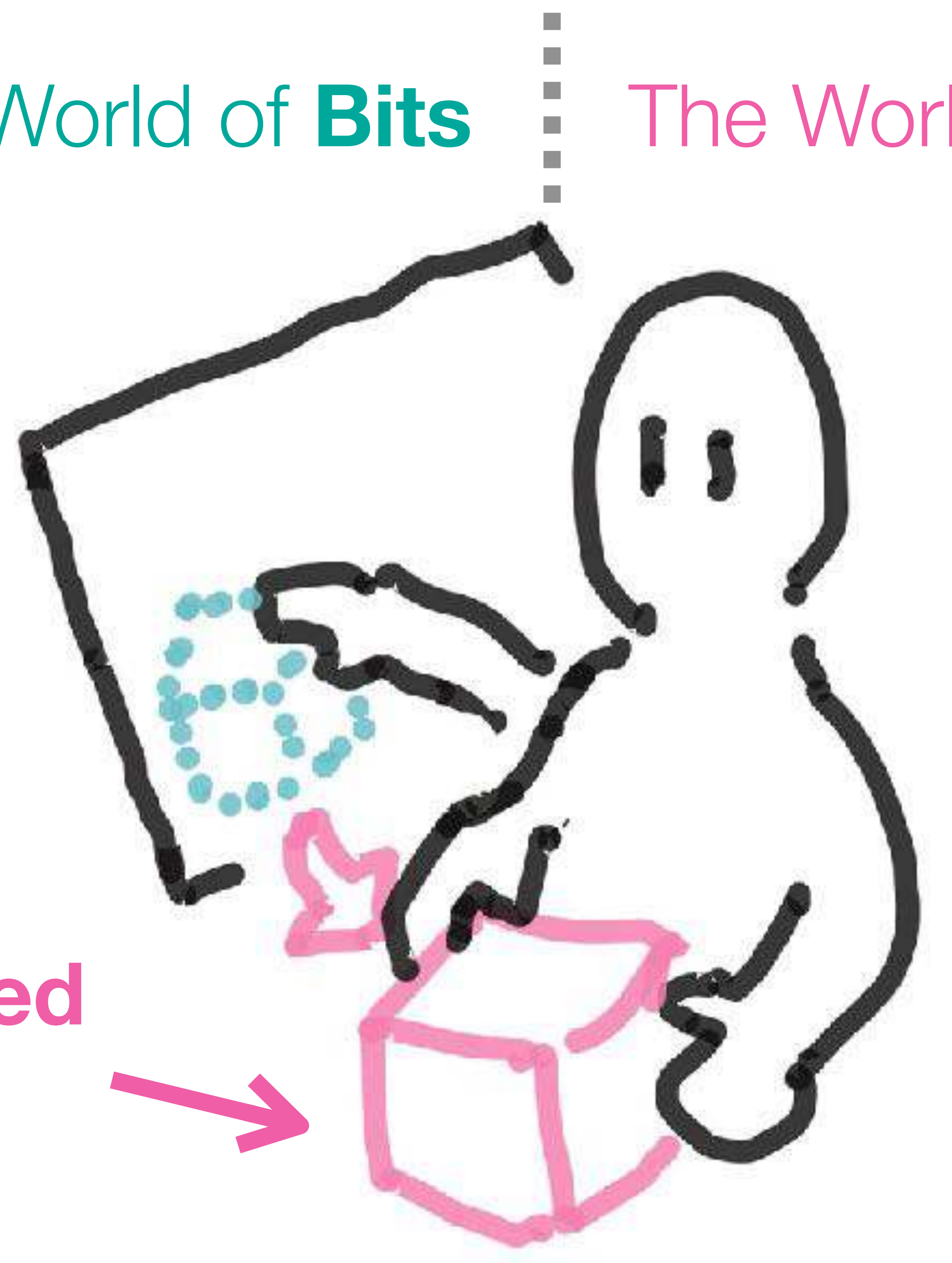


Today

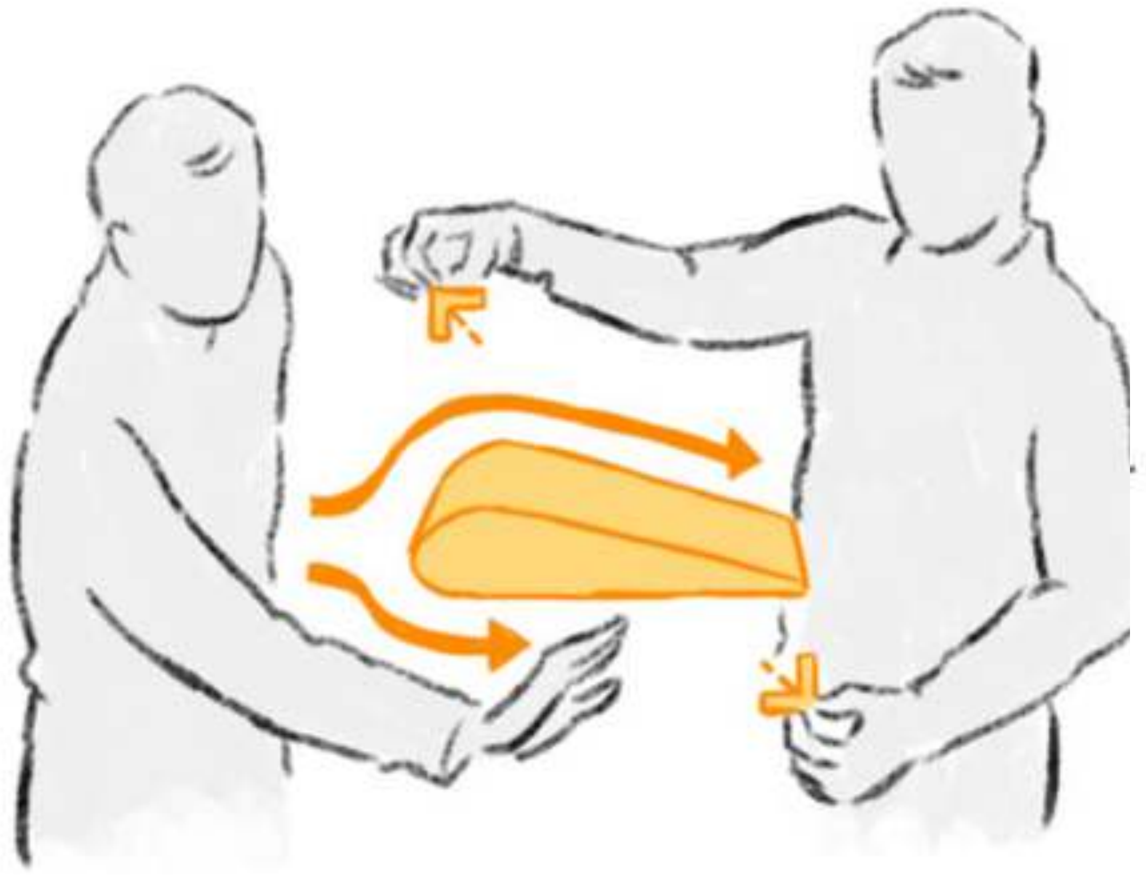
This thesis is about an exploration of ways to dynamically **physicalize** digital information from a computer screen, in the real world.



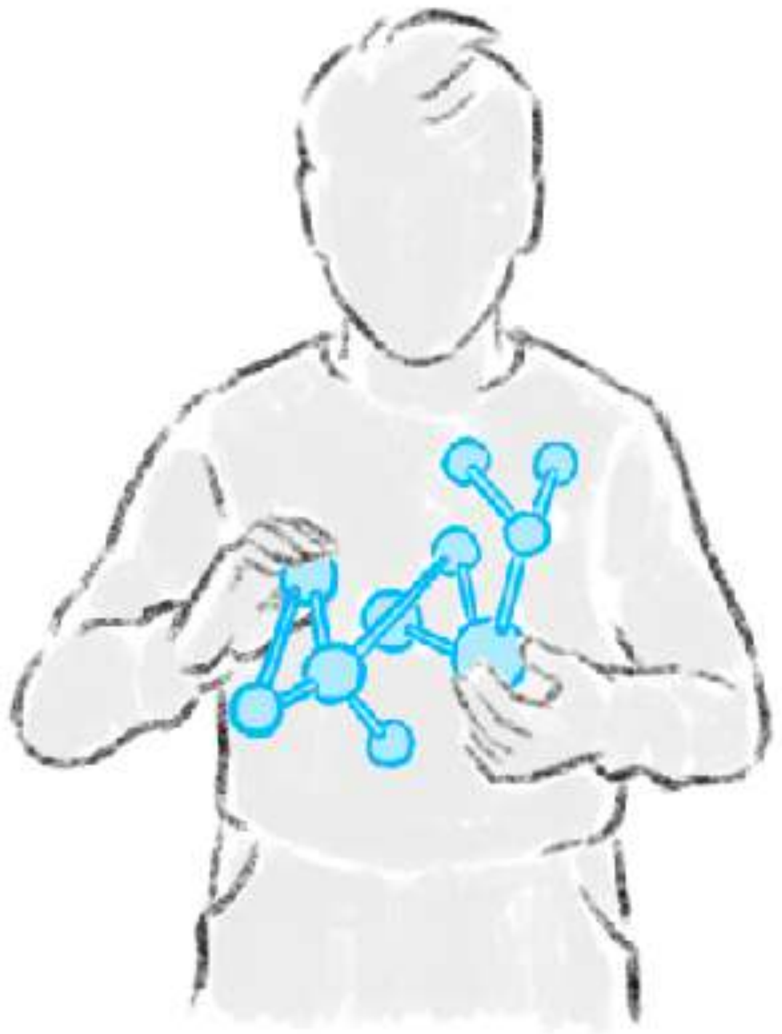
Tomorrow

Towards Dynamic Physical Media

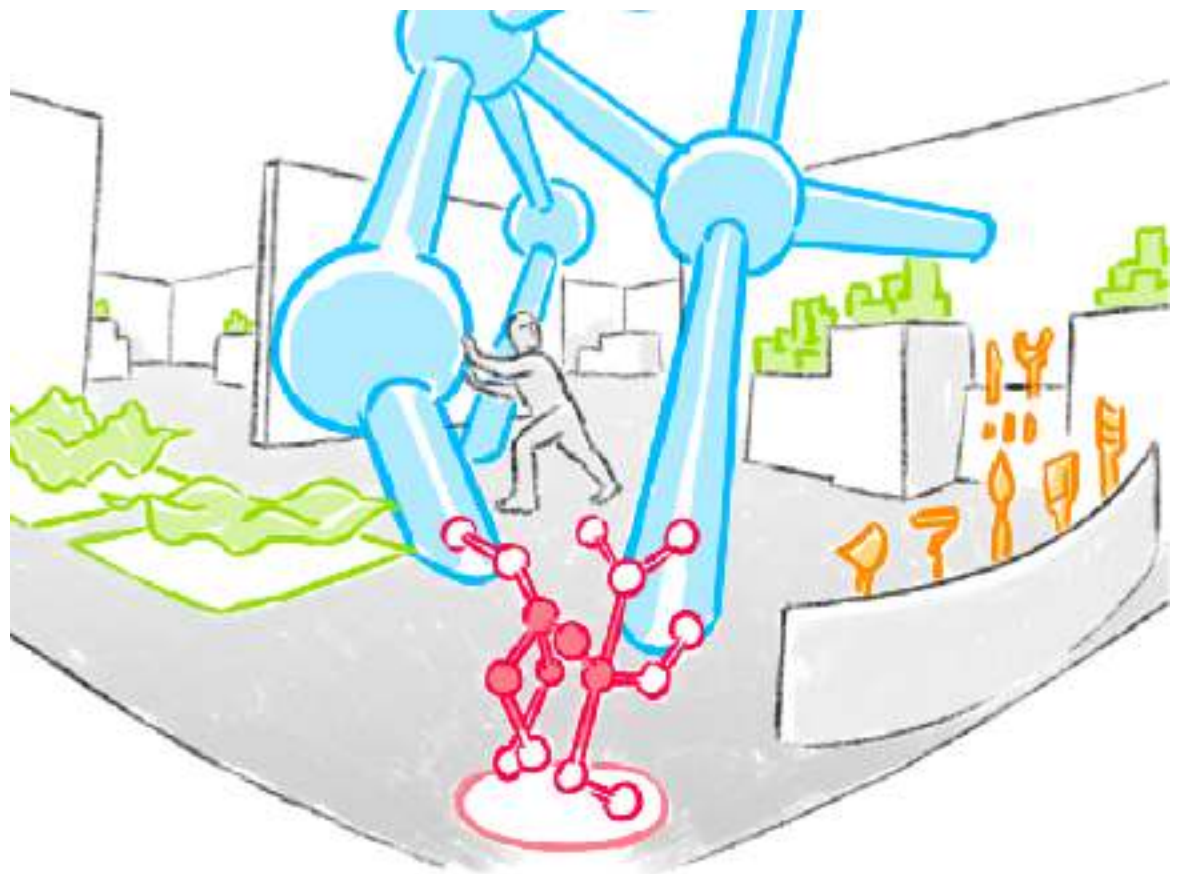
with which the user can touch, feel, grasp, and manipulate to think, design, explore, and collaborate.



dynamic physical object
to communicate



dynamic physical object
to think with

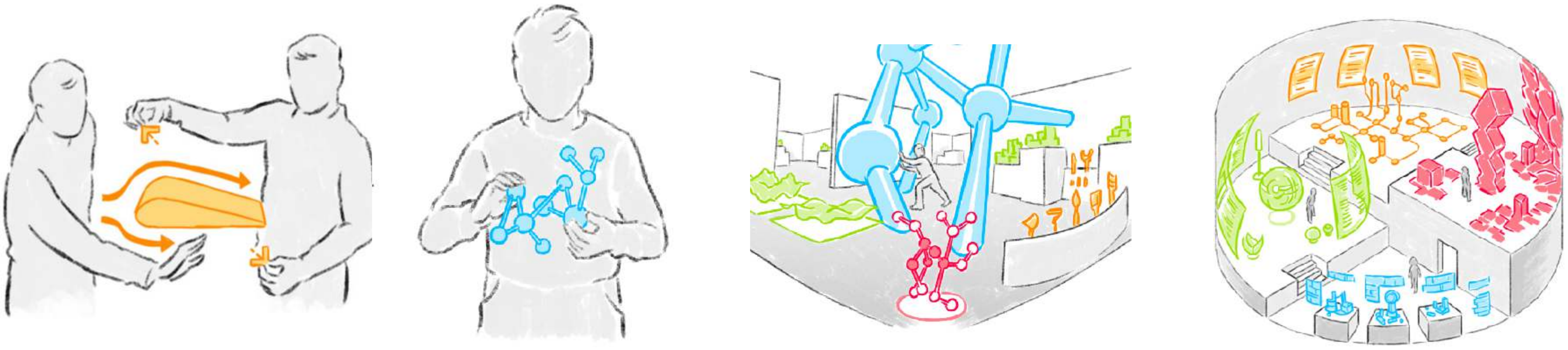


dynamic physical environment
to think

dynamic physical environment
to explore and collaborate

> *This is not AR, not VR, just R or Dynamic Reality*

[Images from Victor 2014: Humane Representation of Thought at UIST 2014 Keynote]

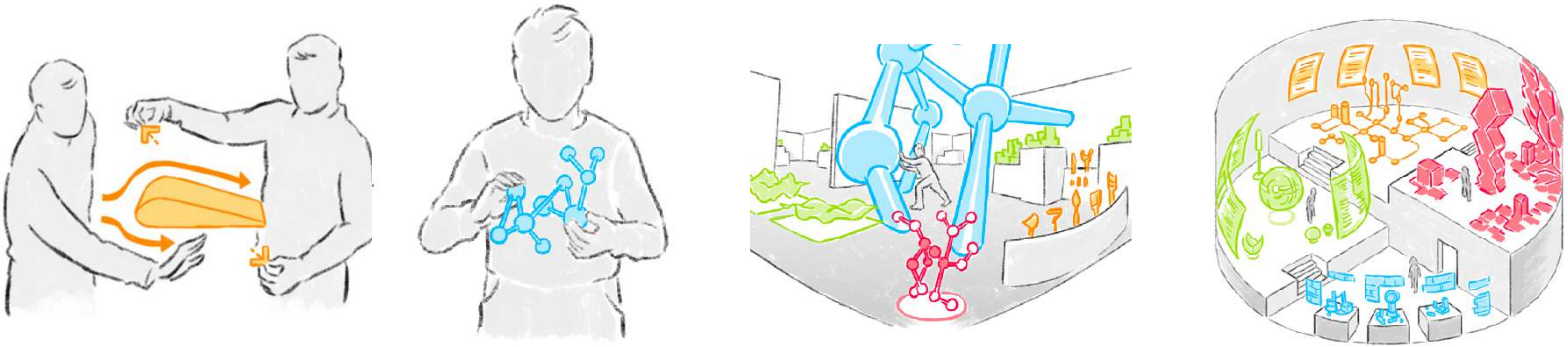


To achieve this goal, we need to develop

1) *general-purpose methods to transform arbitrary digital information into tangible, physical forms*

2) *interaction models to program and manipulate the dynamic physical objects and environments*

[Images from Victor 2014: Humane Representation of Thought at UIST 2014 Keynote]



As a first step, this thesis explores

1) ***dynamic and collective shape construction***
as a *general-purpose method* to physicalize dynamic digital information
2) ***interaction techniques*** *to program and manipulate dynamic collective elements through direct physical manipulations*

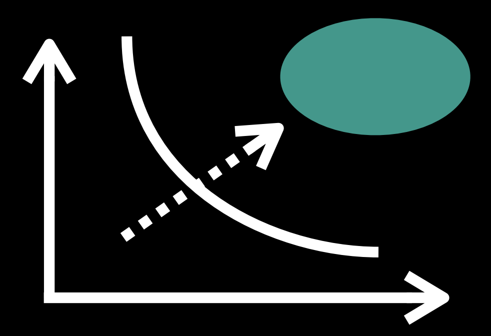
[Images from Victor 2014: Humane Representation of Thought at UIST 2014 Keynote]

Dynamic Shape Construction and Transformation with Collective Elements

Ryo Suzuki
University of Colorado Boulder

Background

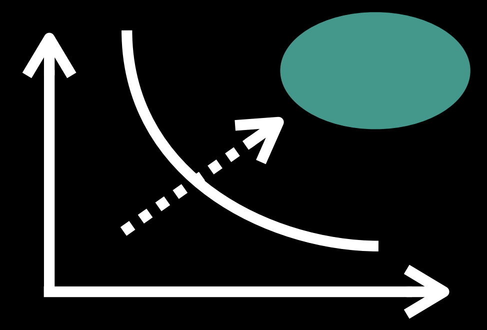
Why This Approach?



Background

Concept

Why This Approach?



What is
Dynamic and Collective
Shape Construction?

Background

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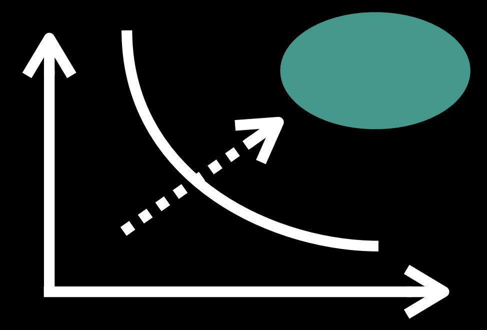

Concept

What is
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Shape Construction
with **Active** Elements

Shape Construction
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Interaction with
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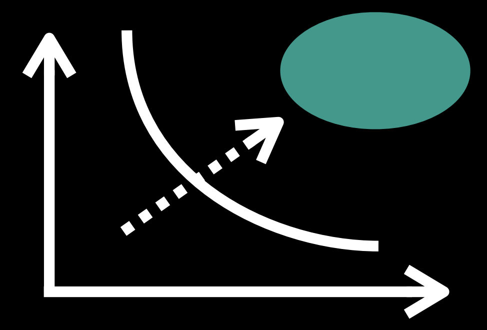

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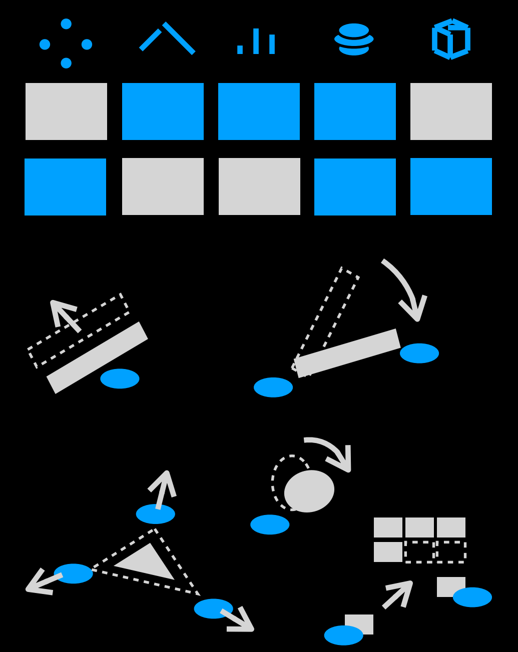

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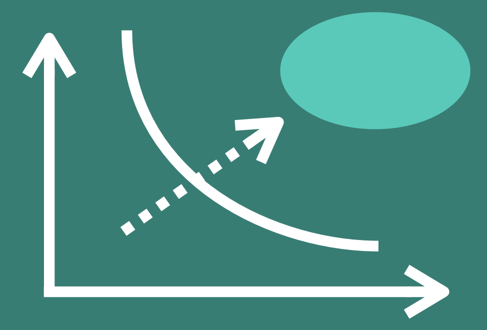

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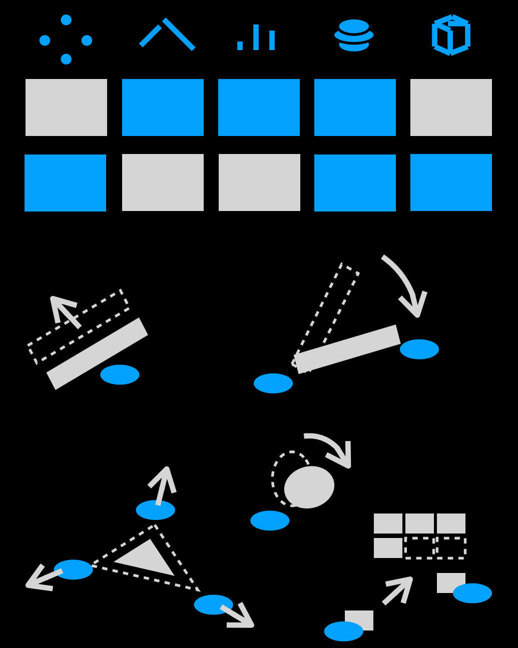


Digital World

Physical World

[Images from Victor 2015: Seeing Spaces]

These two worlds are **divided**

Digital World

Physical World

These two worlds are **divided**

Digital World

Physical World

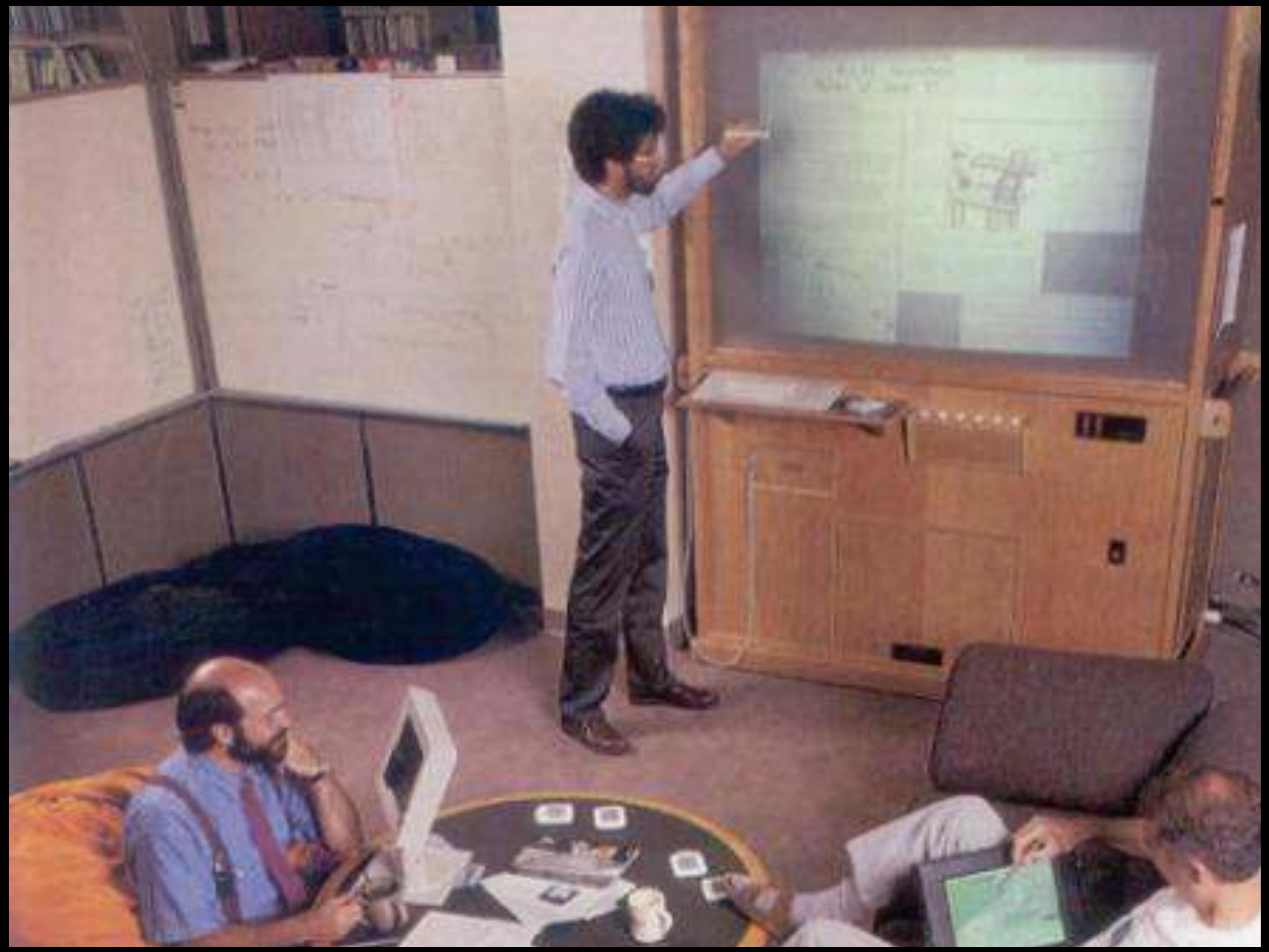
towards the **seamless integration** of digital and physical worlds

Physical World

Digital World

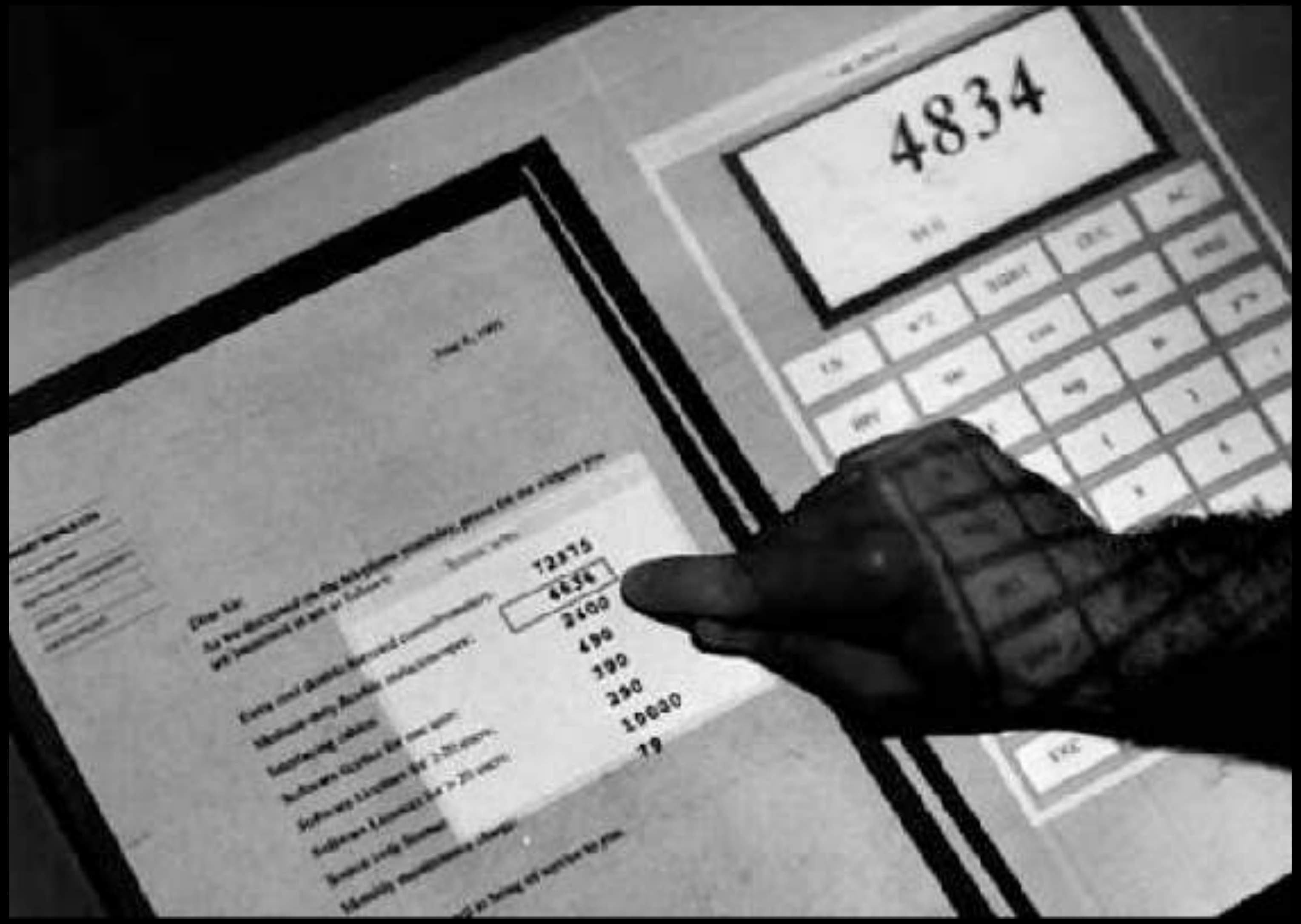
History of Human-Computer Interaction Research

rich history of bringing computation into the real world



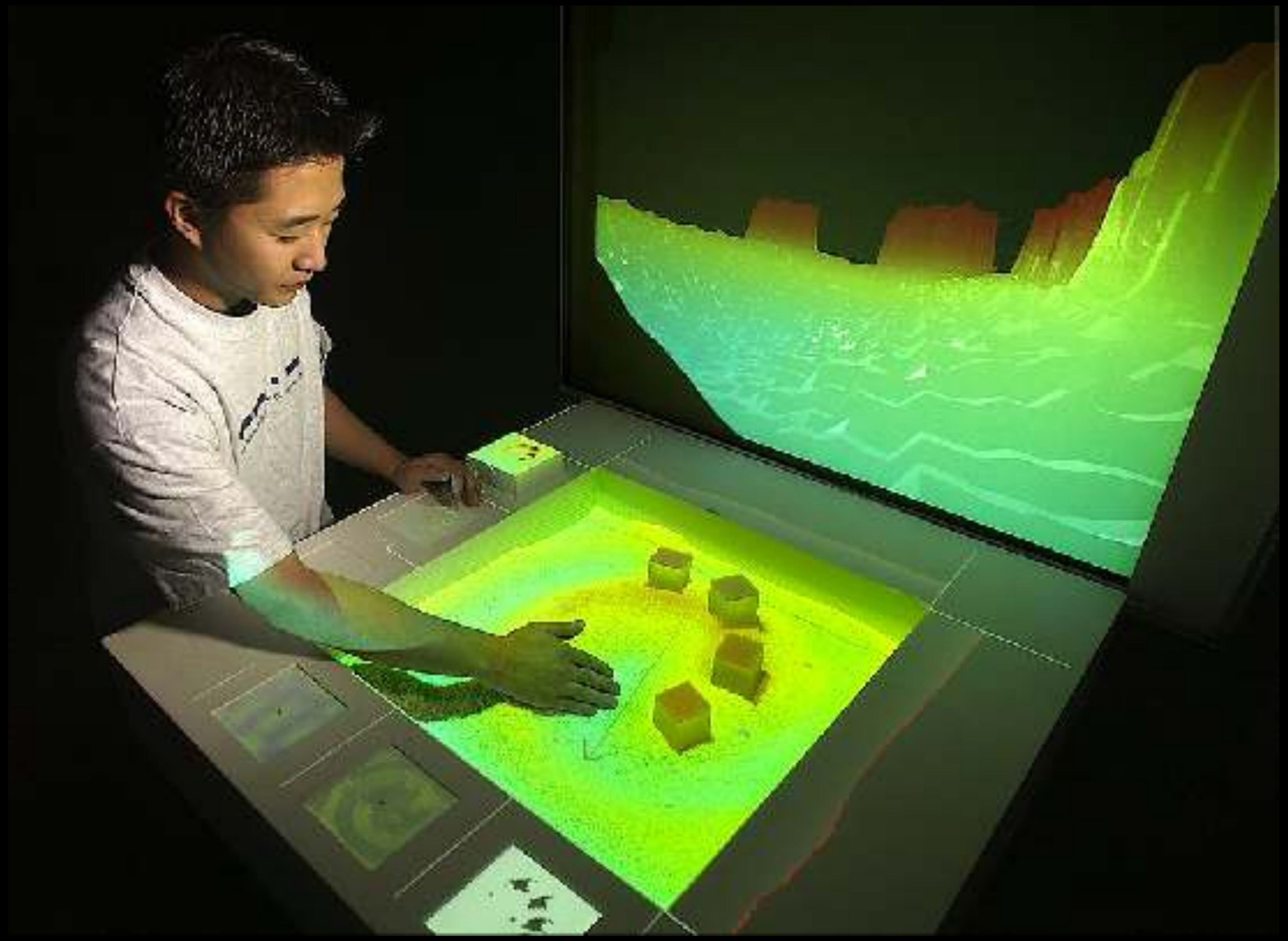
Calm Computing

[Ubiquitous Comp., Weiser 1991]



Augmented Reality

[DigitalDesk, Wellner 1993]

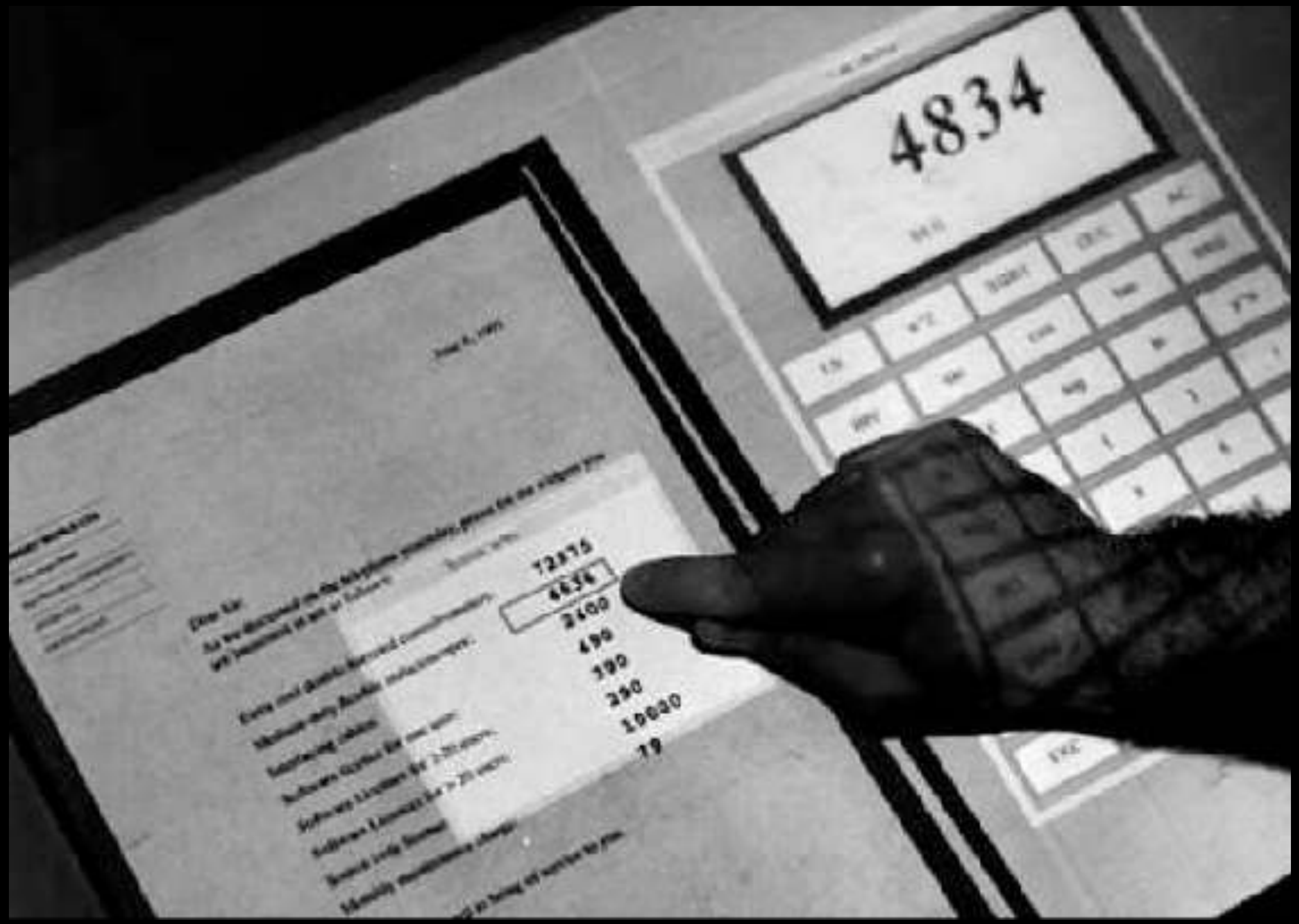


Tangible User Interfaces

[SandScape, Ishii 2004]

History of Human-Computer Interaction Research

more recently, researchers started to investigate dynamic physical UI



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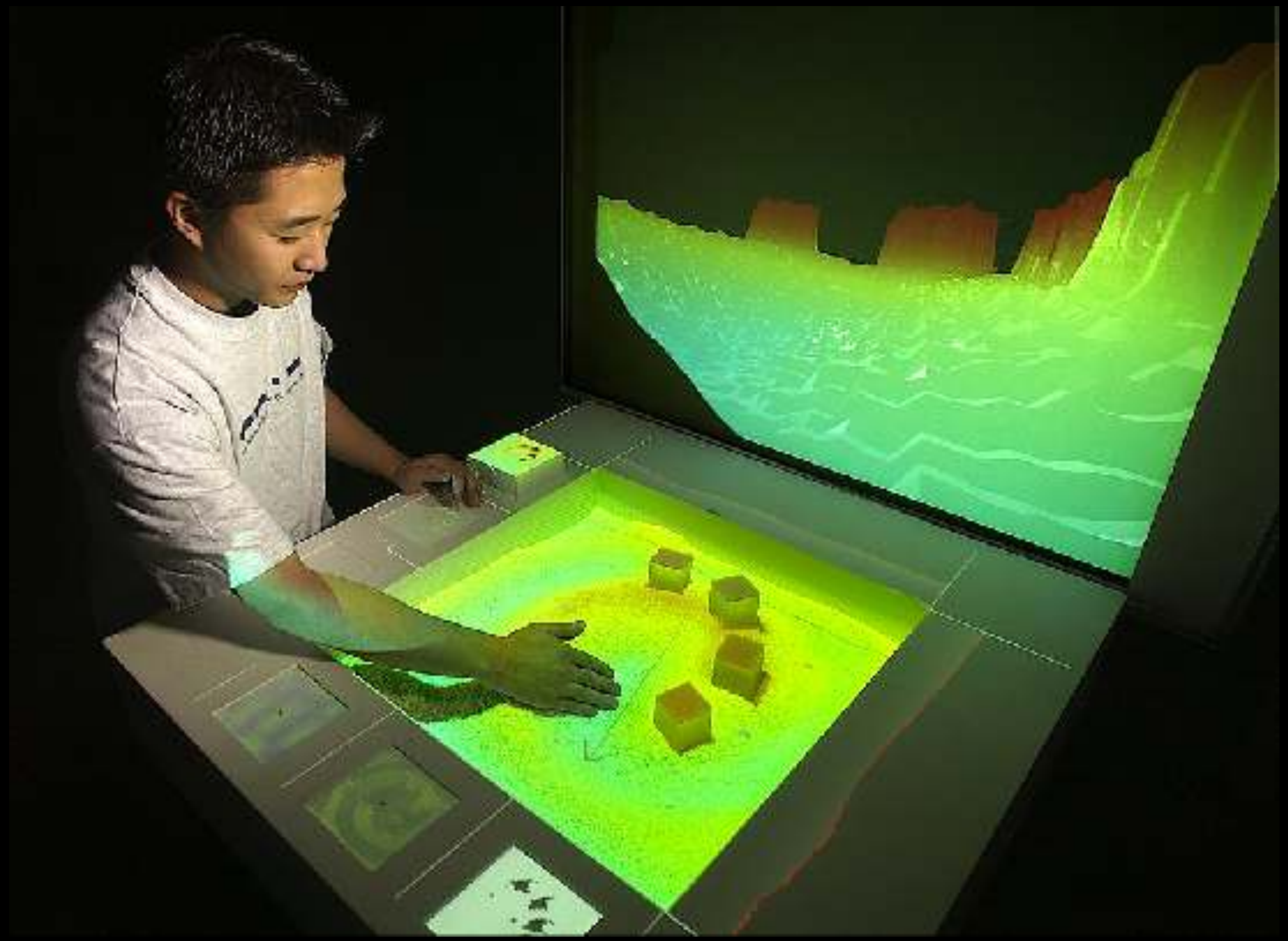
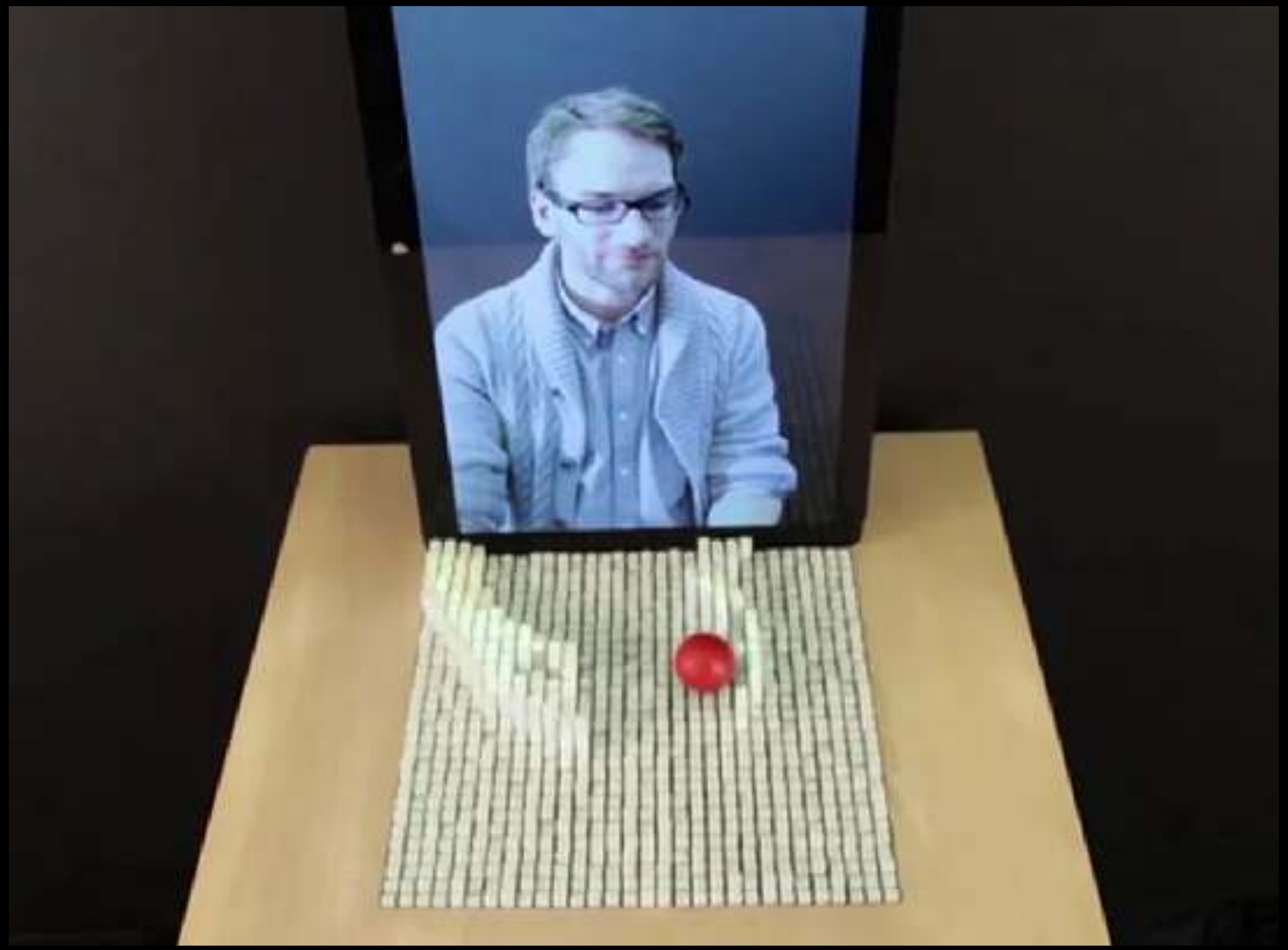
[DigitalDesk, Wellner 1993]



Tangible User Interfaces

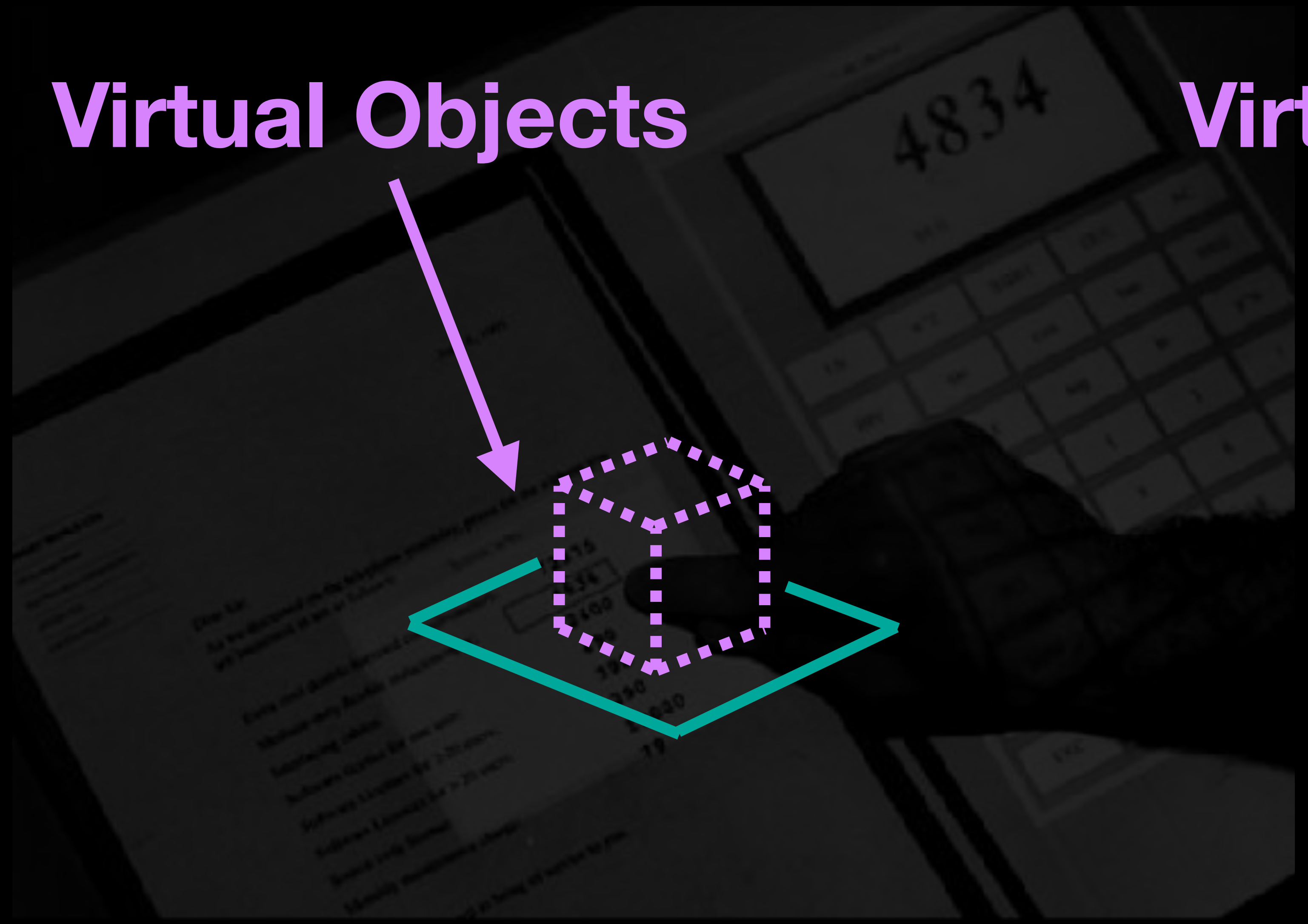
[SandScape, Ishii 2004]



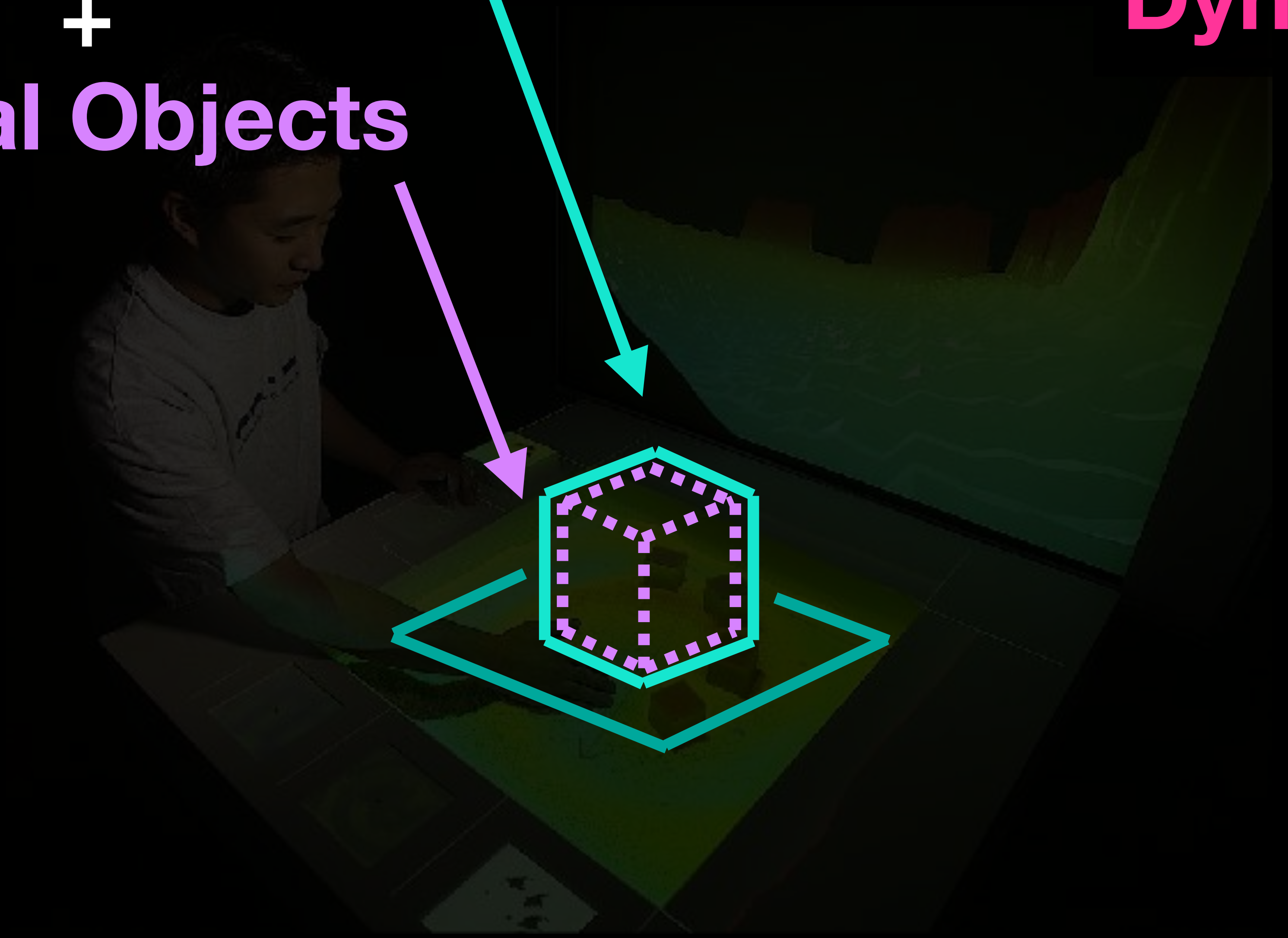
Shape-changing Interfaces

[inFORM, Follmer 2013]

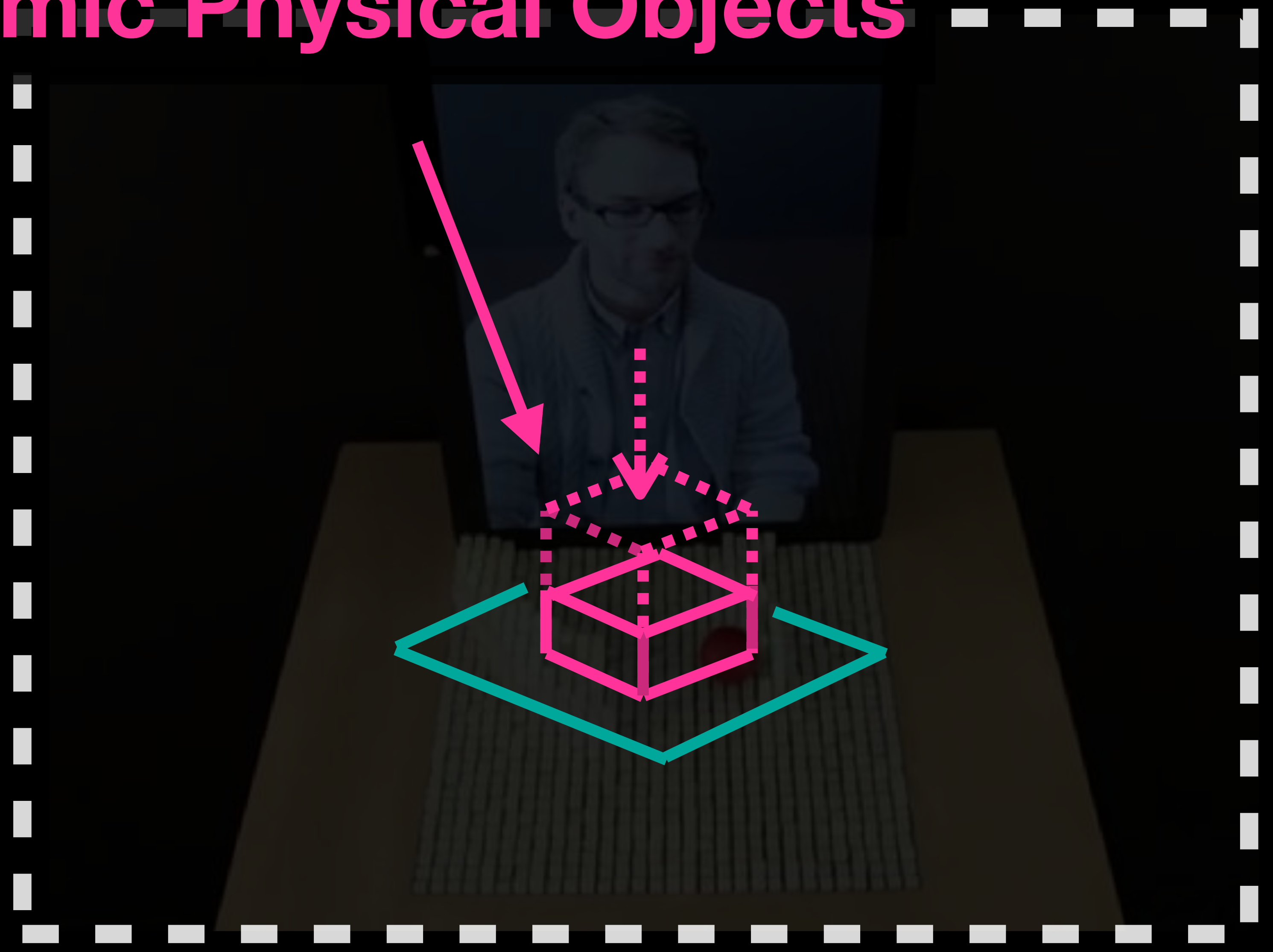
History of Human-Computer Interaction Research



Augmented Reality



Tangible User Interfaces



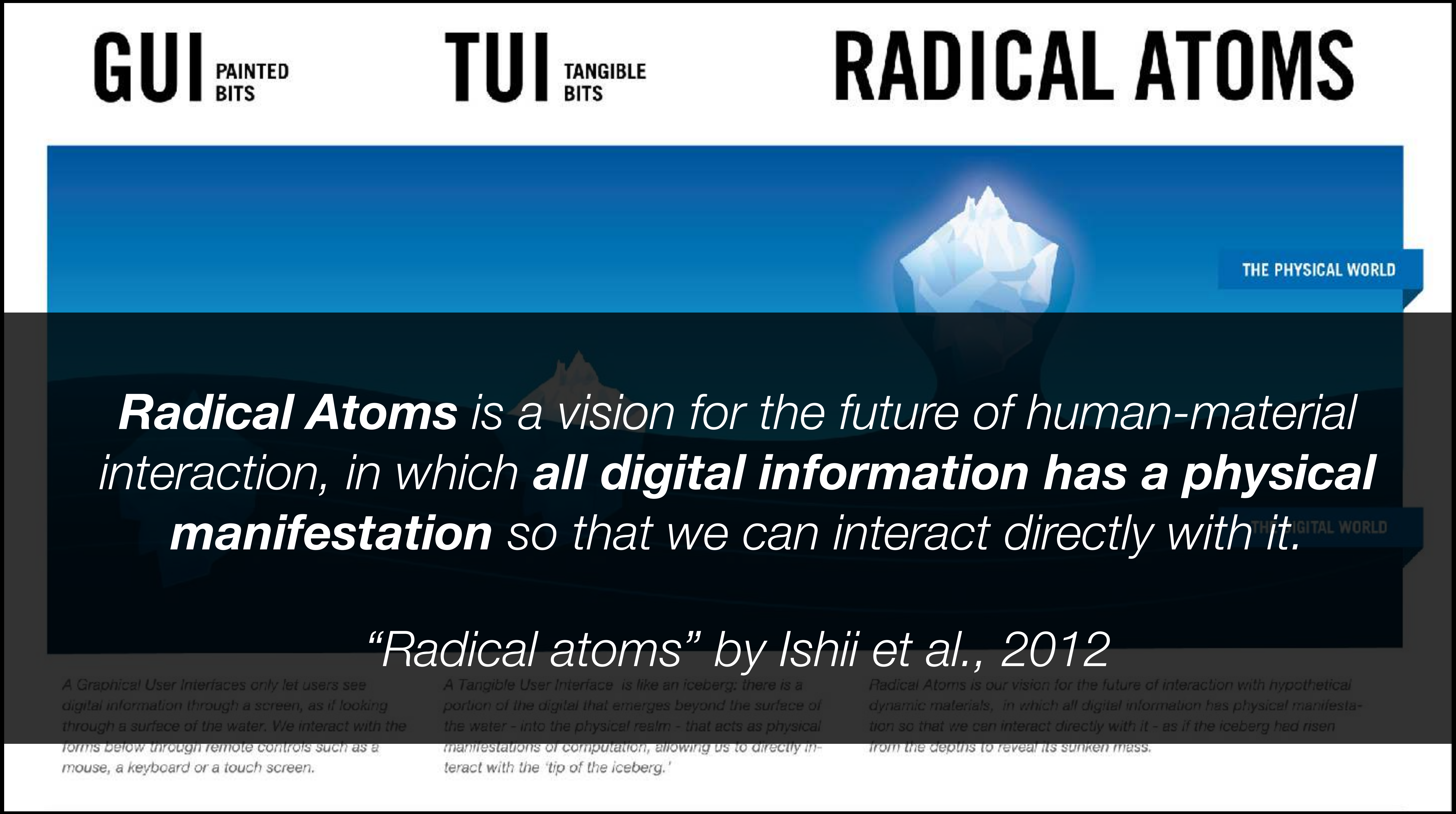
Shape-changing Interfaces

shape-changing interface research is inspired by the vision of

*“The **Ultimate Display** would, of course, be a room within which **the computer can control the existence of matter**.”*

“The Ultimate Display” by Ivan Sutherland, 1965

shape-changing interface research is inspired by the vision of

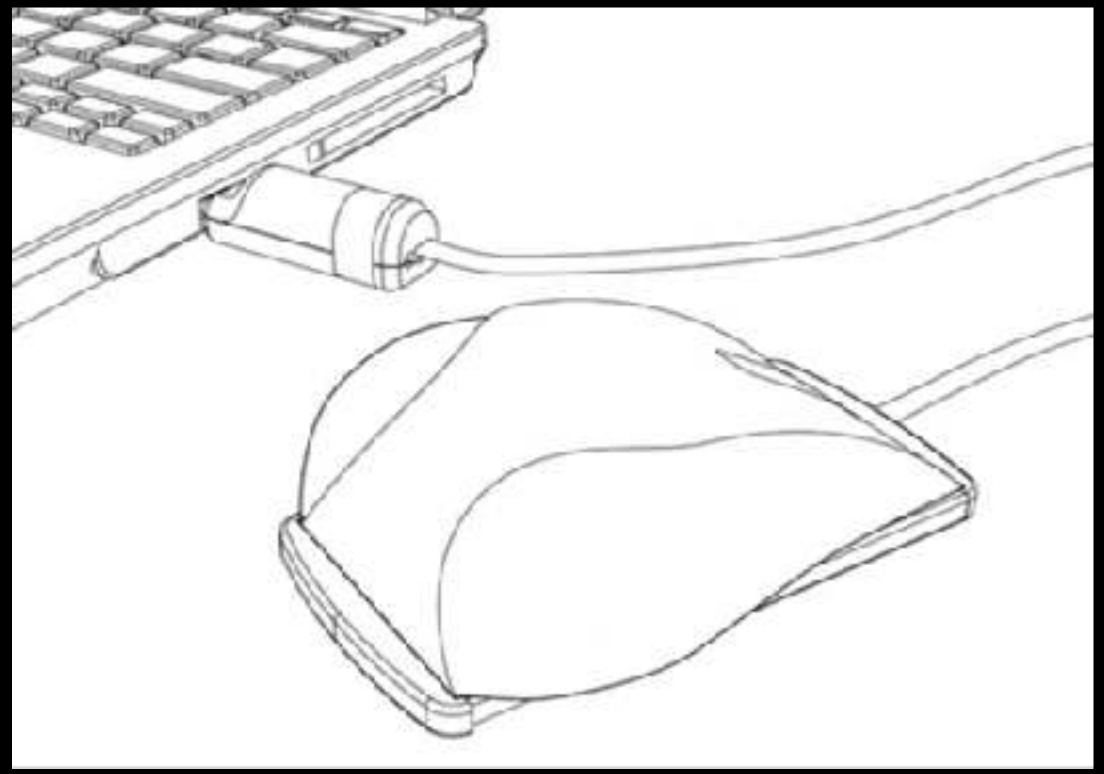


Radical Atoms *is a vision for the future of human-material interaction, in which* ***all digital information has a physical manifestation*** *so that we can interact directly with it.*

"Radical atoms" by Ishii et al., 2012

Shape-changing Interfaces

PneUI [Yao, UIST'13]



Inflatable Mouse [Kim, CHI'08]

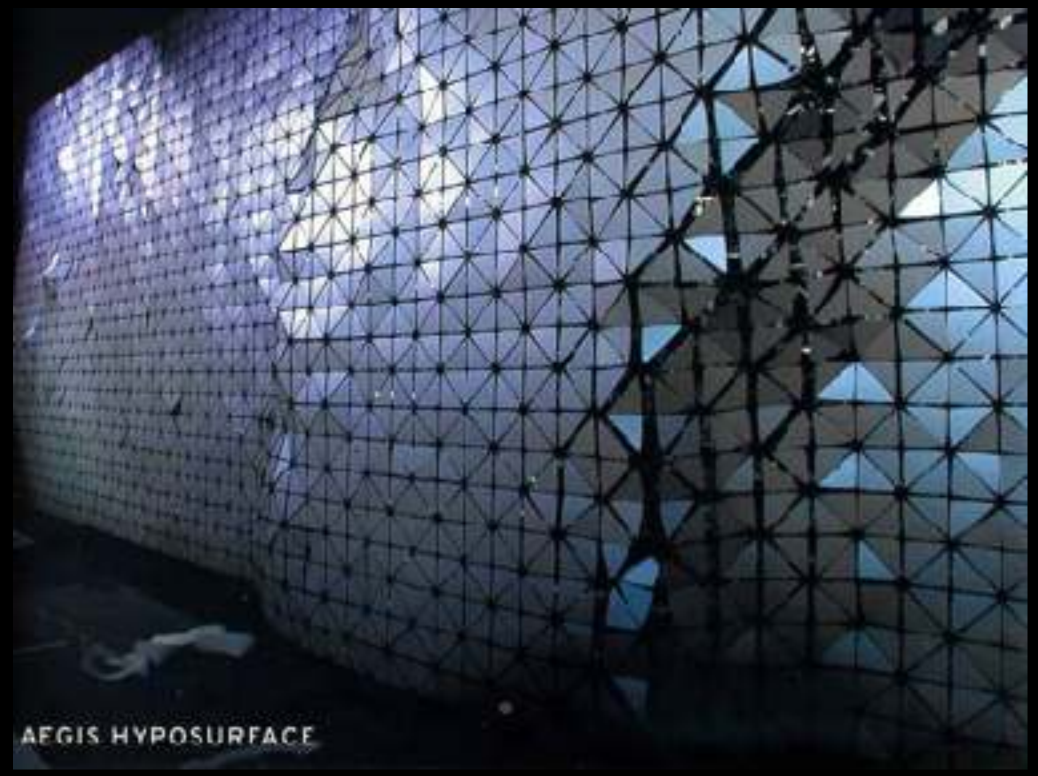
inFORM [Follmer, UIST'13]

BMW Museum [Art+Com '08]

Thrifty Faucet [Togler, TEI'09]

Bendi [Park, CHI'15]

Lumen [Poupyrev '04]



HypoSurface [Goulthorpe '01]

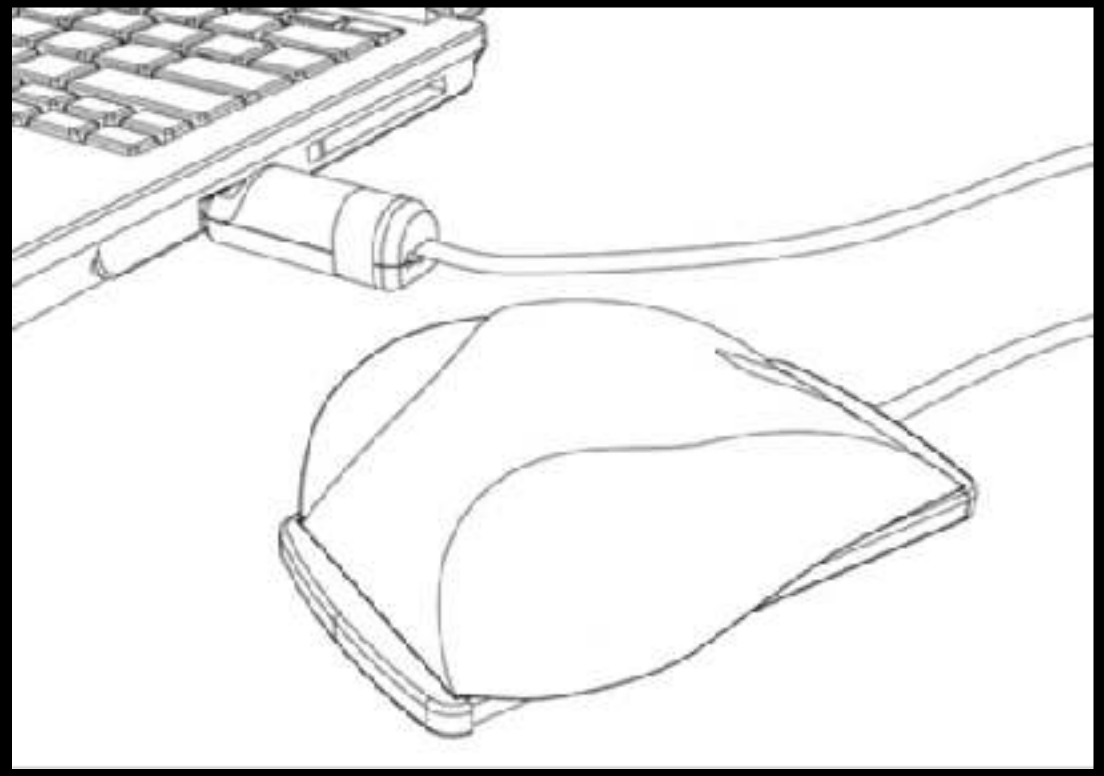
special-purpose
shape-changing interfaces

↔

general-purpose
shape-changing interfaces

Shape-changing Interfaces

PneUI [Yao, UIST’13]



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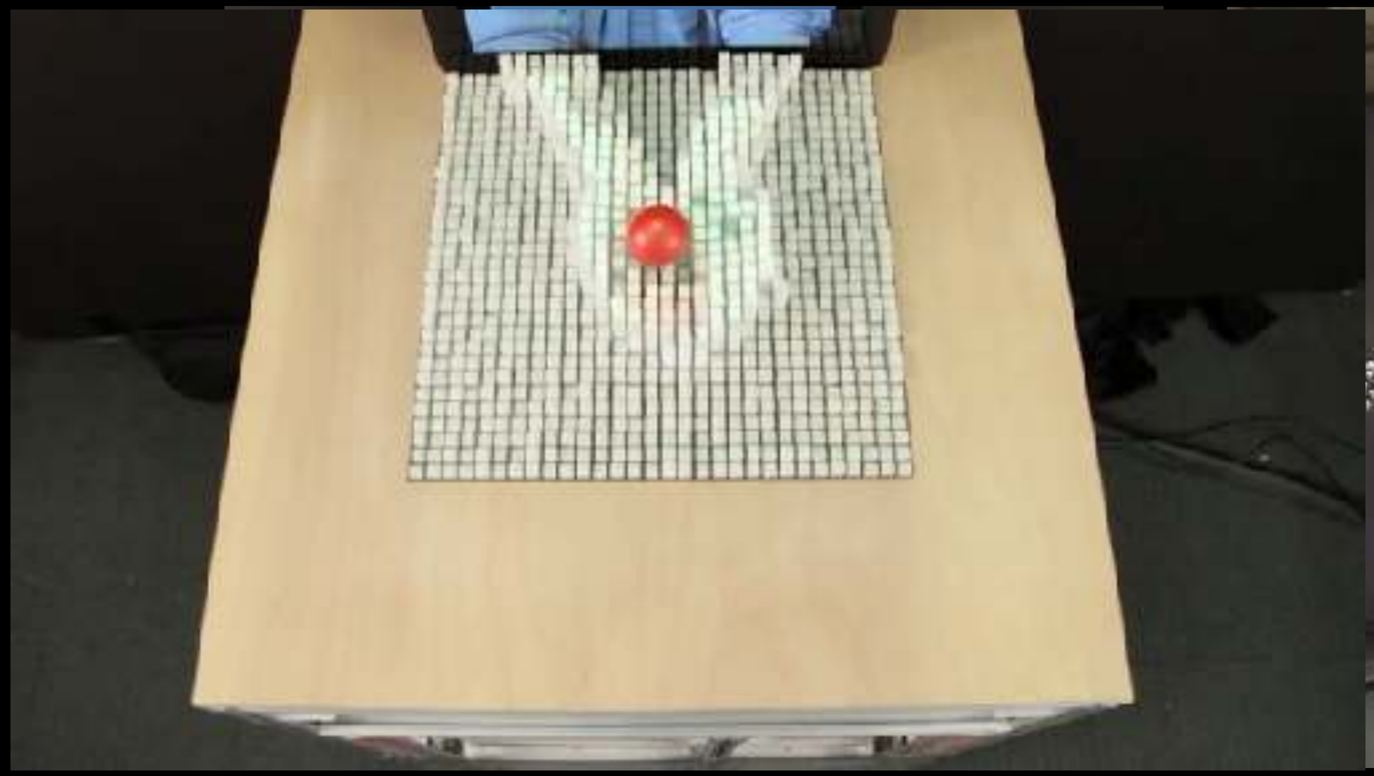

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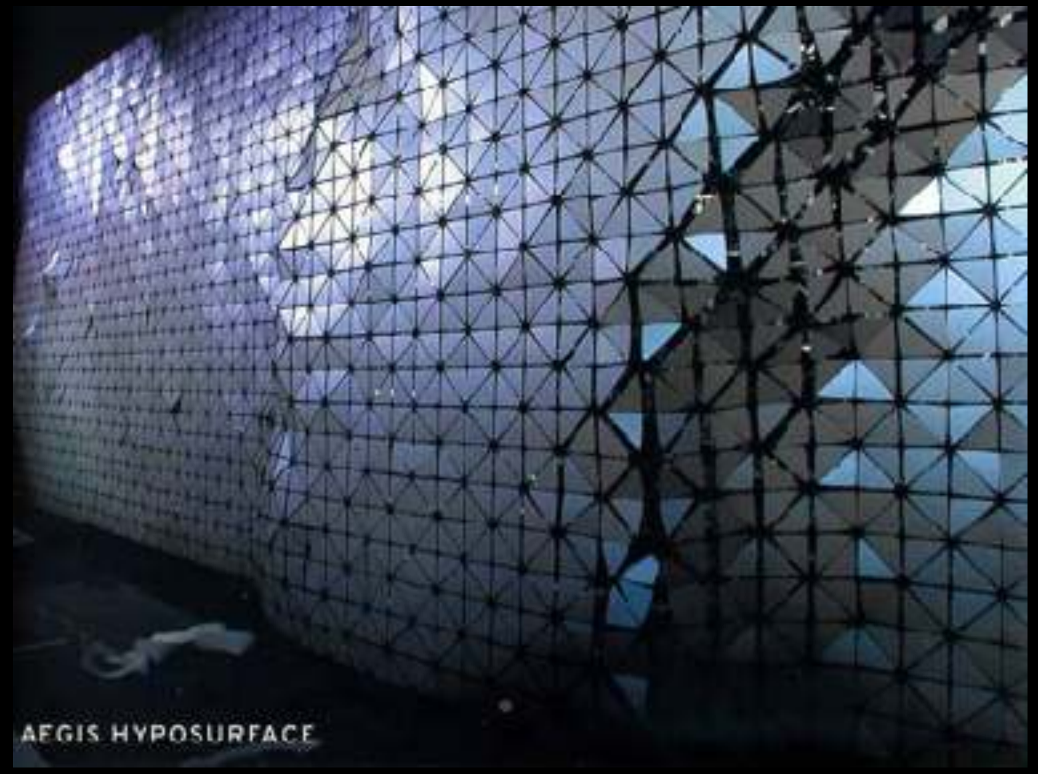
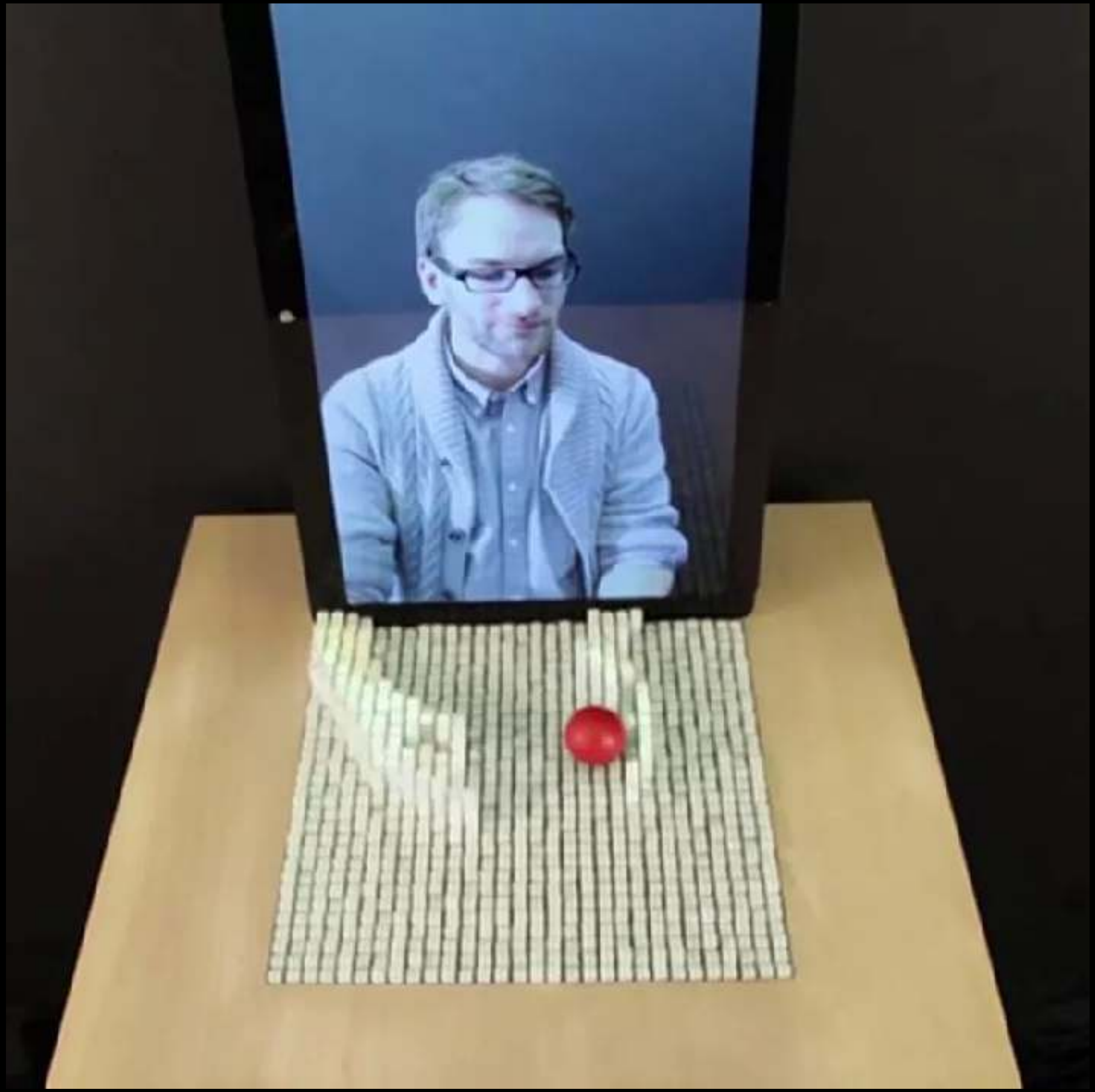


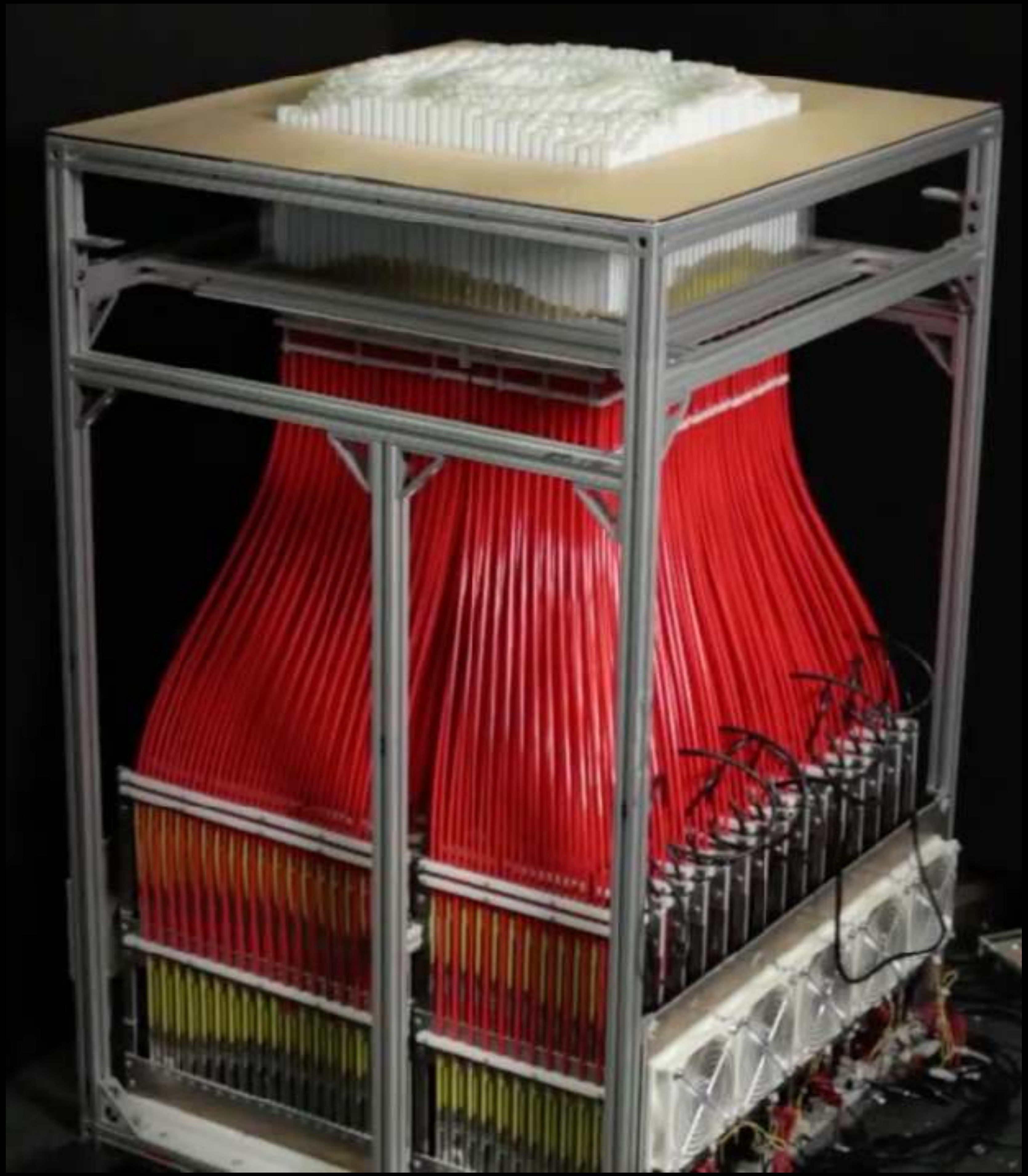
HypoSurface [Goulthorpe ’01]

special-purpose shape-changing interfaces ⟷ general-purpose shape-changing interfaces

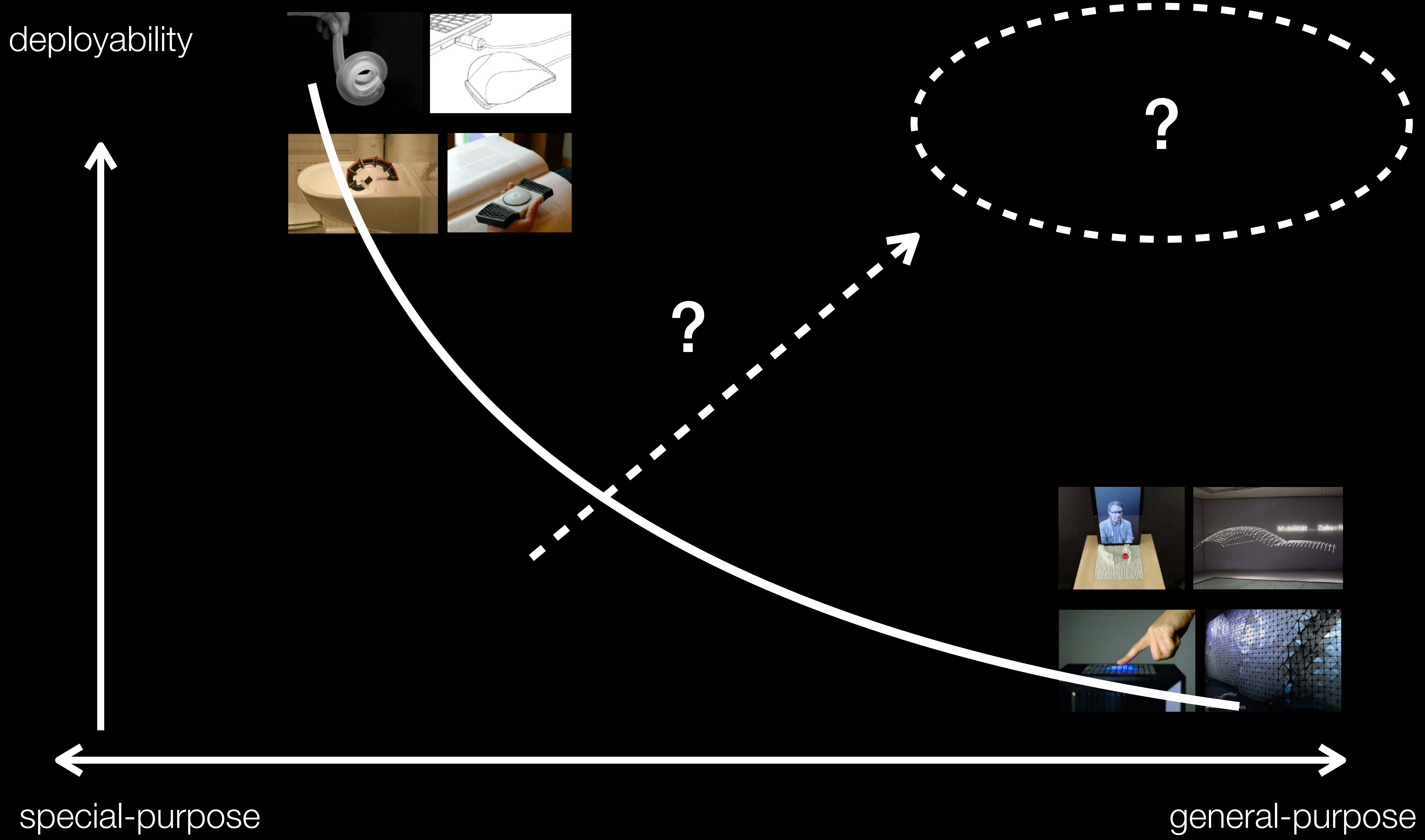
inFORM: Dynamic Physical Affordances and Constraints, Follmer et al, UIST 2013

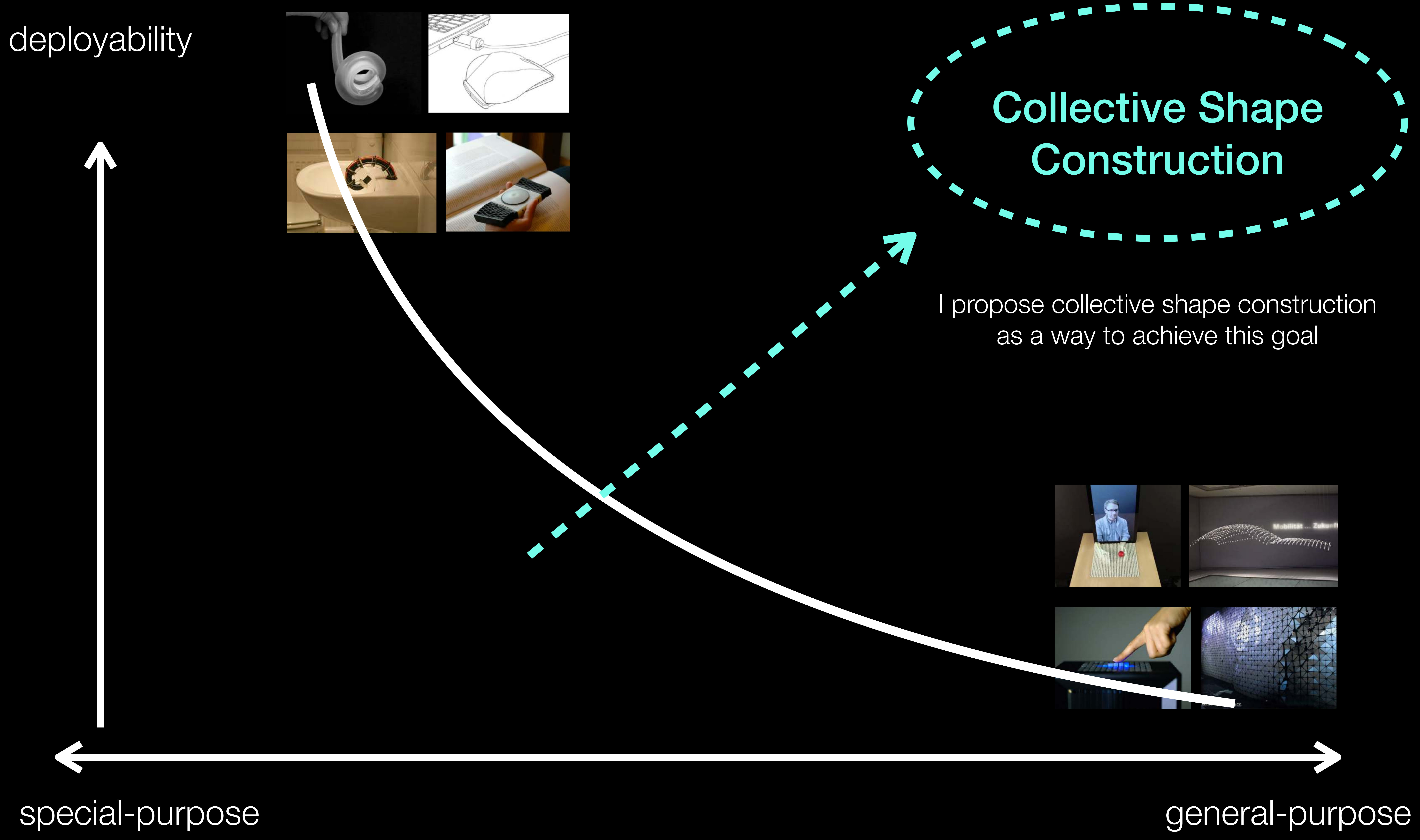
These systems require a **large, mechanically complex** device, which is **difficult to deploy** into existing environments





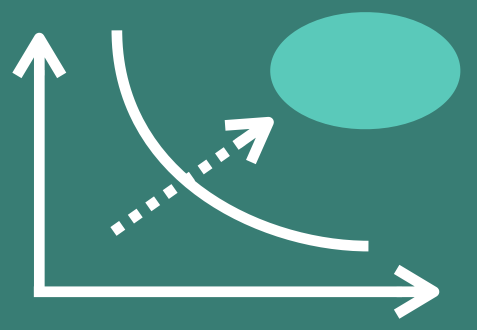
general-purpose but **not deployable**


deployability
?
?
special-purpose
general-purpose


deployability
Collective Shape Construction
I propose collective shape construction
as a way to achieve this goal
special-purpose
general-purpose

Background

Why This Approach?



Concept

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Shape Construction
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Interaction with
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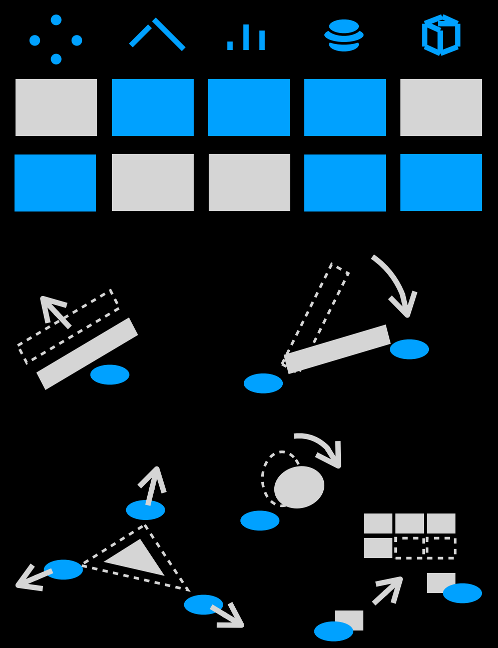

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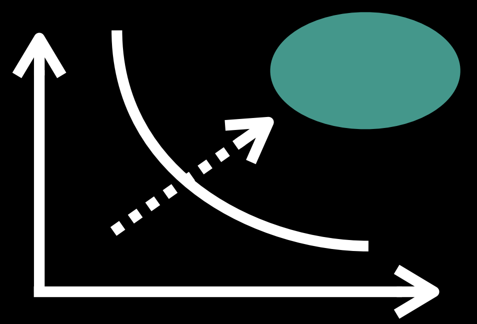

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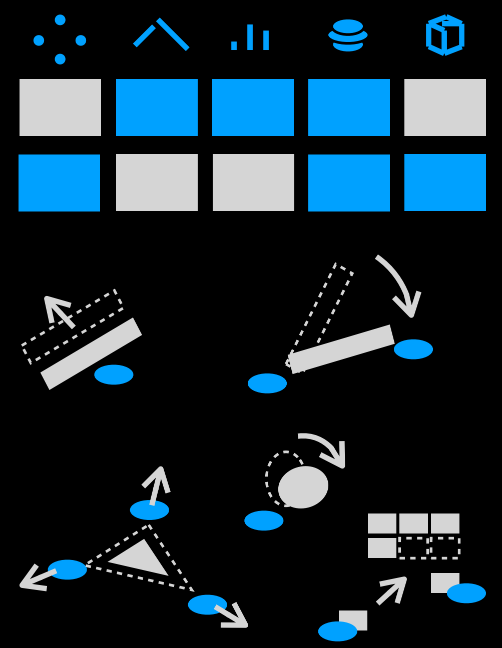
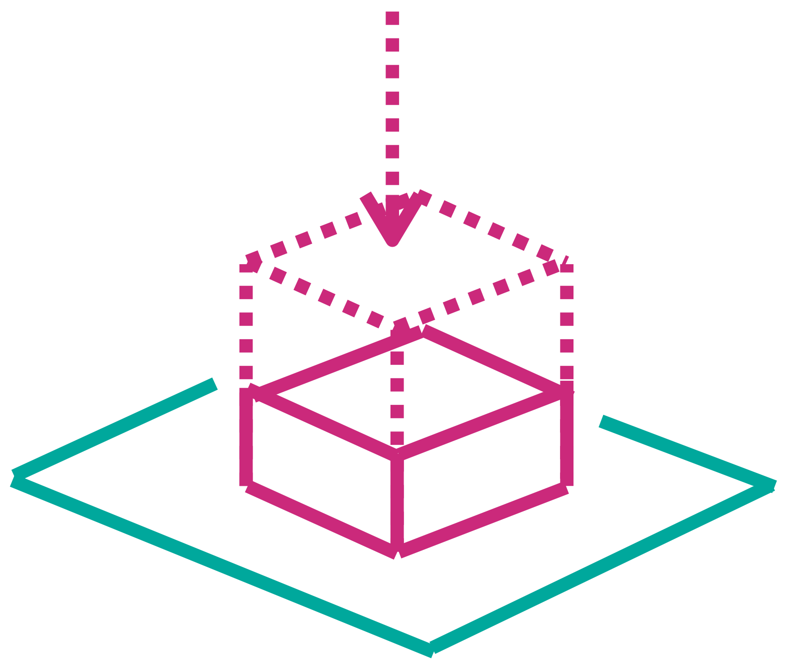
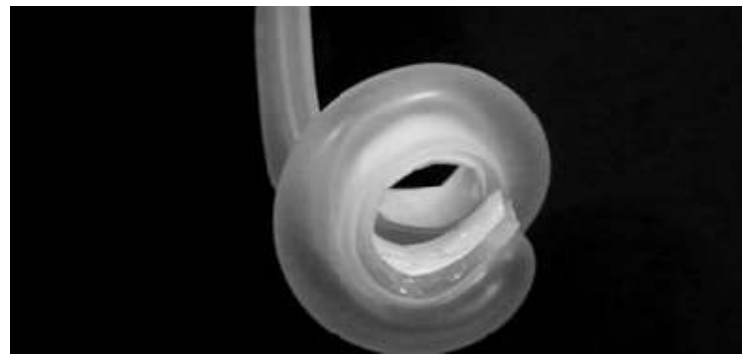


Dynamic Physical UI

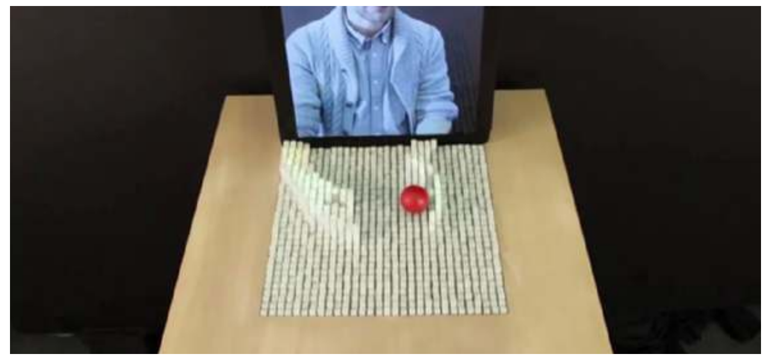


Shape-changing UI

Single materials



Monolithic devices



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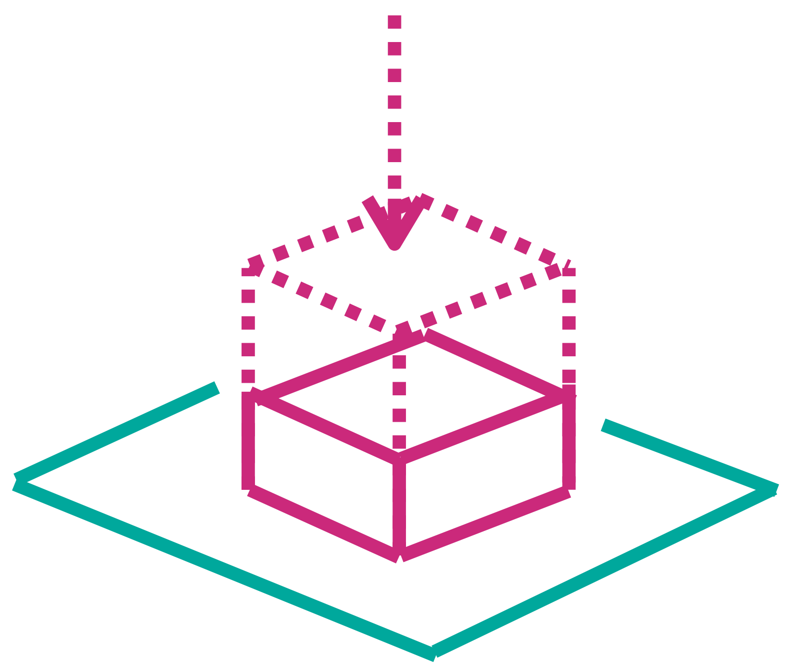

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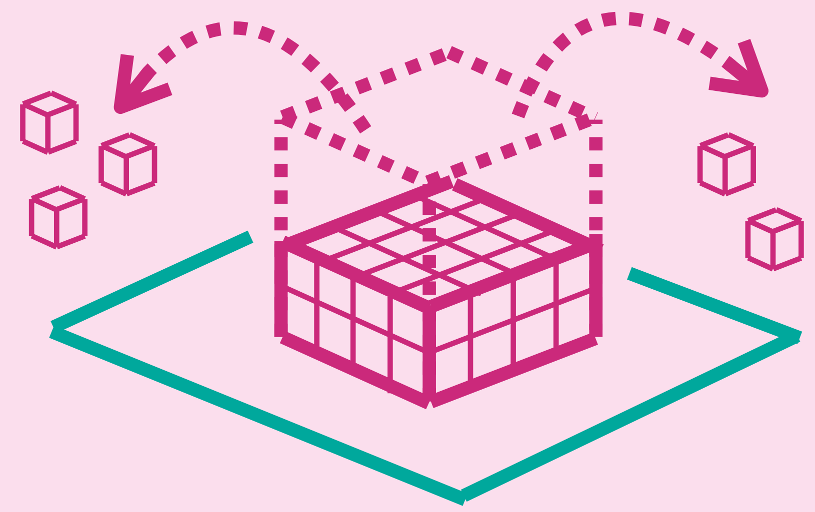
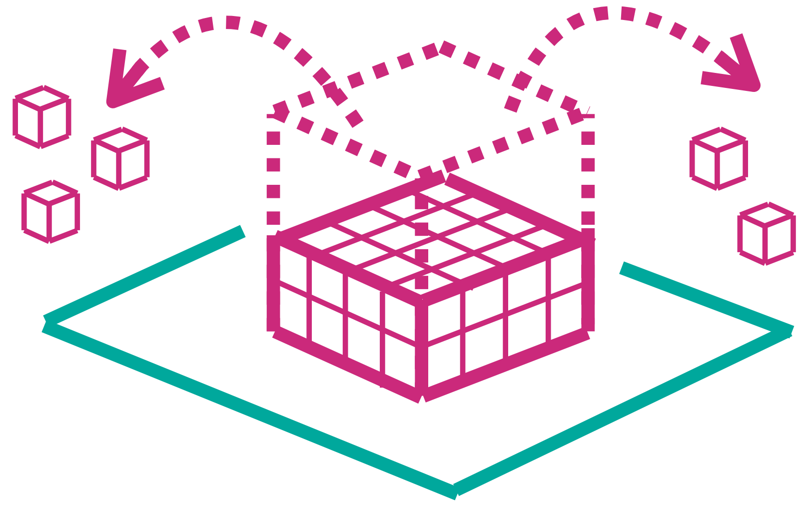


Shape Change with
Collective Elements

Dynamic Physical UI



Shape Change with
Collective Elements

The focus of this thesis

Dynamic shape made of
discrete collective elements

||

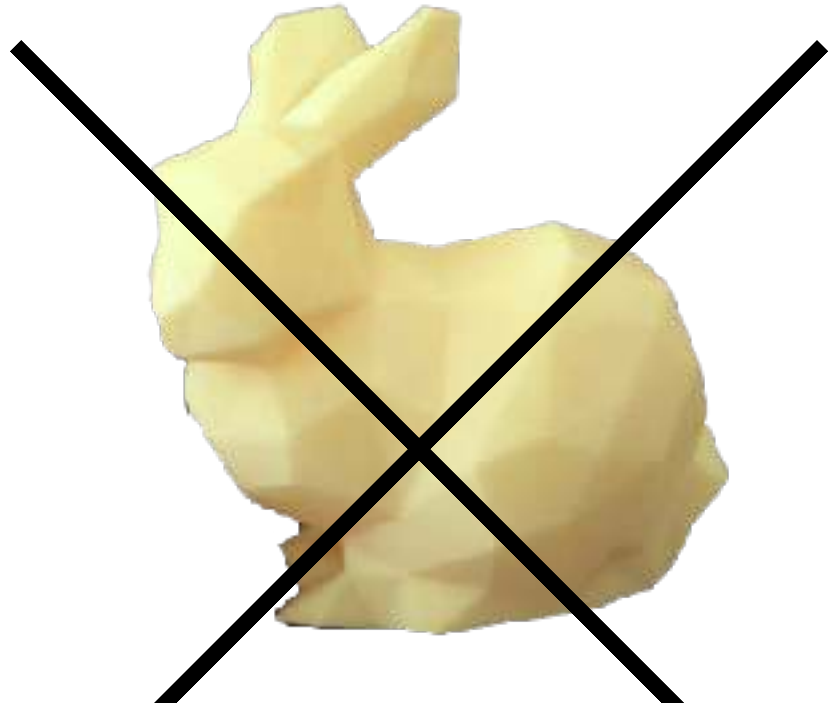
a shape that consists of a set of physical units
that are separable from each other

|| ~~||~~

(Static) **Discrete** Elements

e.g., LEGO Blocks

(Static) **Non-discrete** Elements



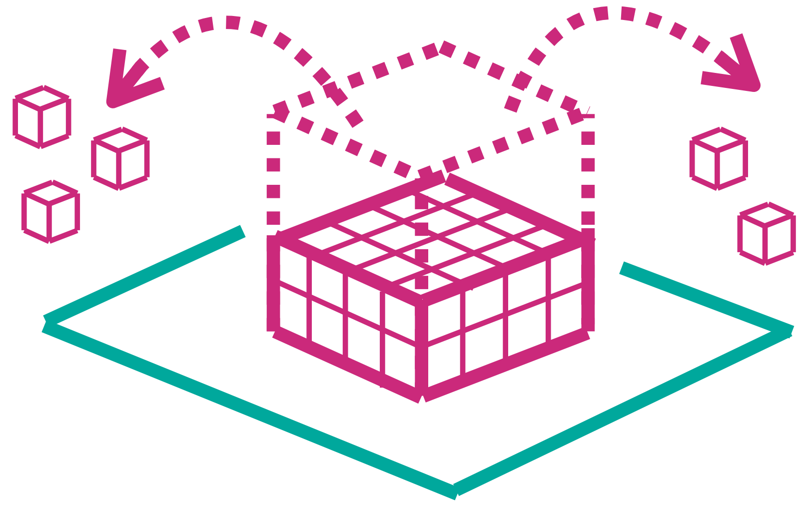
e.g., 3D Printed Objects

The focus of this thesis

Dynamic shape made of **discrete** collective elements

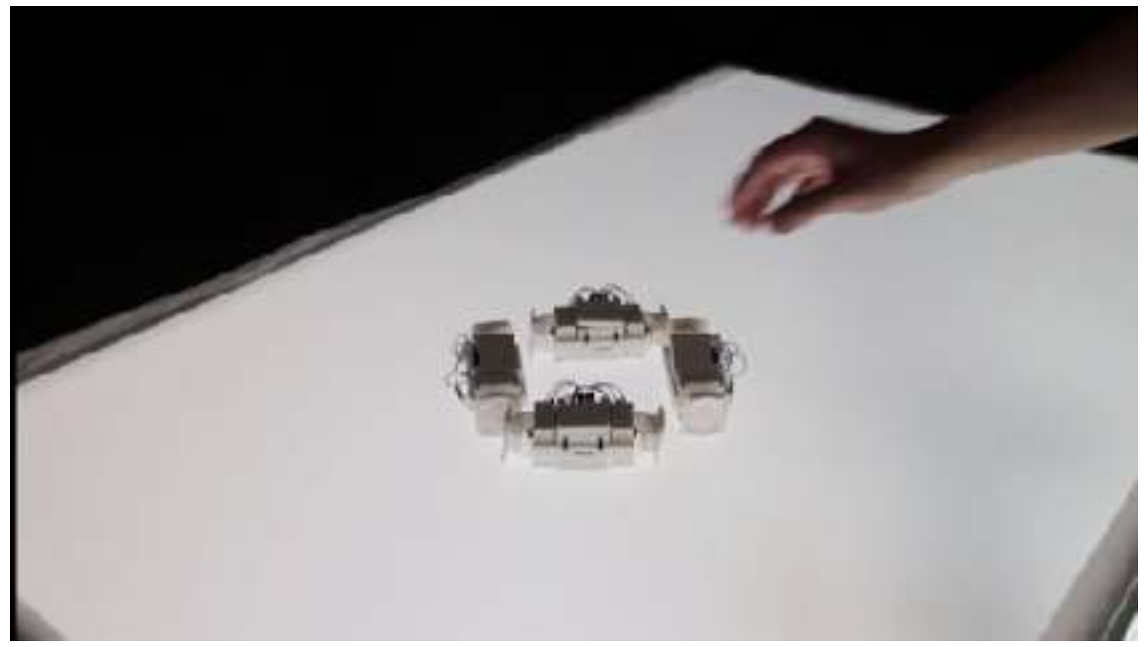
I argue there are two ways to construct dynamic shape

Dynamic Physical UI



Shape Change with
Collective Elements

Active
collective elements
||
self-actuated elements
that can move or reconfigure
themselves with internal actuation



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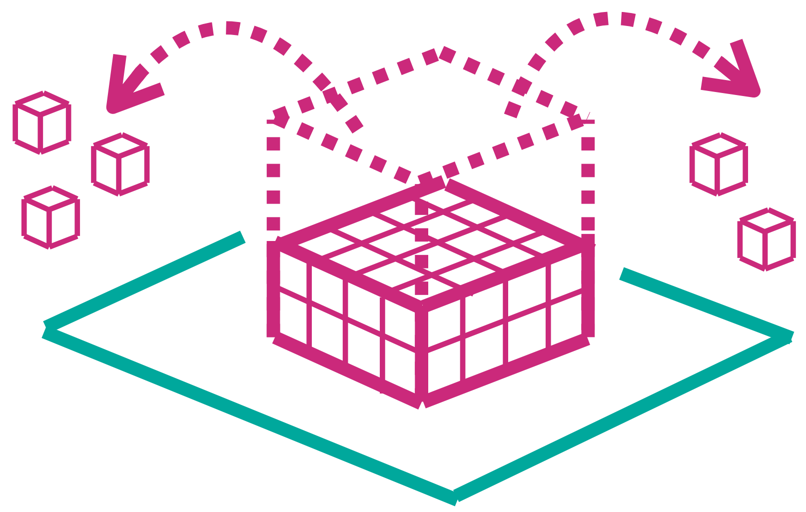

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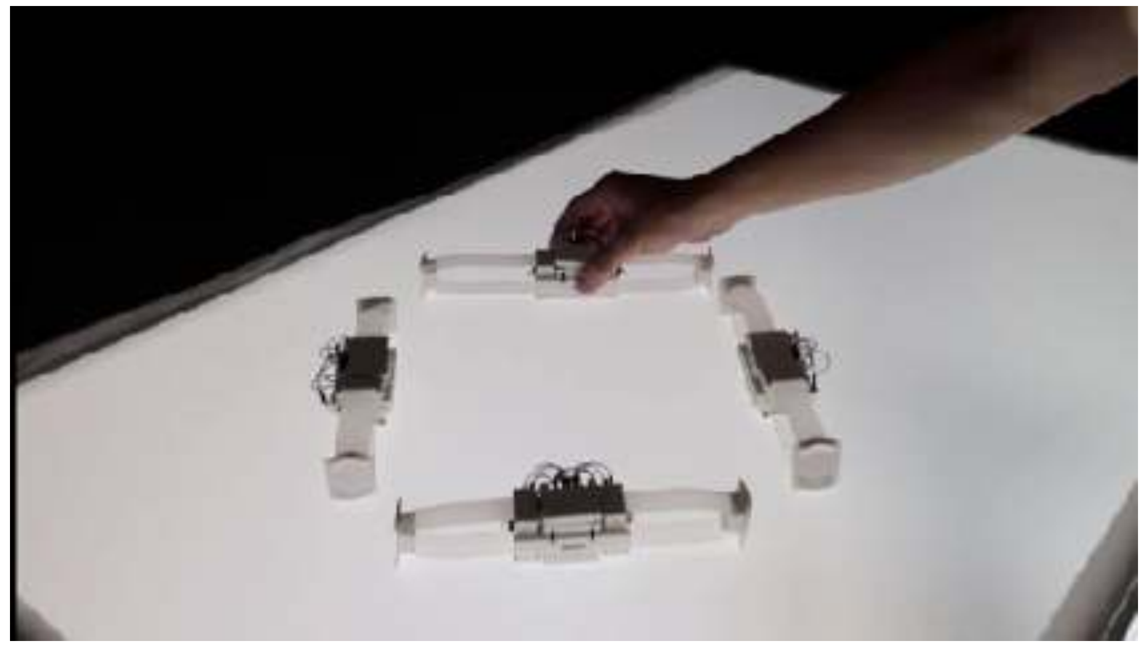
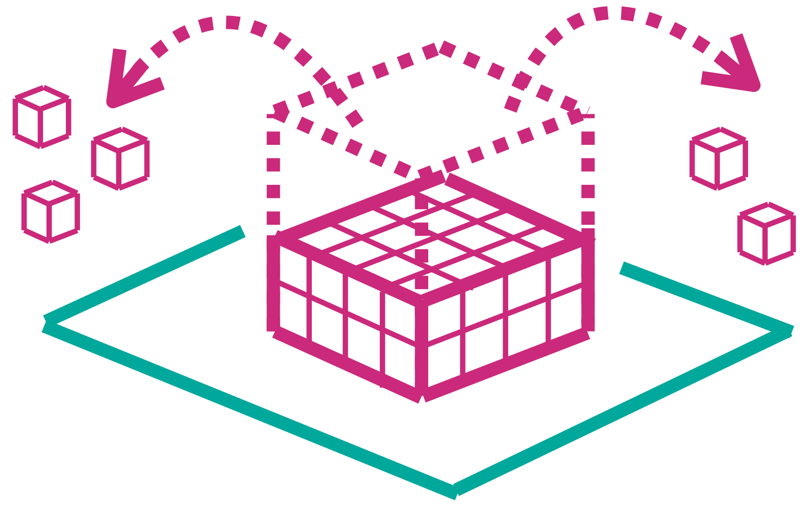


Passive
collective elements
||
externally-actuated elements
that can move or reconfigure
through external actuation

Dynamic Physical UI



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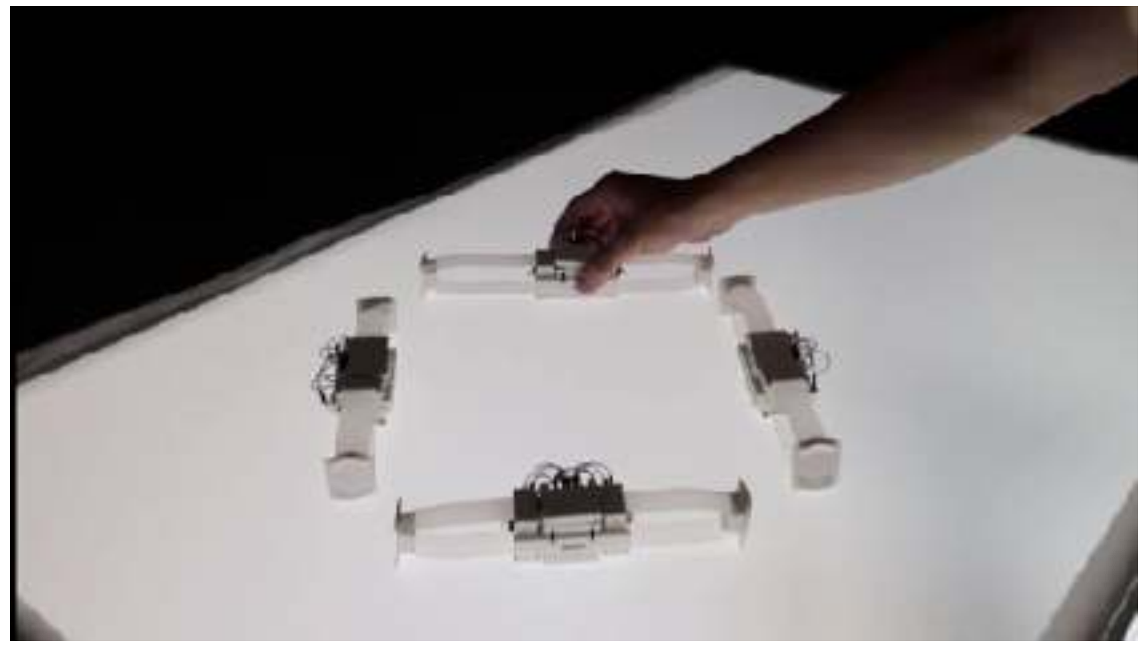

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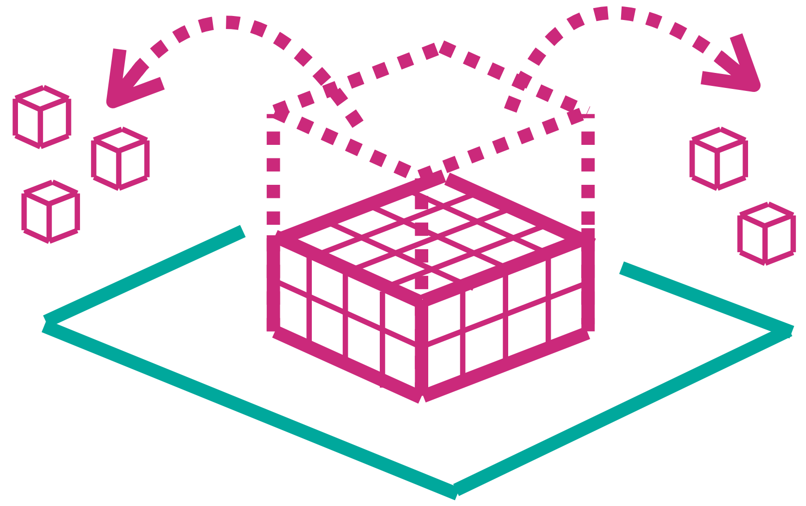


Shape Change with
Collective Elements

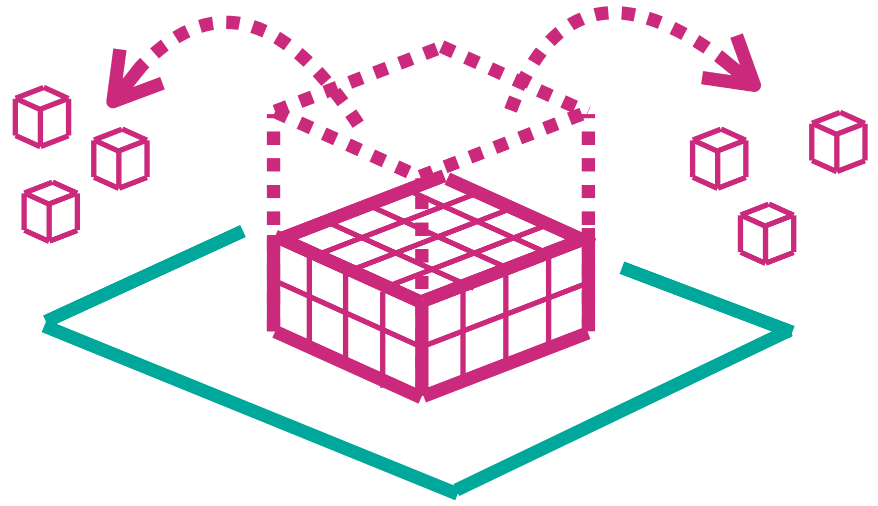
Universal shape transformation with discrete collective elements has been explored in the context of robotics

self-reconfigurable robots
(e.g., [Yim et al. 2007])

swarm robots
(e.g., [Rubesnstein et al. 2014])

programmable matter
(e.g., [Gilpin et al. 2010])

Dynamic Physical UI



Shape Change with
Collective Elements

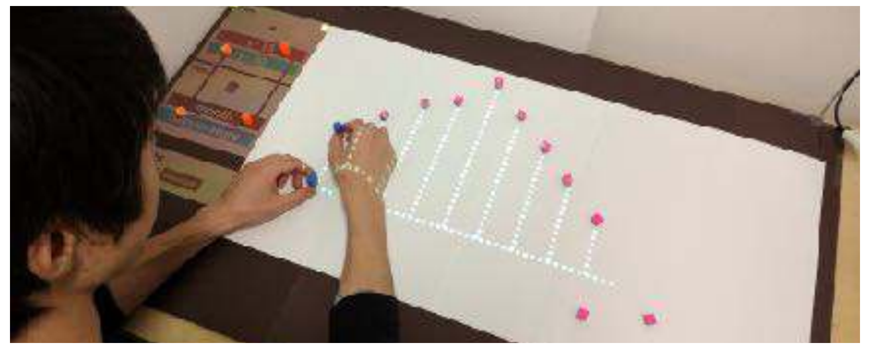
This thesis investigates **HCI aspects** of this dynamic and collective shape construction

For information display

(e.g., [Suzuki et al., UIST 2018])

For tangible user interfaces

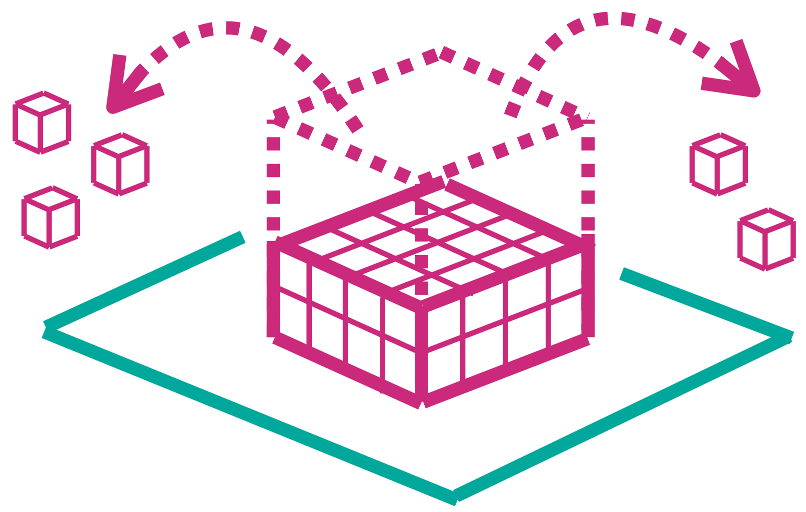
(e.g., [Suzuki et al., UIST 2019])



Interaction with collective elements

(e.g., [Suzuki et al., CHI 2018])

Dynamic Physical UI



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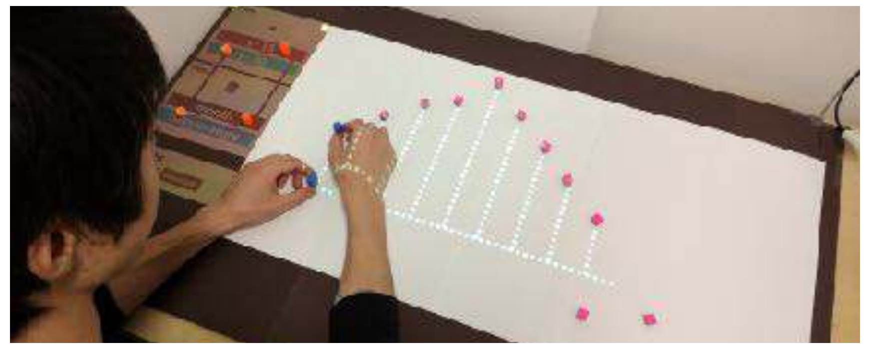
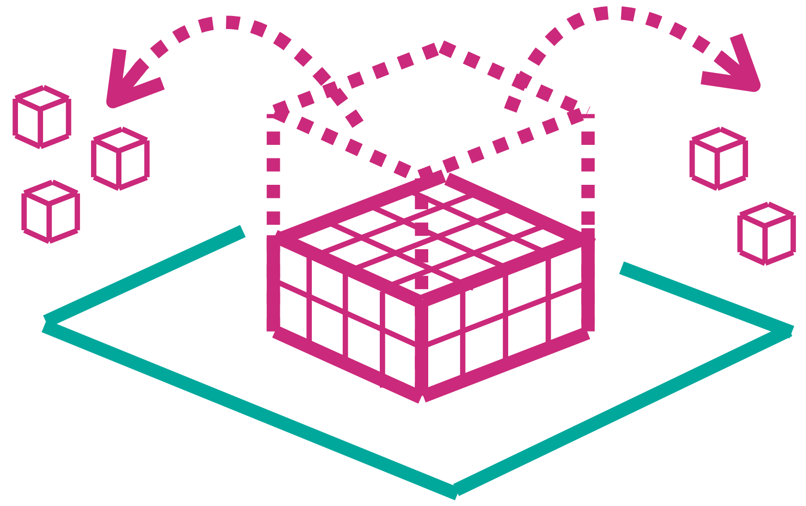
For tangible user interfaces
(e.g., [Suzuki et al., UIST 2019])



Interaction with collective elements
(e.g., [Suzuki et al., CHI 2018])

Dynamic Physical UI



Shape Change with
Collective Elements

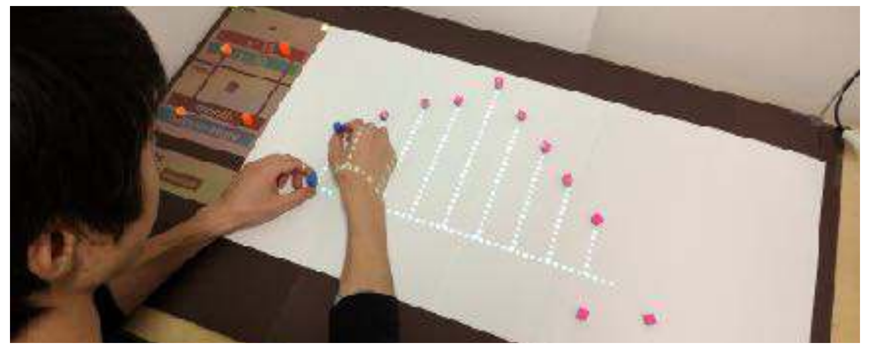
This thesis investigates **HCI aspects** of this dynamic and collective shape construction

For information display

(e.g., [Suzuki et al., UIST 2018])

For tangible user interfaces

(e.g., [Suzuki et al., UIST 2019])



Interaction with collective elements

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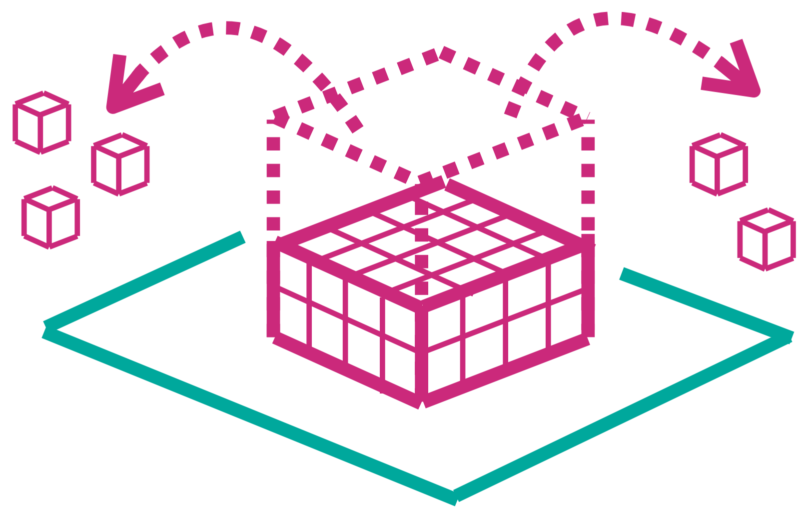
Dynamic Physical UI



Shape Change with
Collective Elements

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For information display
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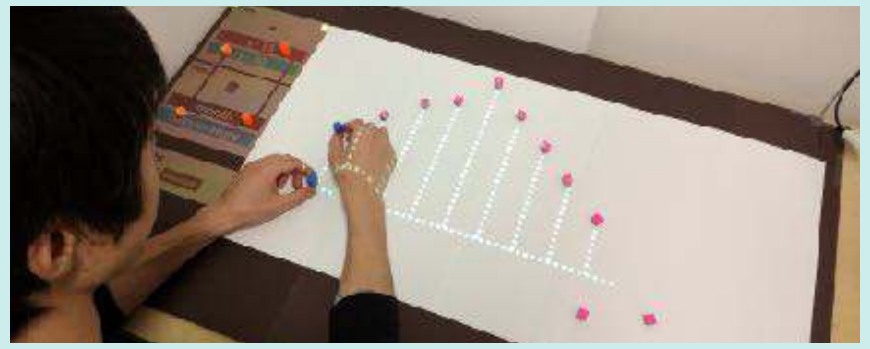
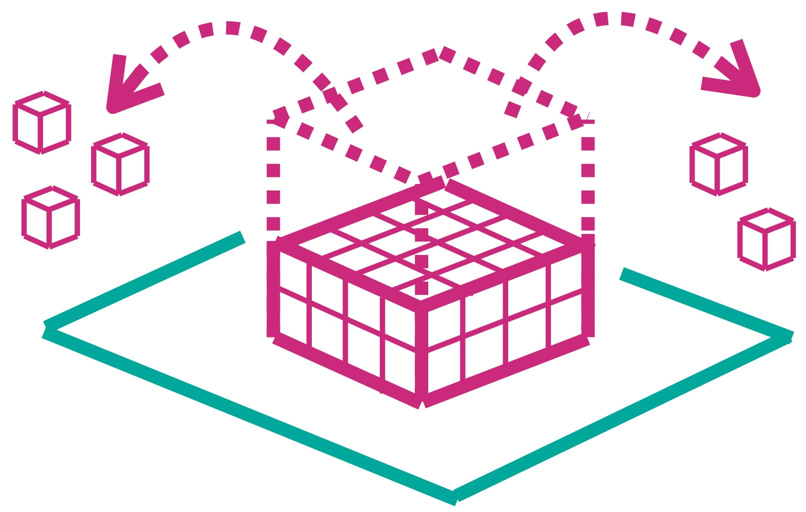


Interaction with collective elements
(e.g., [Suzuki et al., CHI 2018])

Dynamic Physical UI



Shape Change with
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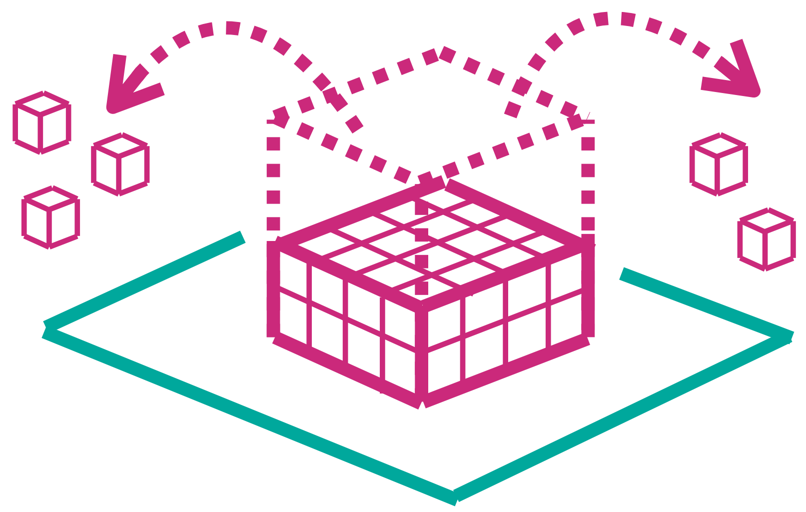
Dynamic Physical UI



Shape Change with
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For information display

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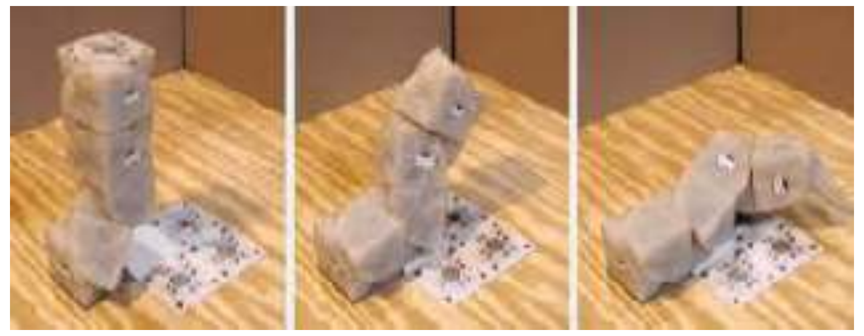
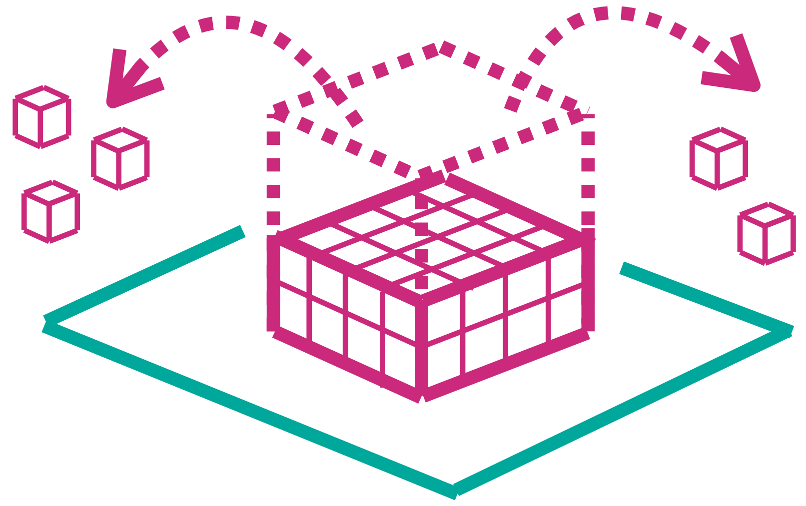


In robotics, self-reconfigurable robots or programmable matter research often assume **lattice or voxel-like structure**

Dynamic Physical UI

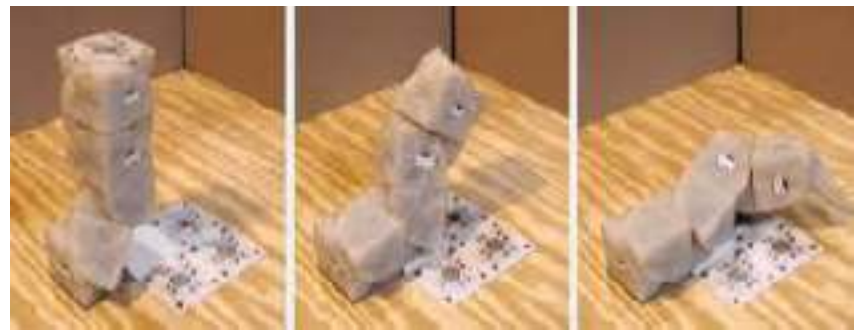


Shape Change with
Collective Elements

This thesis investigates **HCI aspects** of this dynamic and collective shape construction

For information display
(e.g., [Suzuki et al., UIST 2018])

Q. Are there any other ways or approaches to construct and represent a physical shape?



In robotics, self-reconfigurable robots or programmable matter research often assume **lattice or voxel-like structure**

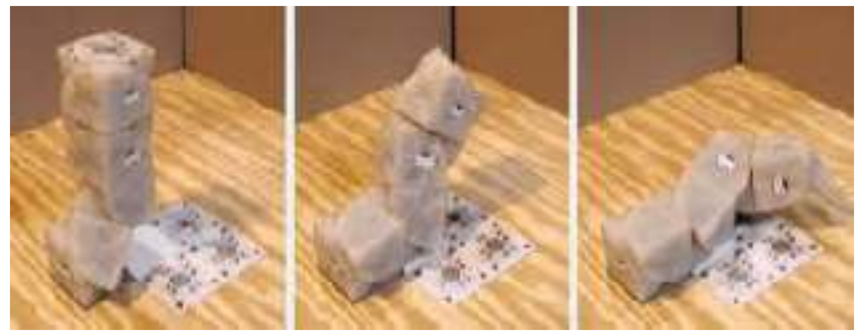
This thesis investigates **HCI aspects** of this dynamic and collective shape construction

For information display

(e.g., [Suzuki et al., UIST 2018])

Q. Are there any other ways or approaches to construct and represent a physical shape?

To answer this question,
I systematically explore a range of possible representations for dynamic physical shape



In robotics, self-reconfigurable robots or programmable matter research often assume **lattice or voxel-like structure**

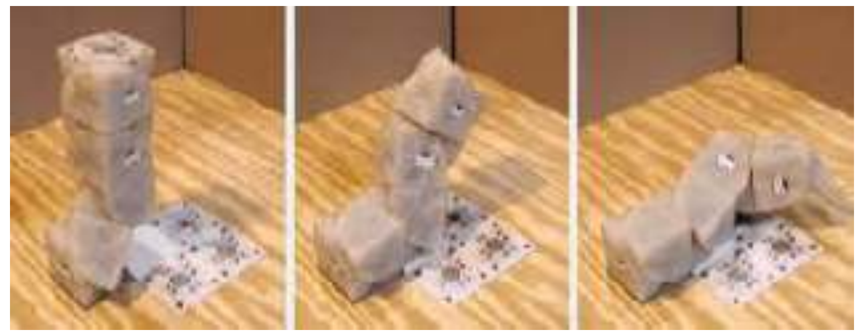
This thesis investigates **HCI aspects** of
this dynamic and collective shape construction

For information display

(e.g., [Suzuki et al., UIST 2018])

Q. Are there any other ways or approaches to construct and represent a physical shape?

Before jumping in, I'd like to first explain with a metaphor to think about how we can render information.



In robotics, self-reconfigurable robots or programmable matter research often assume **lattice or voxel-like structure**

(e.g., Stanford bunny)

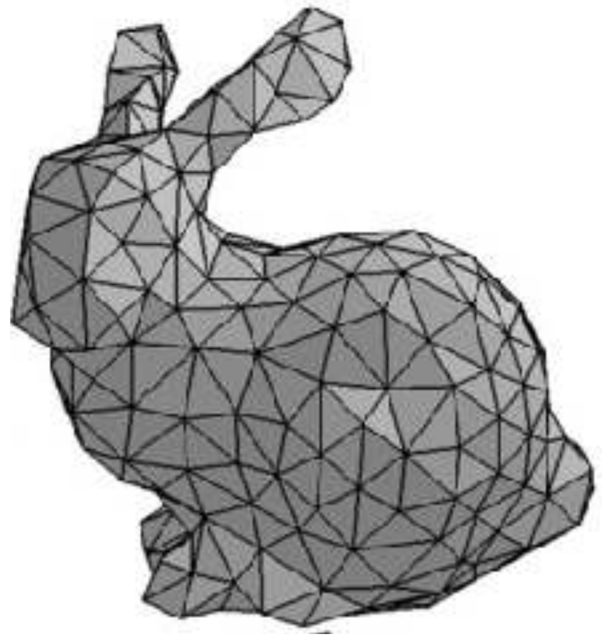
how can we physically render information?
(e.g., Stanford bunny?)

Metaphor: Representations in Computer Graphics

In Computer Graphics, these are many different ways to render and represent information

original information

point cloud



mesh surface

voxels

wireframe

Metaphor: Representations with Static Physical Elements

In the same way, there are many ways to physically render and represent with **static** elements.

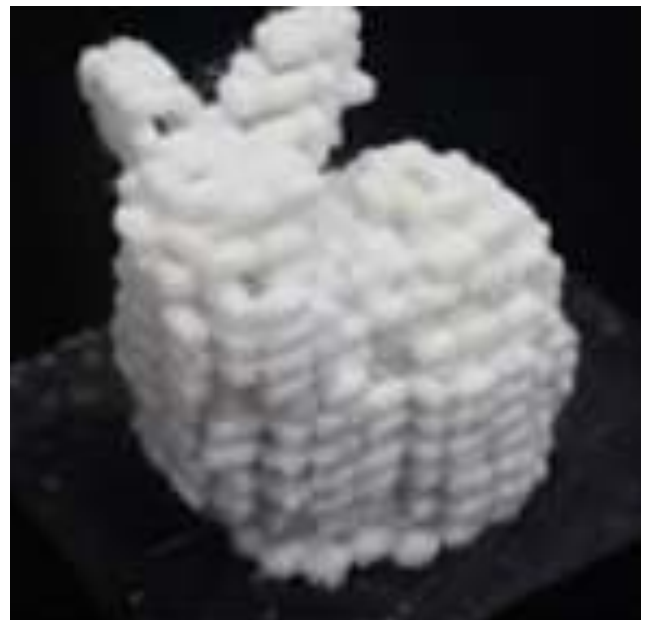
original information

voxel

(e.g., LEGO Blocks)

surface

(e.g., Origami)



connected line

(e.g., 3D Printed Chain)

wireframe

(e.g., Zome Tools)

sliced layers

(e.g., 123D Make)

How can we physically render and represent information with **dynamic** collective elements?

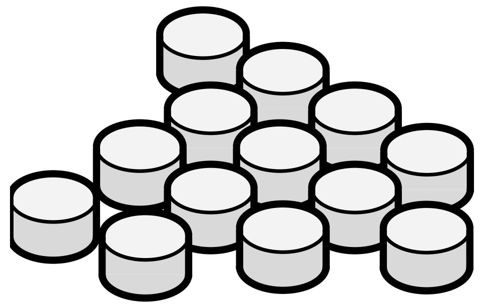
How can we physically render and represent information with **dynamic** collective elements?

↓

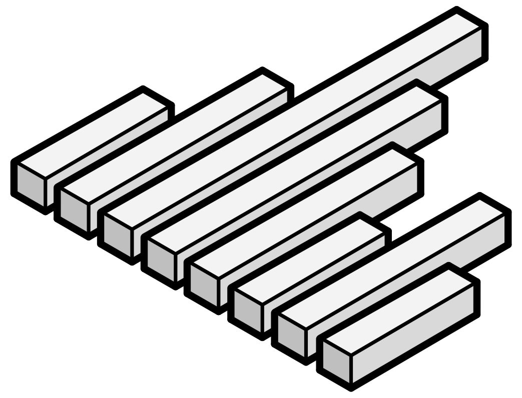
To answer this question

I explored eight **possible representations** for dynamic and collective shape construction

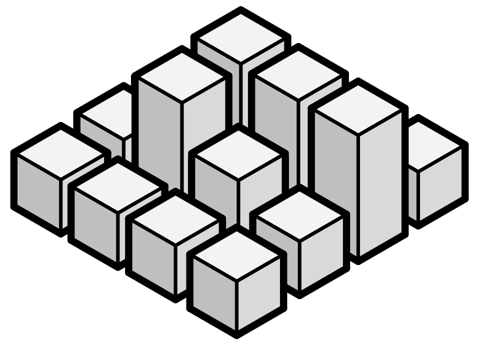
I explored eight **possible representations** for dynamic and collective shape construction



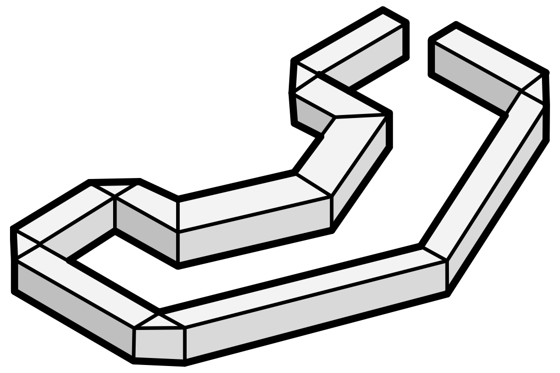
Sparse Dots



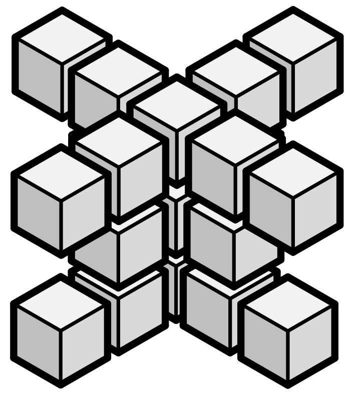
Sparse Lines



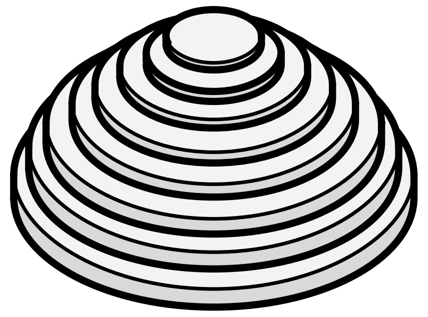
Pin Array



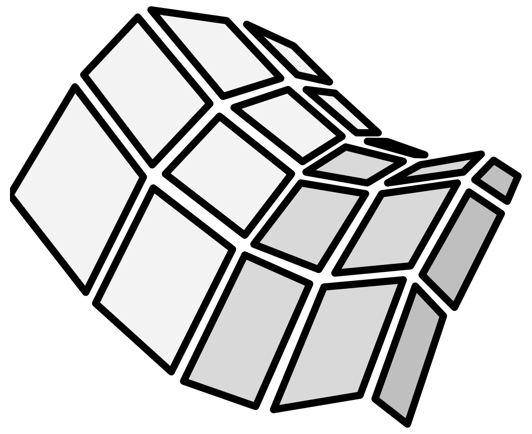
Single Line



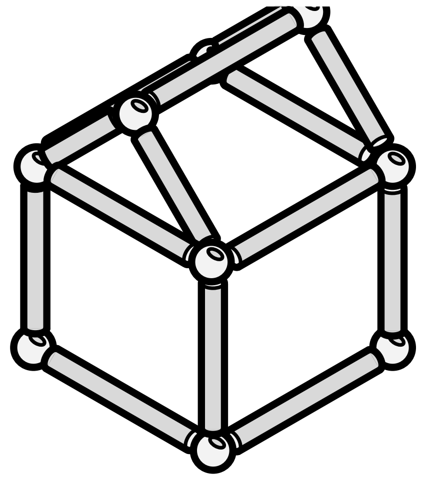
Voxel



Layers

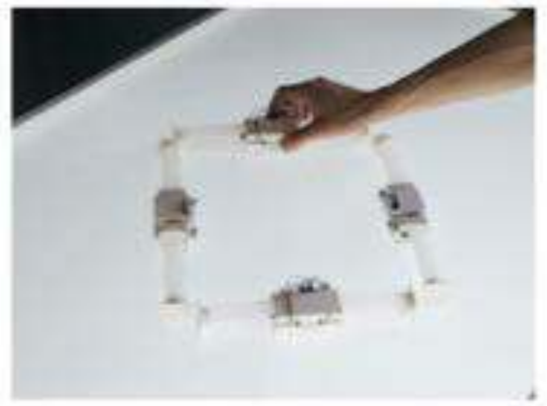


Surface



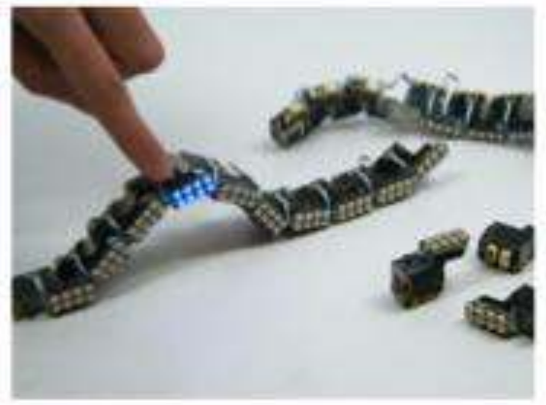
Hub and Struts

Reactile
[Suzuki 2018]

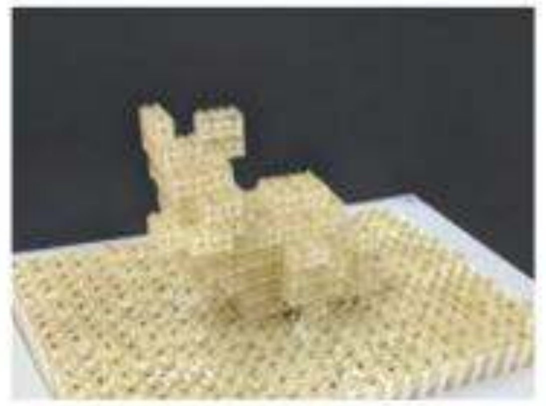


ShapeBots
[Suzuki 2018]

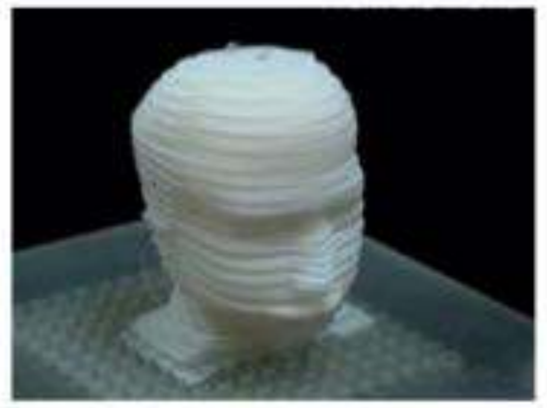
LiftTiles
[Suzuki 2019]



ChainFORM
[Nakagaki 2016]



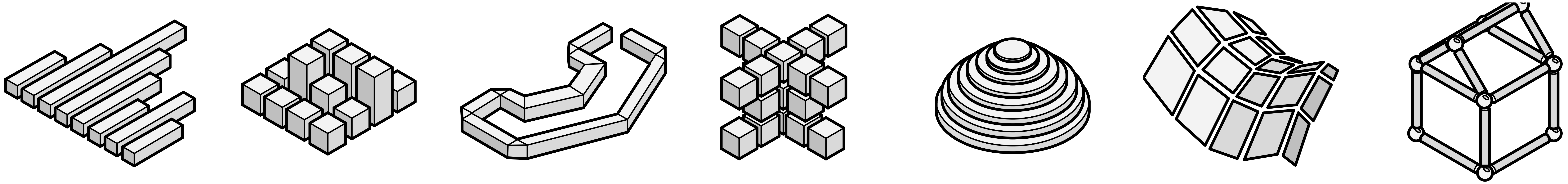
Dynablock
[Suzuki 2018]



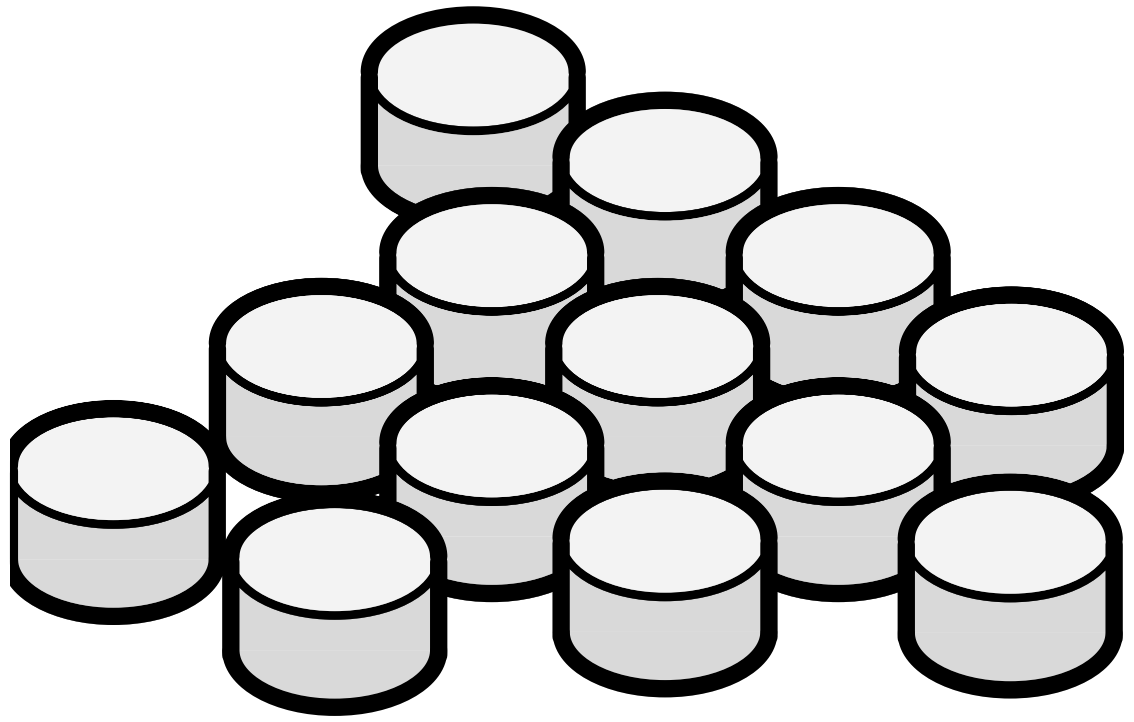
Additive Folding
[Yim 2018]

MORI
[Beike 2017]

Morphys
[Takei 2012]

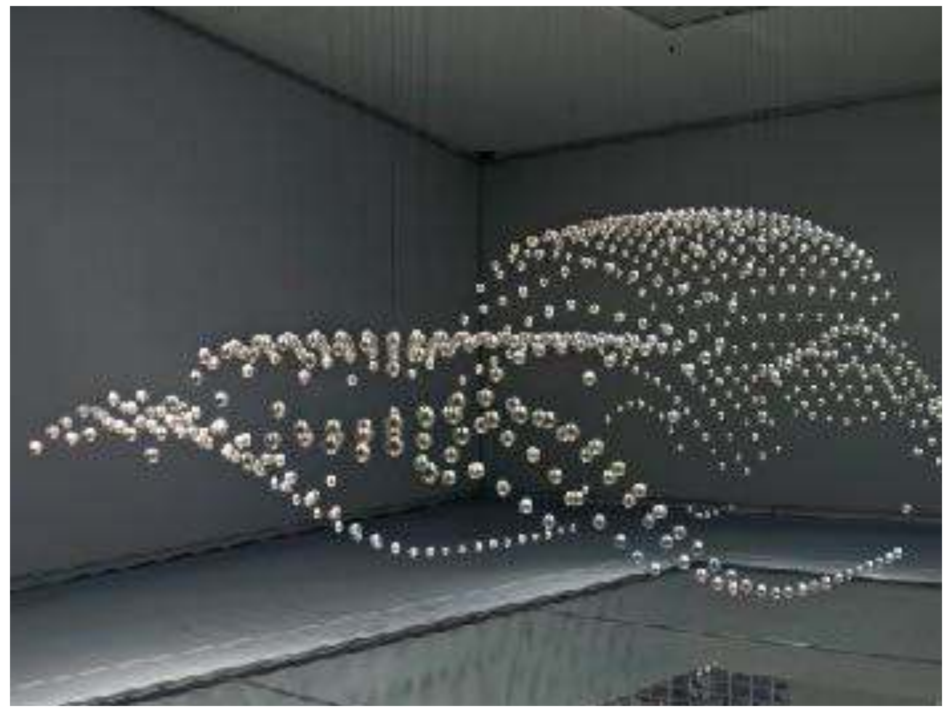


Sparse Lines | Pin Array | Single Line | Voxel | Layers | Surface | Hub and Struts

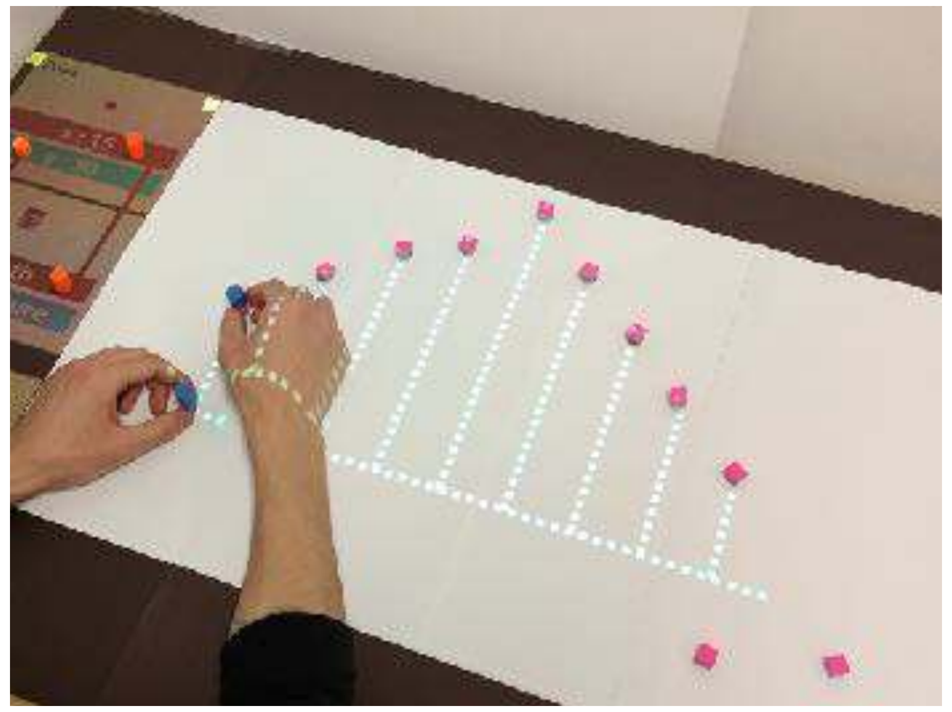


Sparse Dots

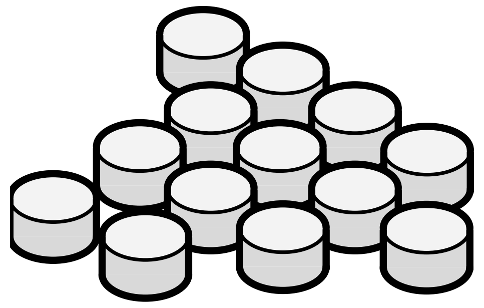
[Zooids, LeGoc 2016]

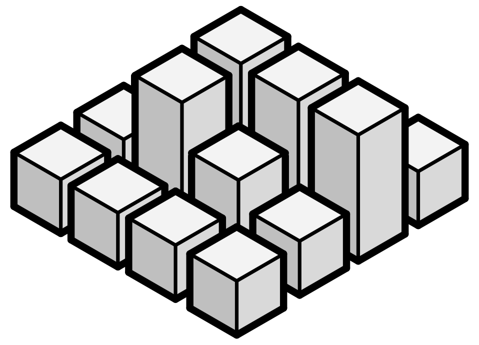


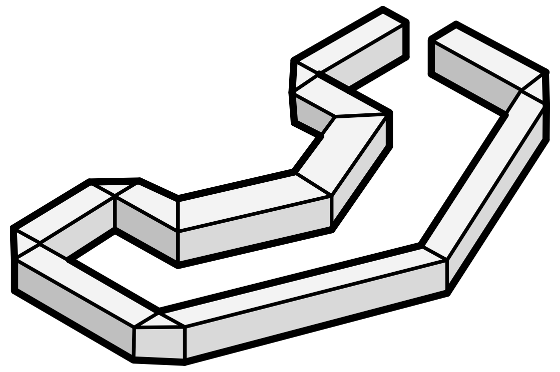
[ART+COM 2008]

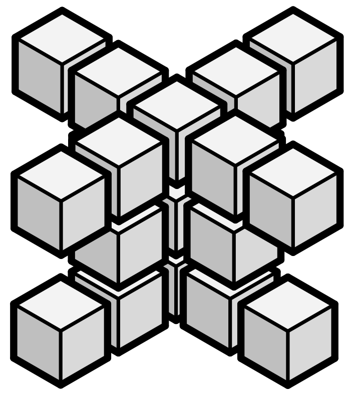


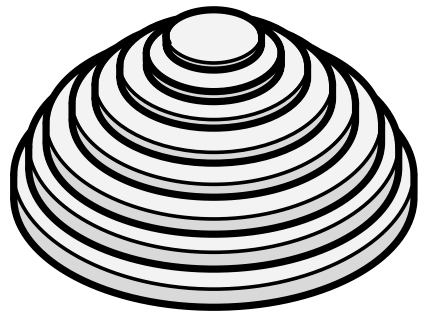
[Reactile, Suzuki 2018]

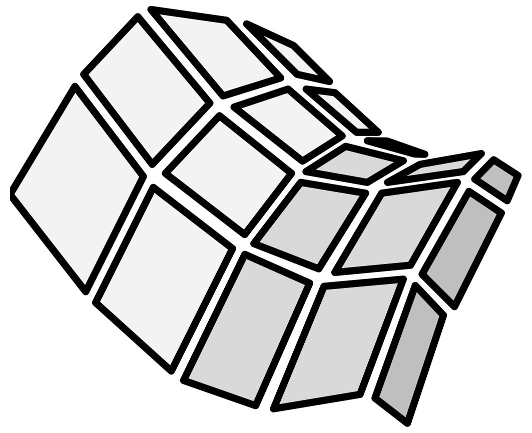

Sparse Dots

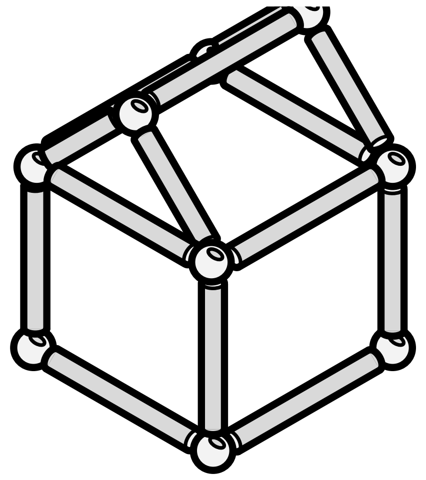

Pin Array

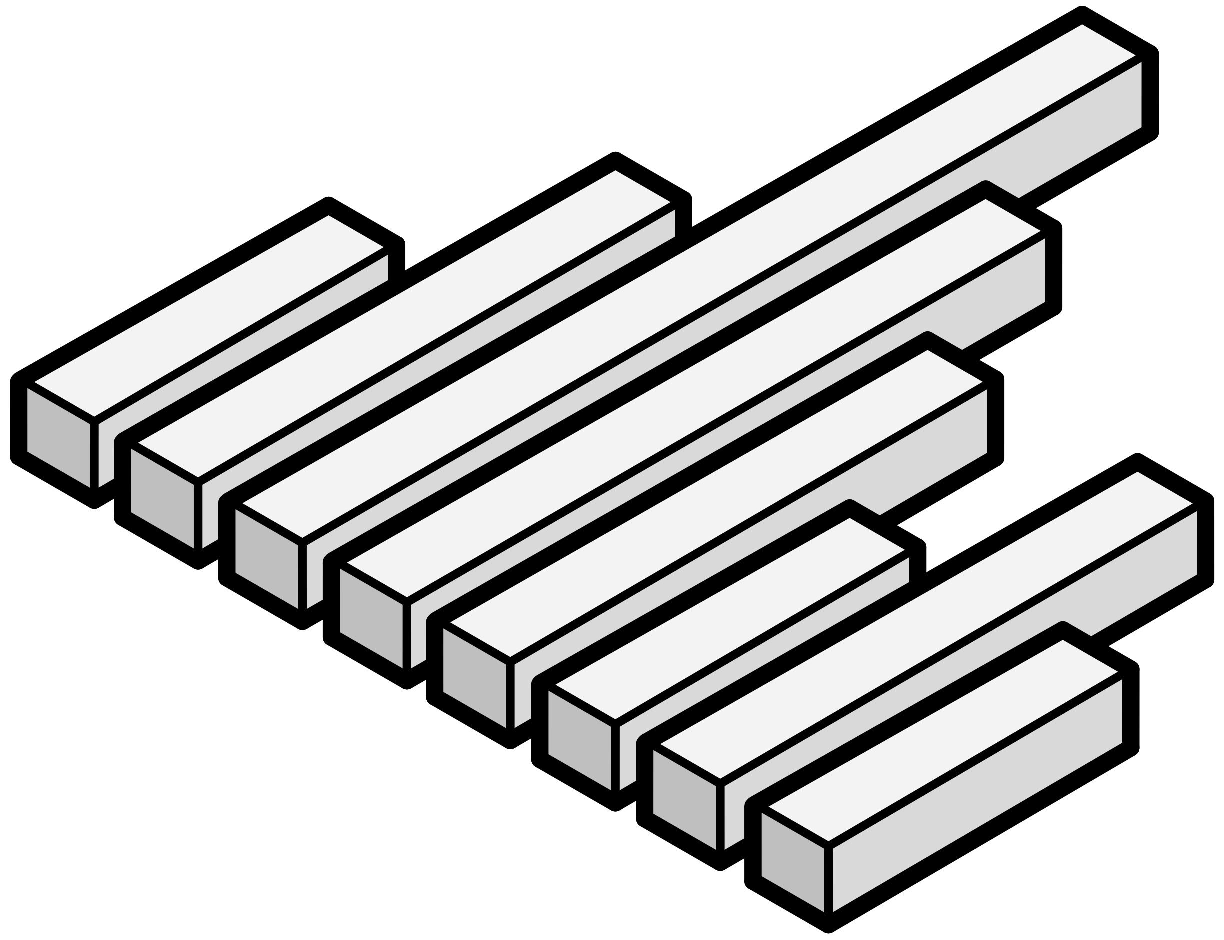

Single Line


Voxel

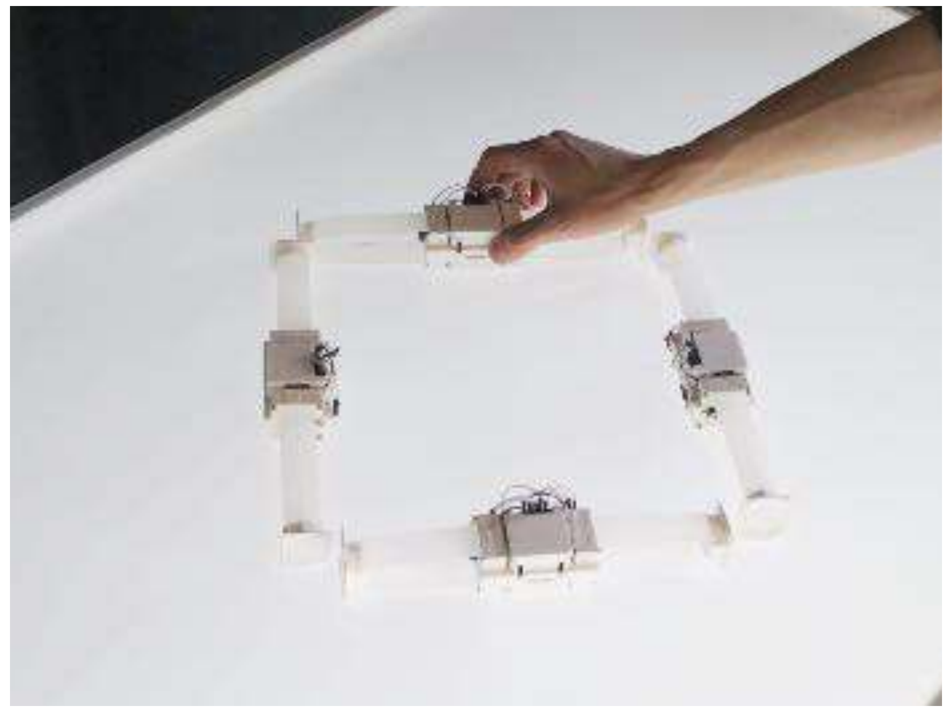

Layers


Surface

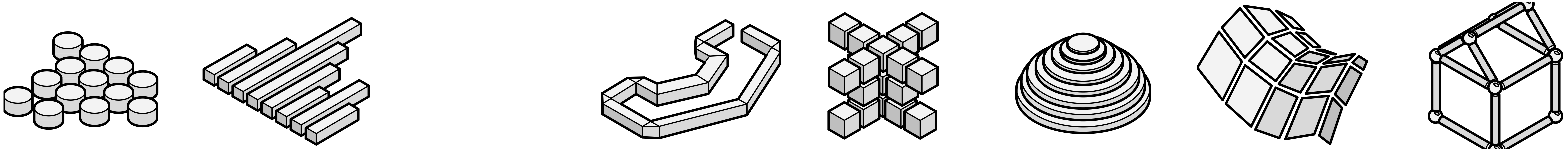

Hub and Struts



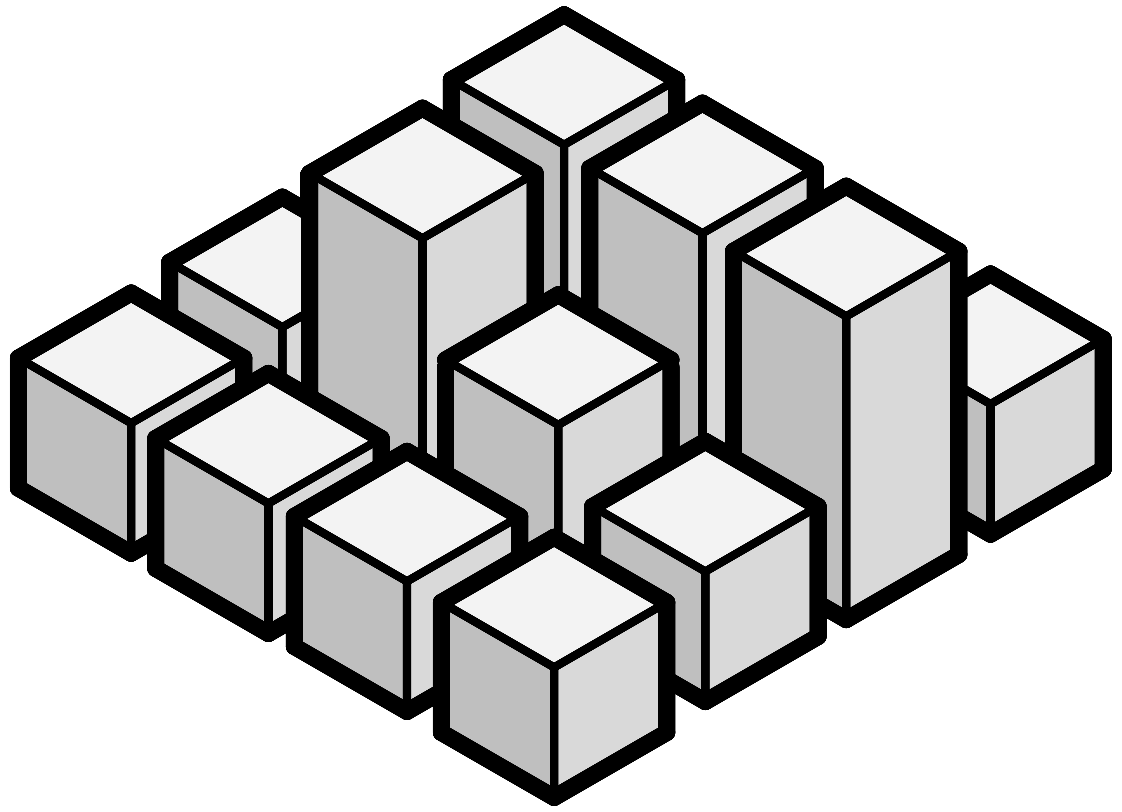
Sparse Lines


[ShapeBots, Suzuki 2018]

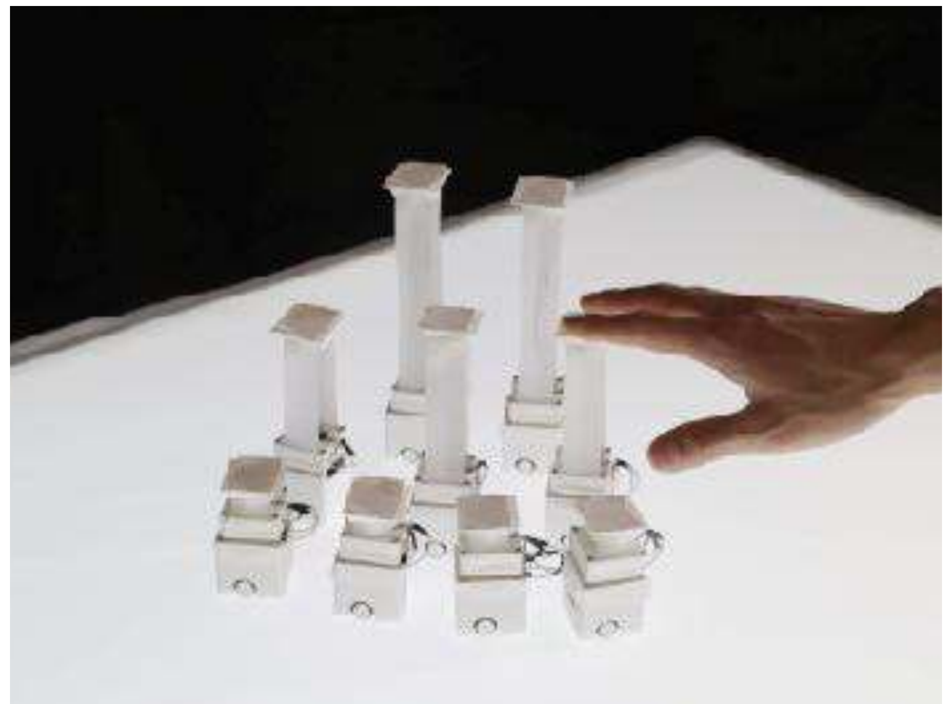

[Torres 2014]



Sparse Dots | Sparse Lines | Single Line | Voxel | Layers | Surface | Hub and Struts

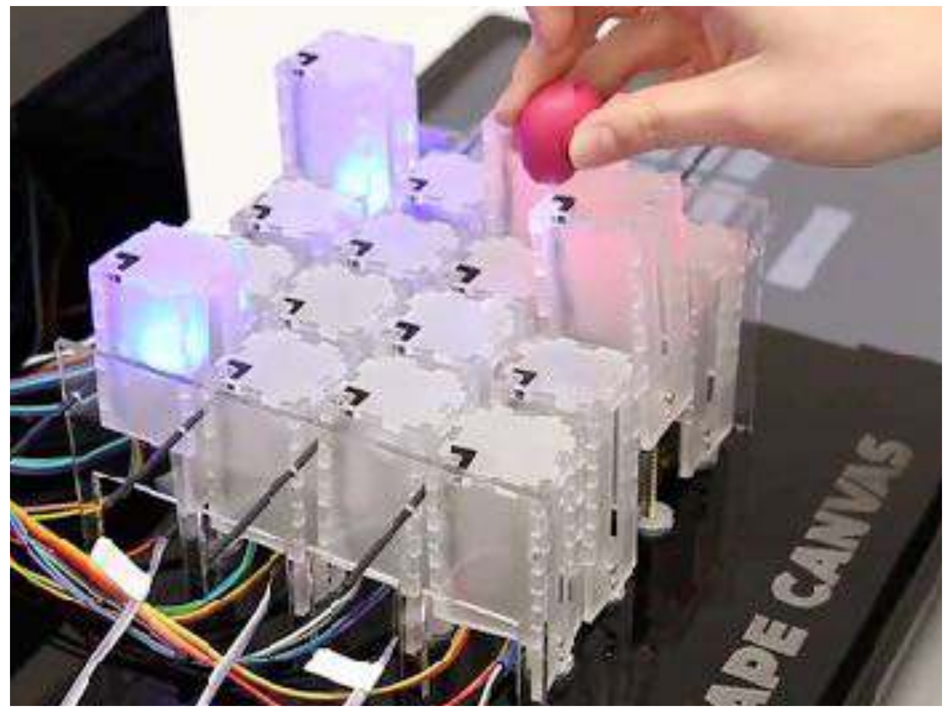


Pin Array

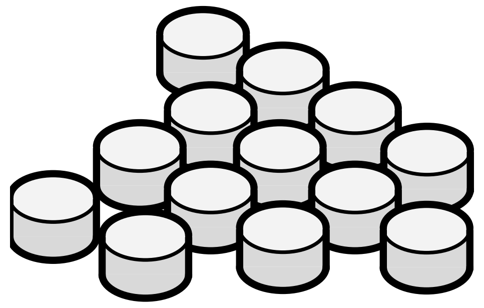


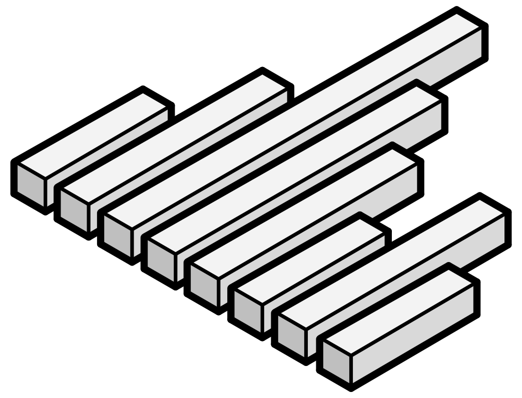
[ShapeBots, Suzuki 2018]

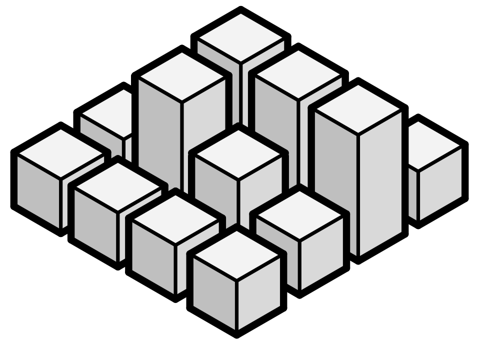
[LiftTiles, Suzuki 2020]

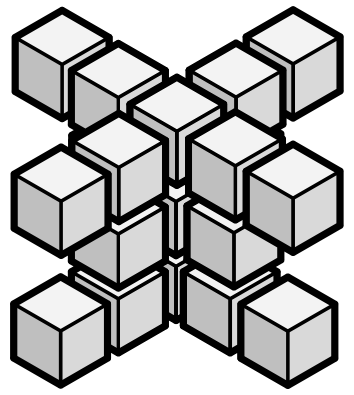


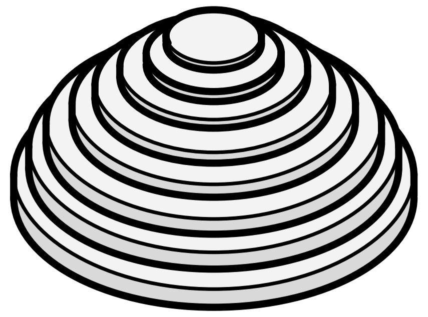
[ShapeCanvas, Everitt 2016]

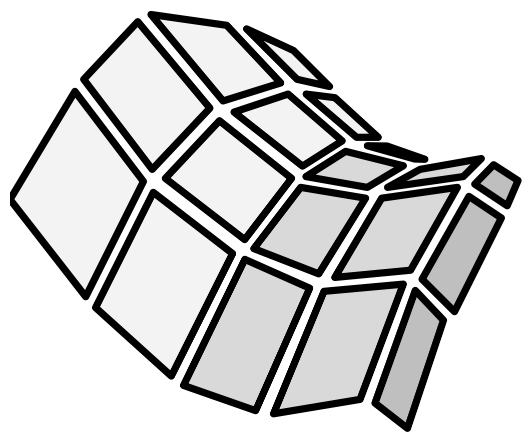

Sparse Dots

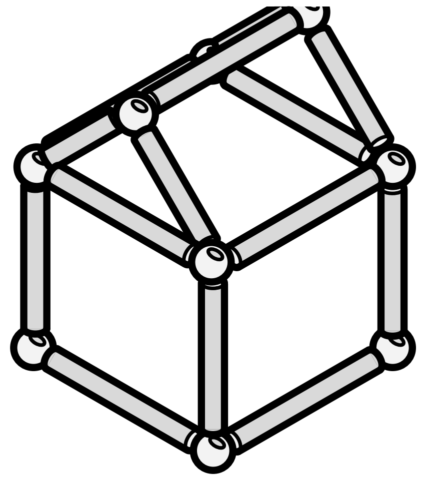

Sparse Lines

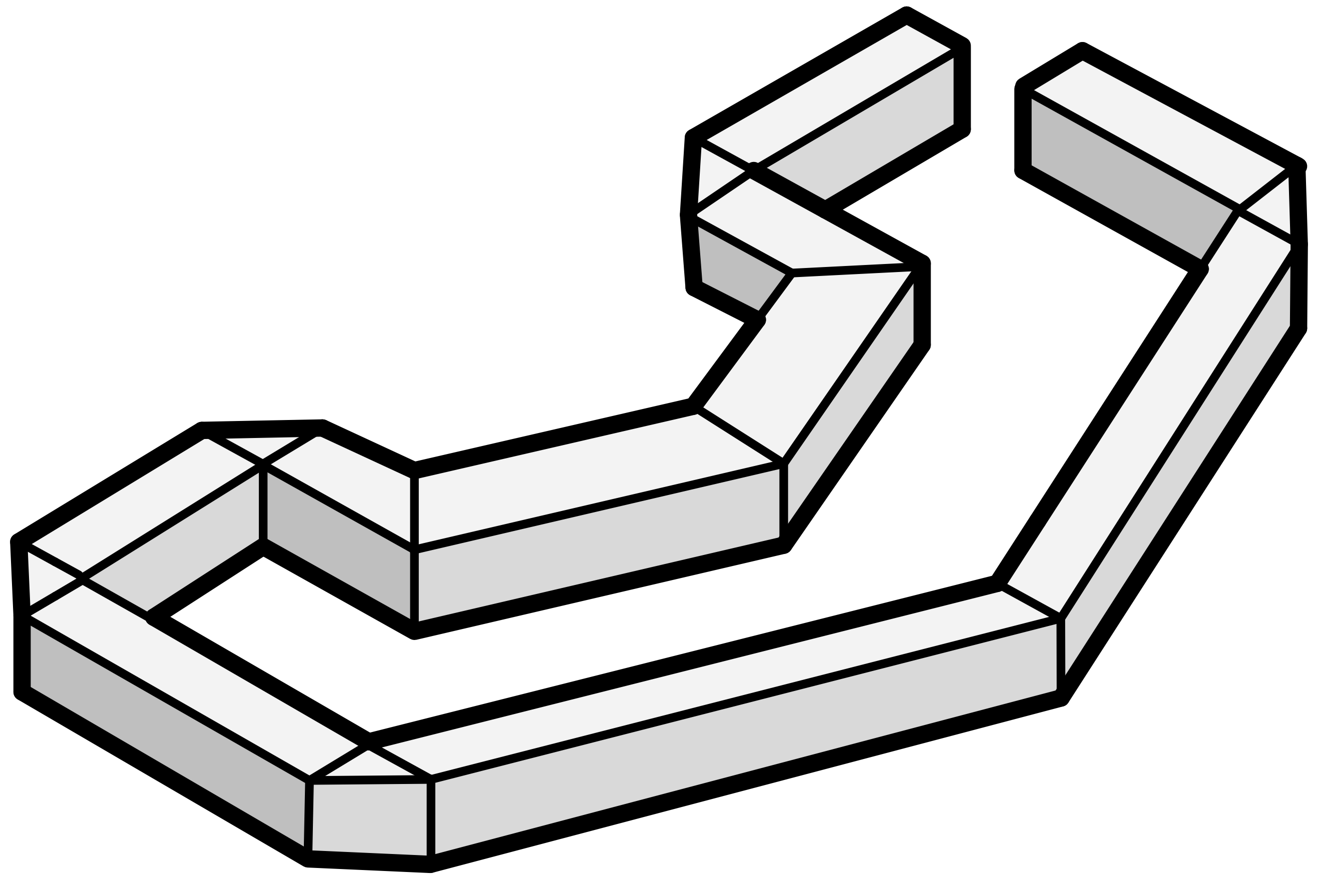

Pin Array


Voxel


Layers

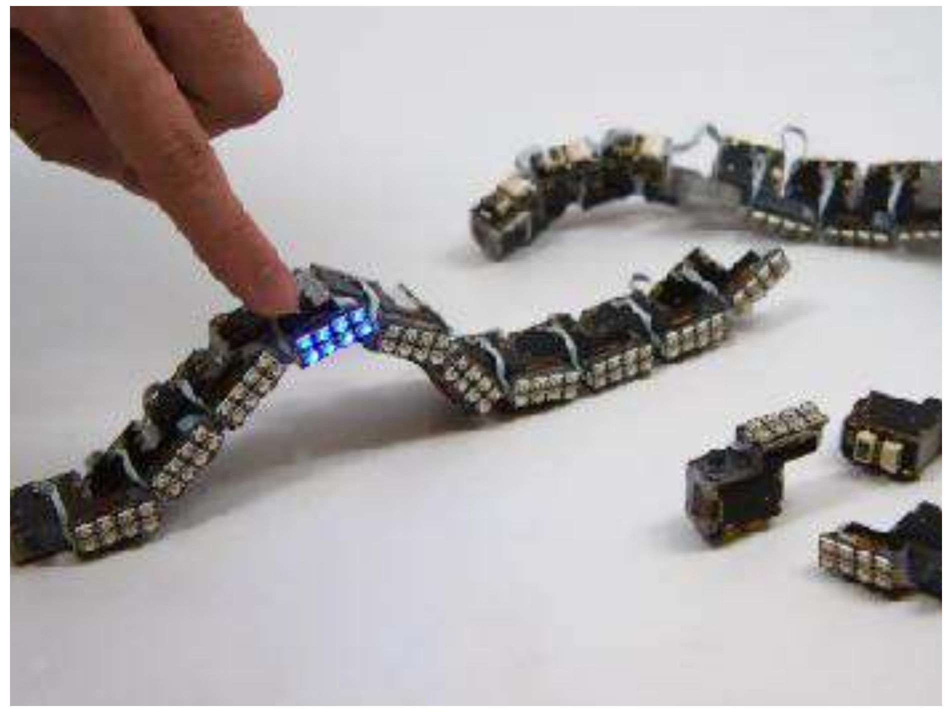

Surface

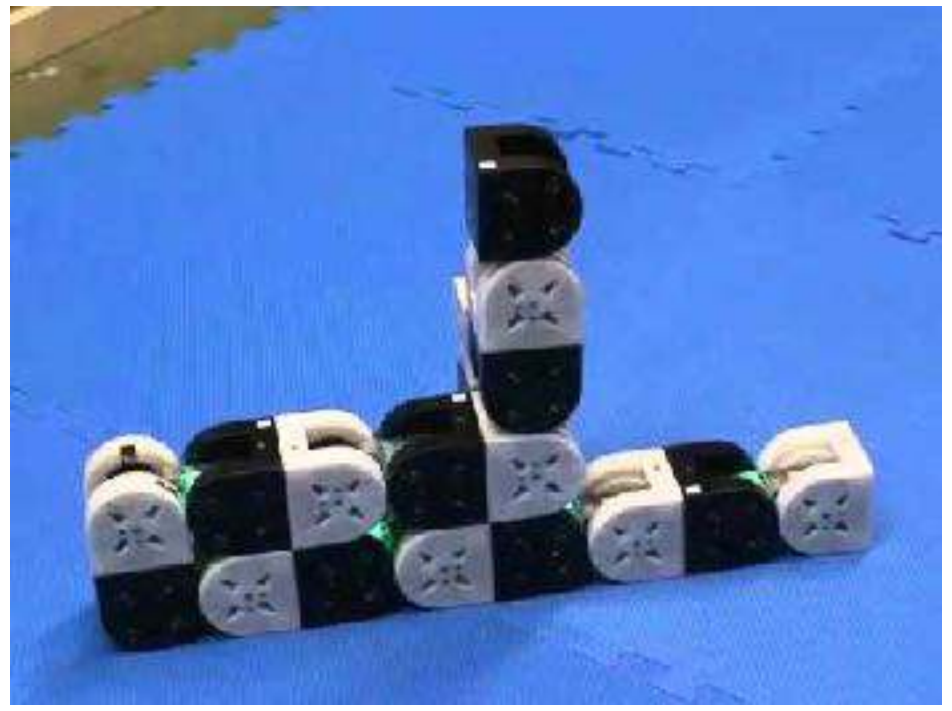

Hub and Struts

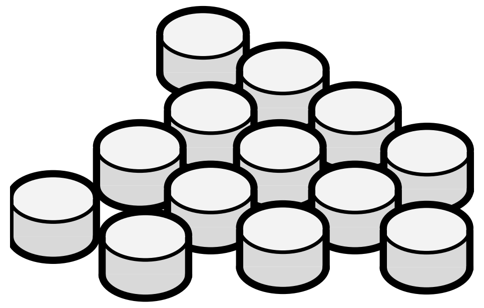


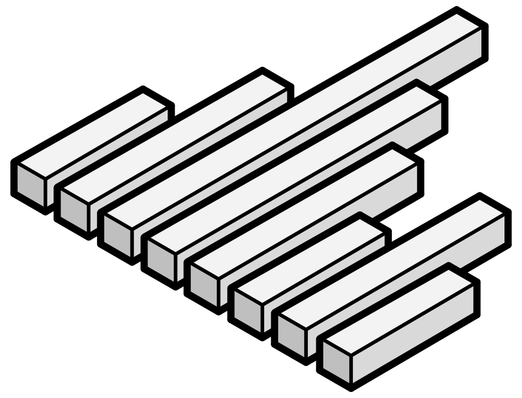
Single Line

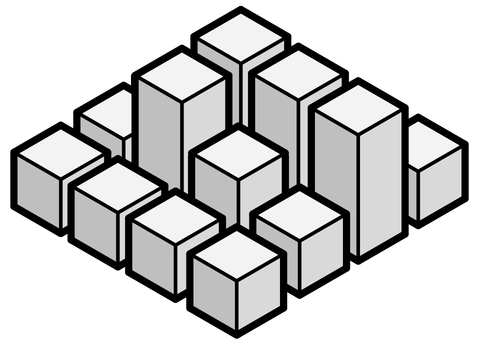

[Cubimorph, Roudaut 2016]

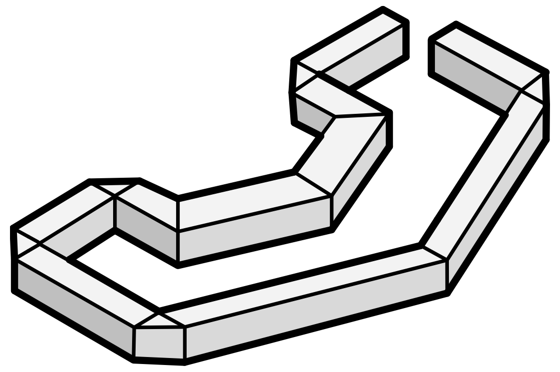

[ChainFORM, Nakagaki 2016]

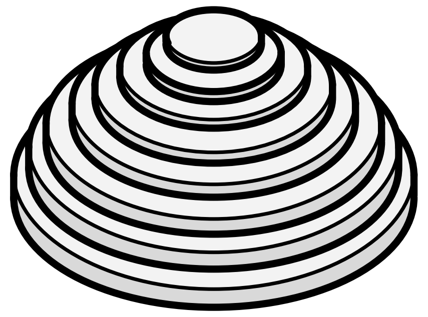

[M-TRAN, Murata 2002]

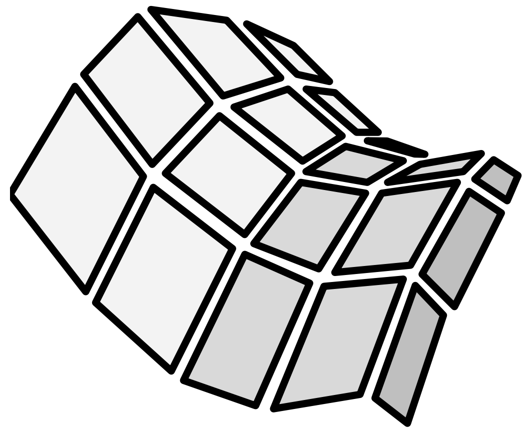

Sparse Dots

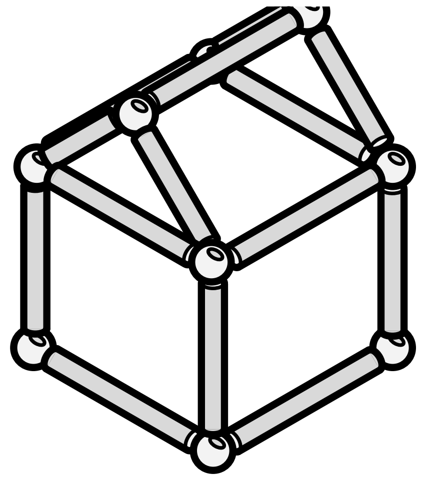

Sparse Lines

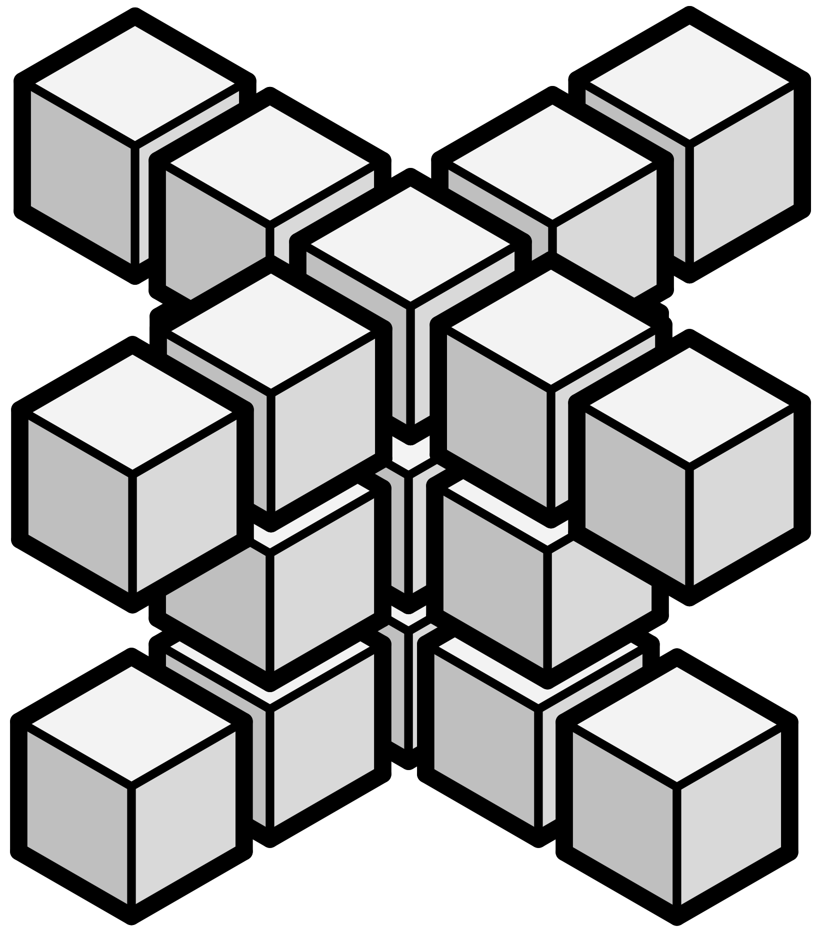

Pin Array

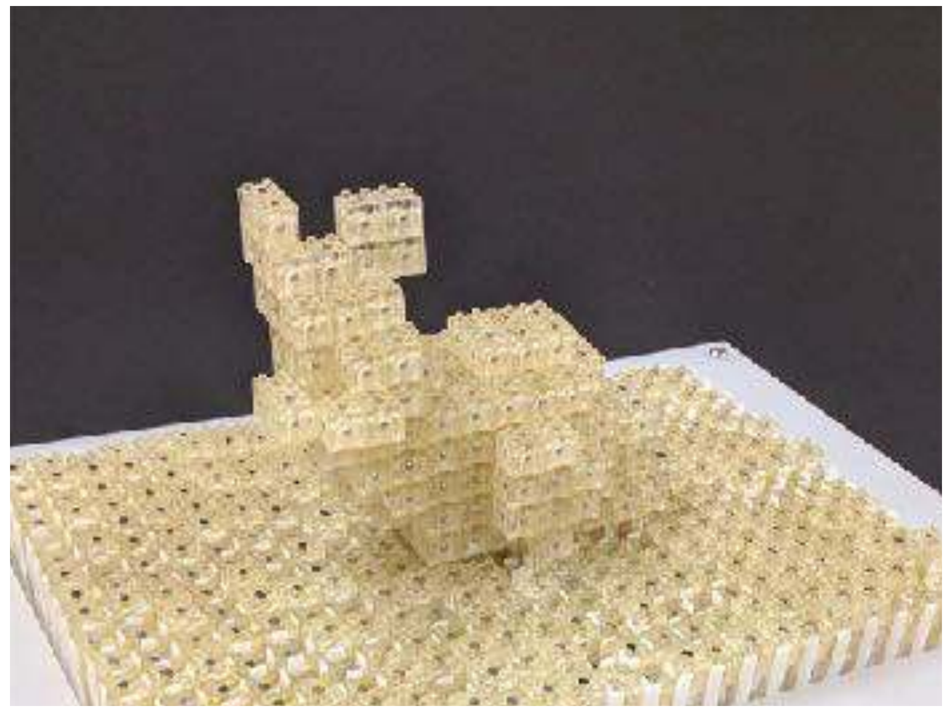

Single Line


Layers

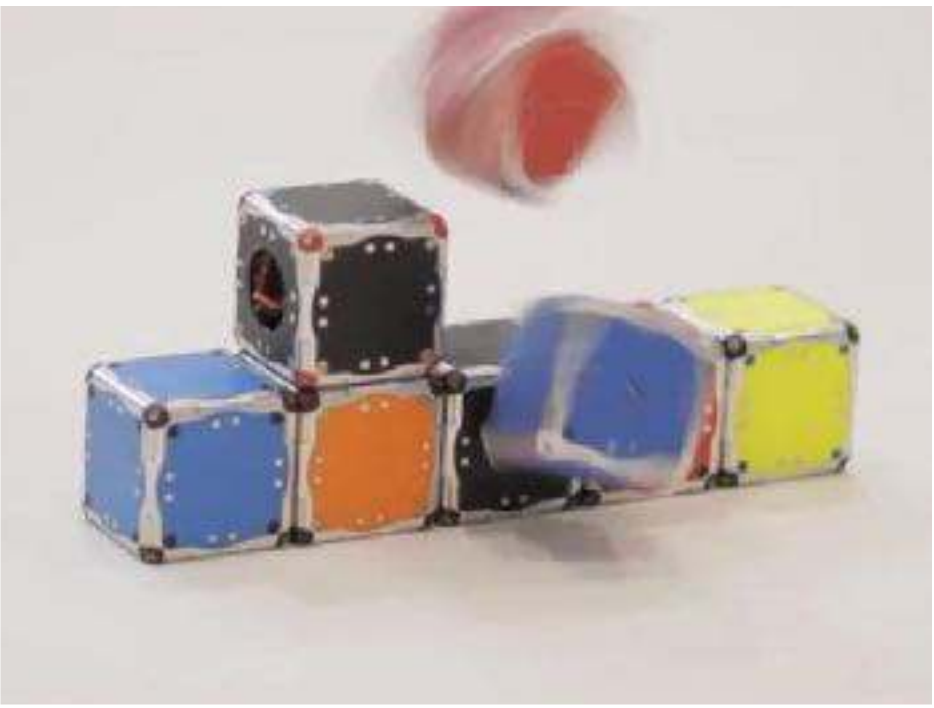

Surface

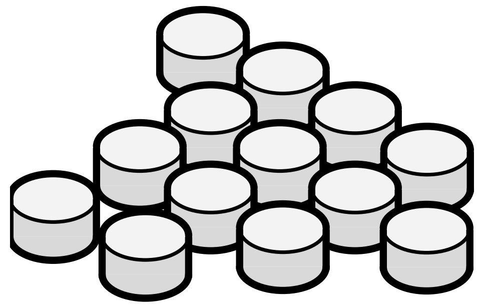

Hub and Struts

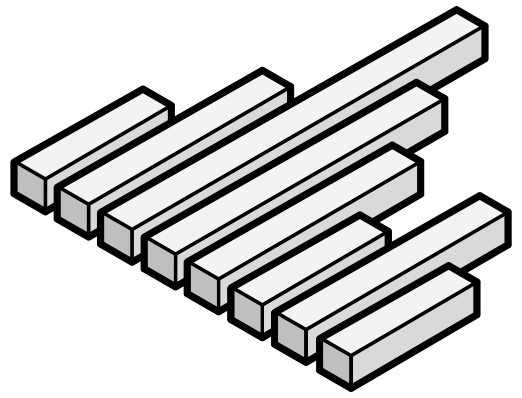

Voxel

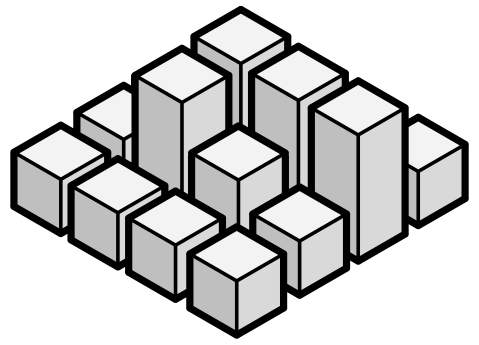

[Dynablock, Suzuki 2018]


[Zhao 2017]


[M-Blocks, Romanishin 2013]


Sparse Dots


Sparse Lines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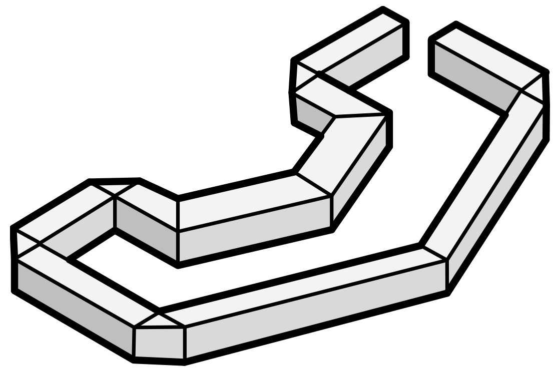
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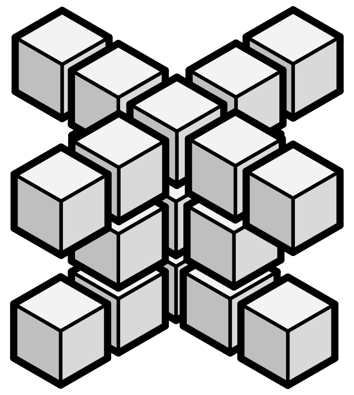
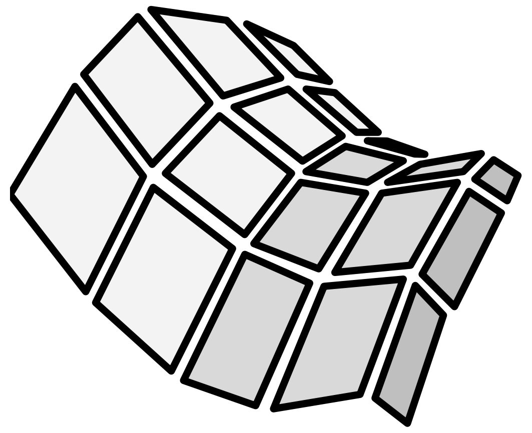
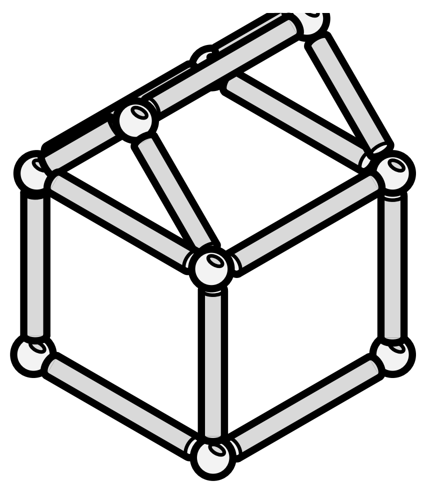
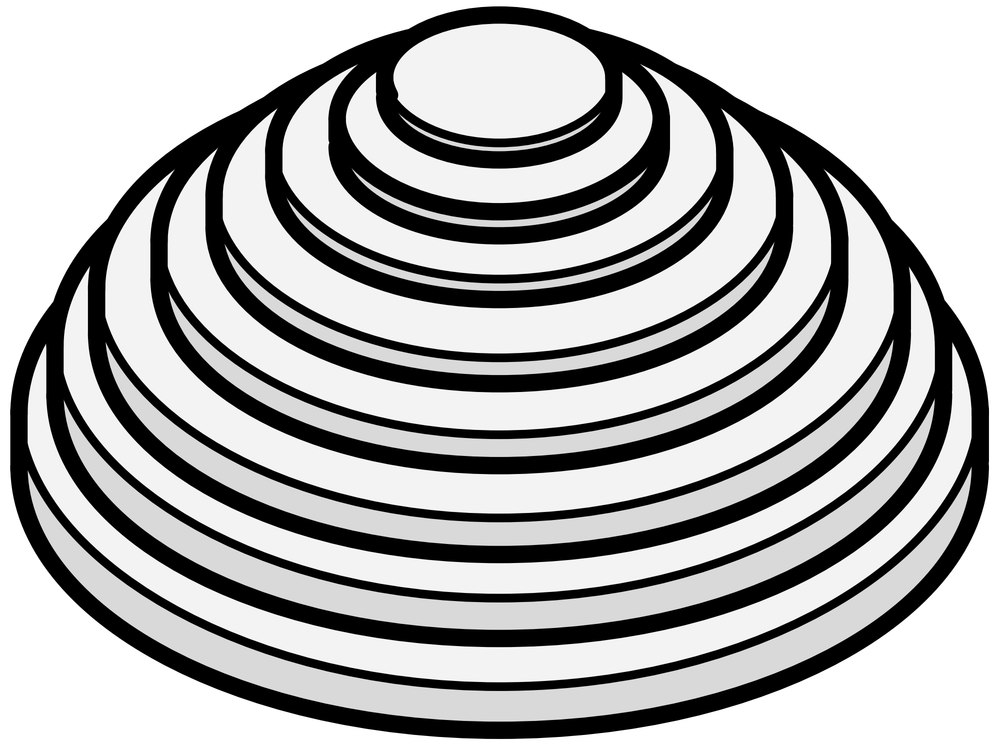
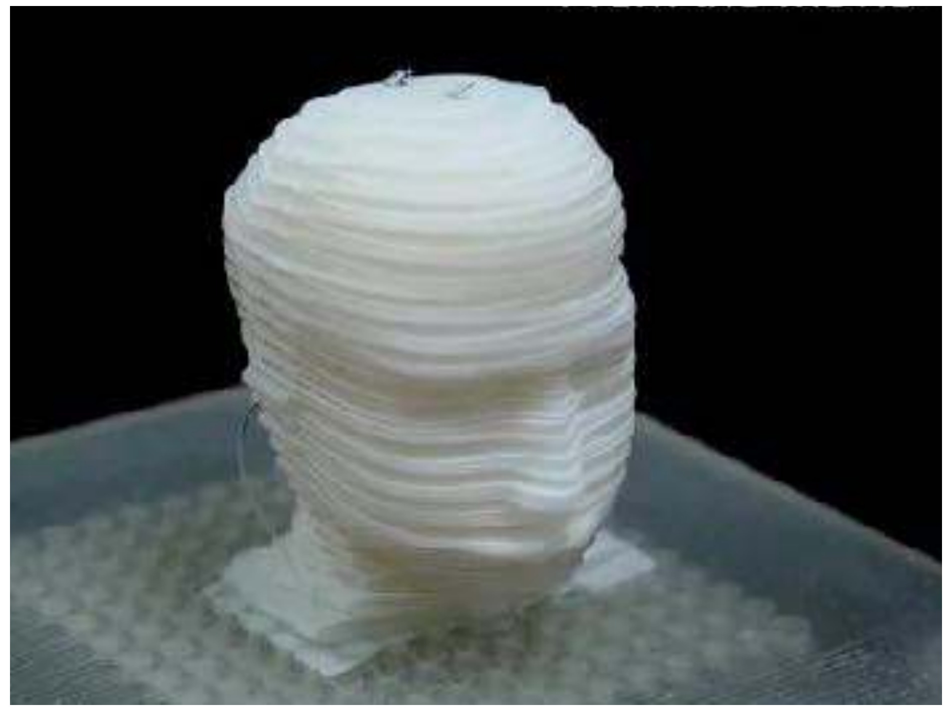

Voxel

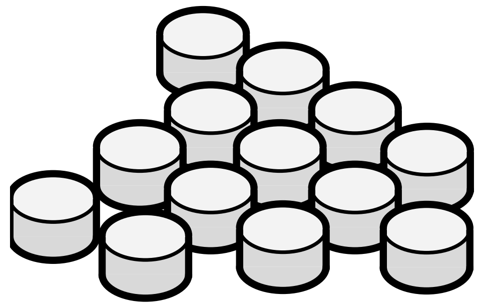

Surface

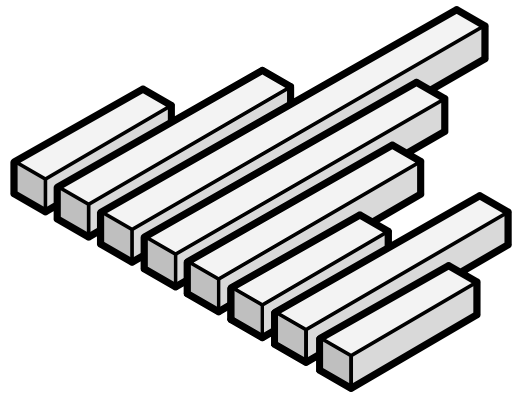

Hub and Struts

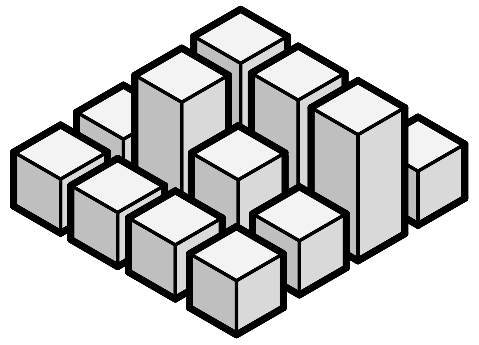

Layers

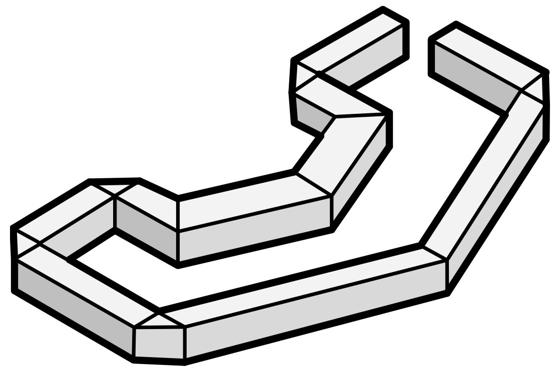

[Additive Folding, Yim 2018]

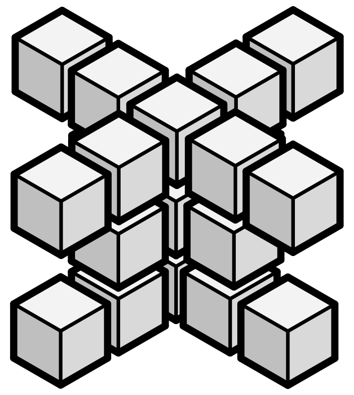

[BendingArches, Morten 2016]

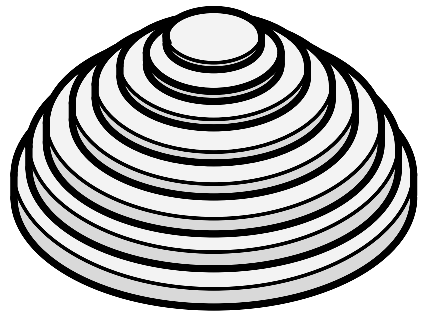

Sparse Dots

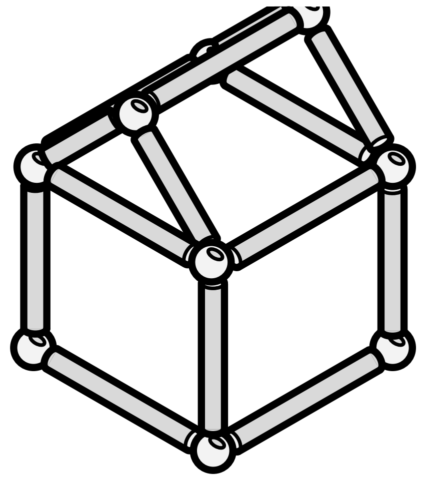

Sparse Lines

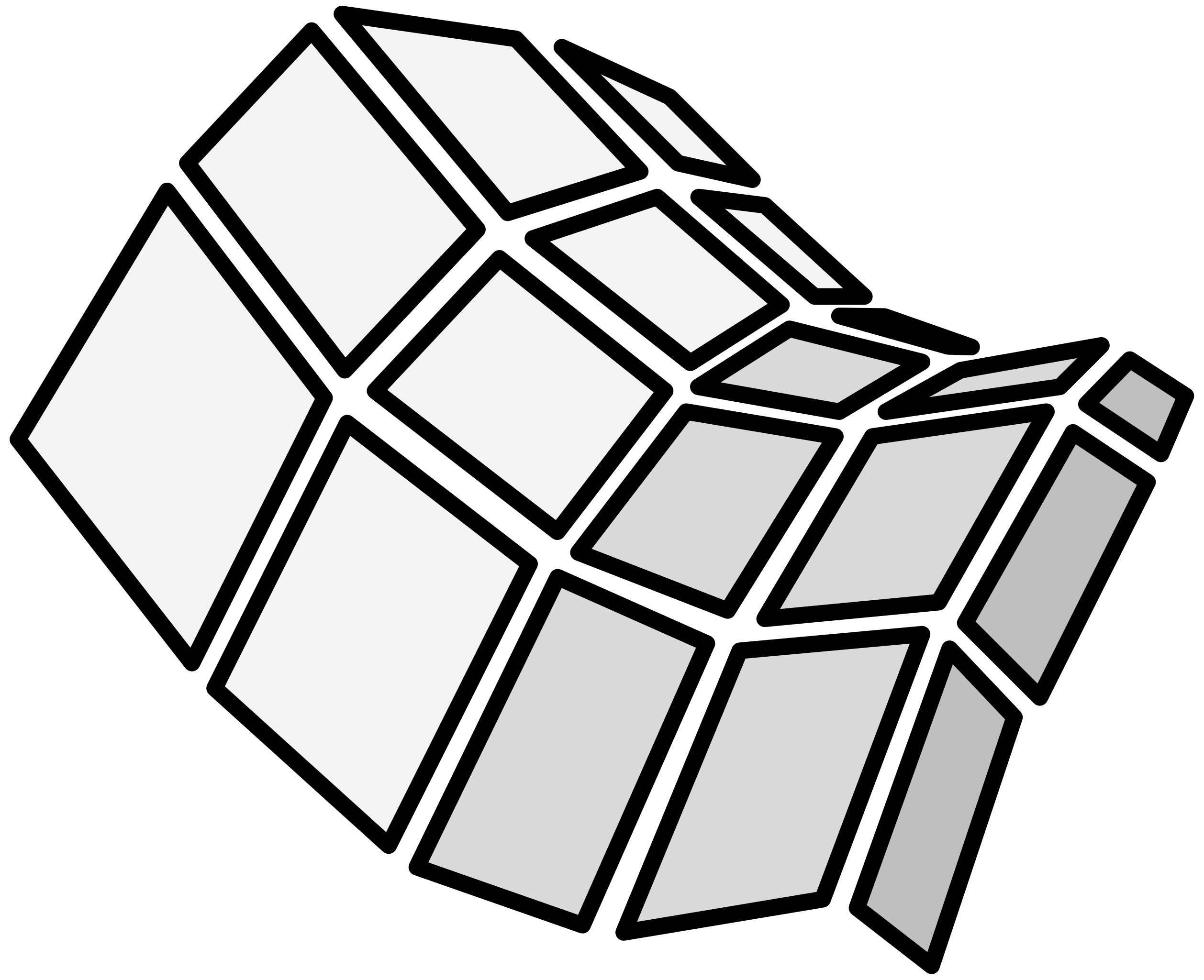

Pin Array


Single Line


Voxel

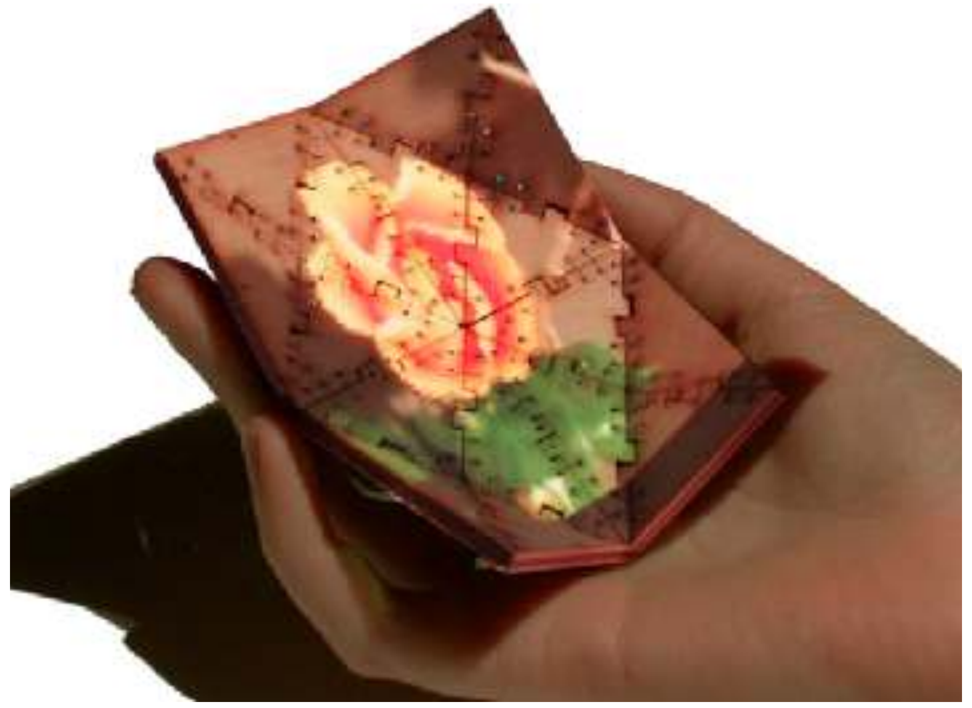

Layers

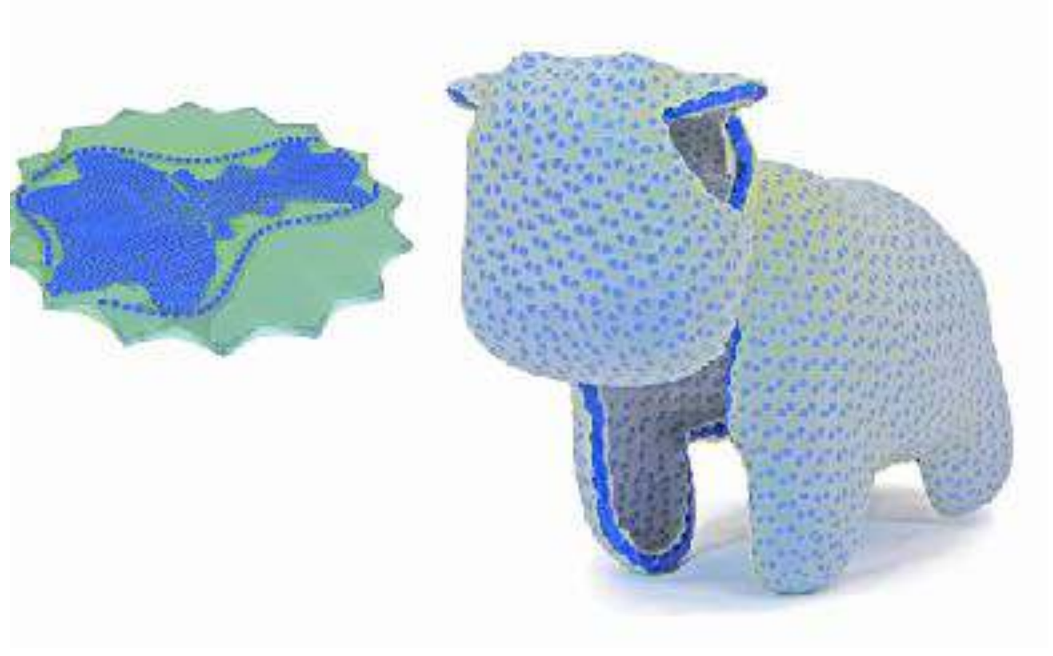

Hub and Struts

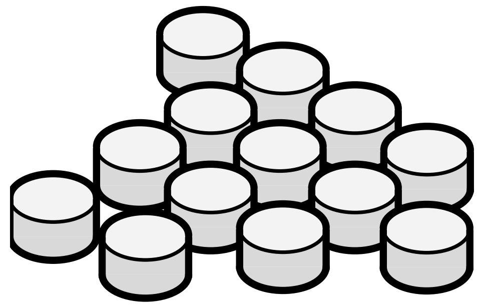


Surface

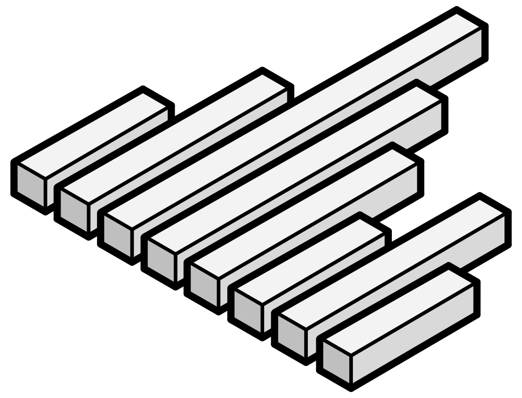

[MORI, Belke 2017]


[Morphees, Roudaut 2013]

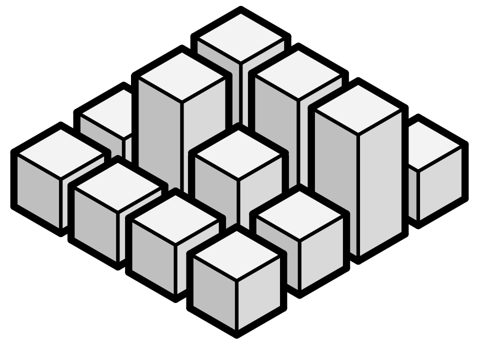

[CurveUps, Guseinov 2017]



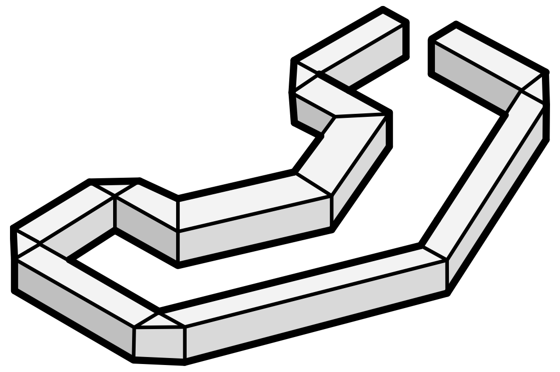
Sparse Dots



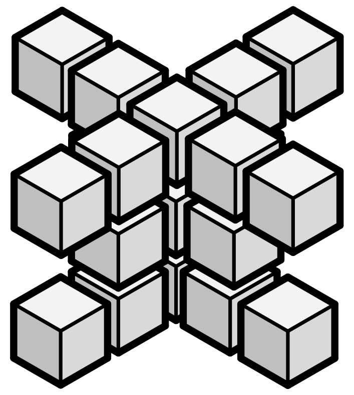
Sparse Lines



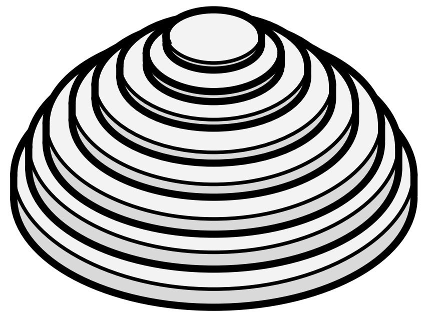
Pin Array



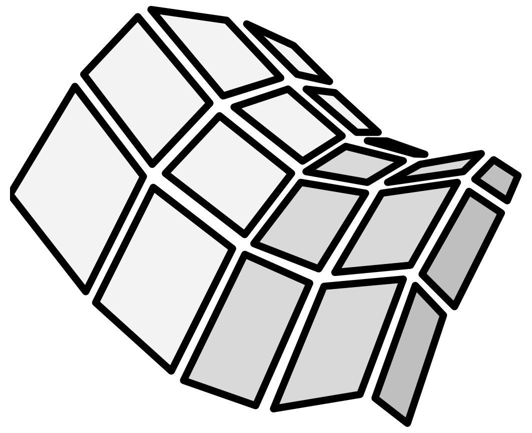
Single Line



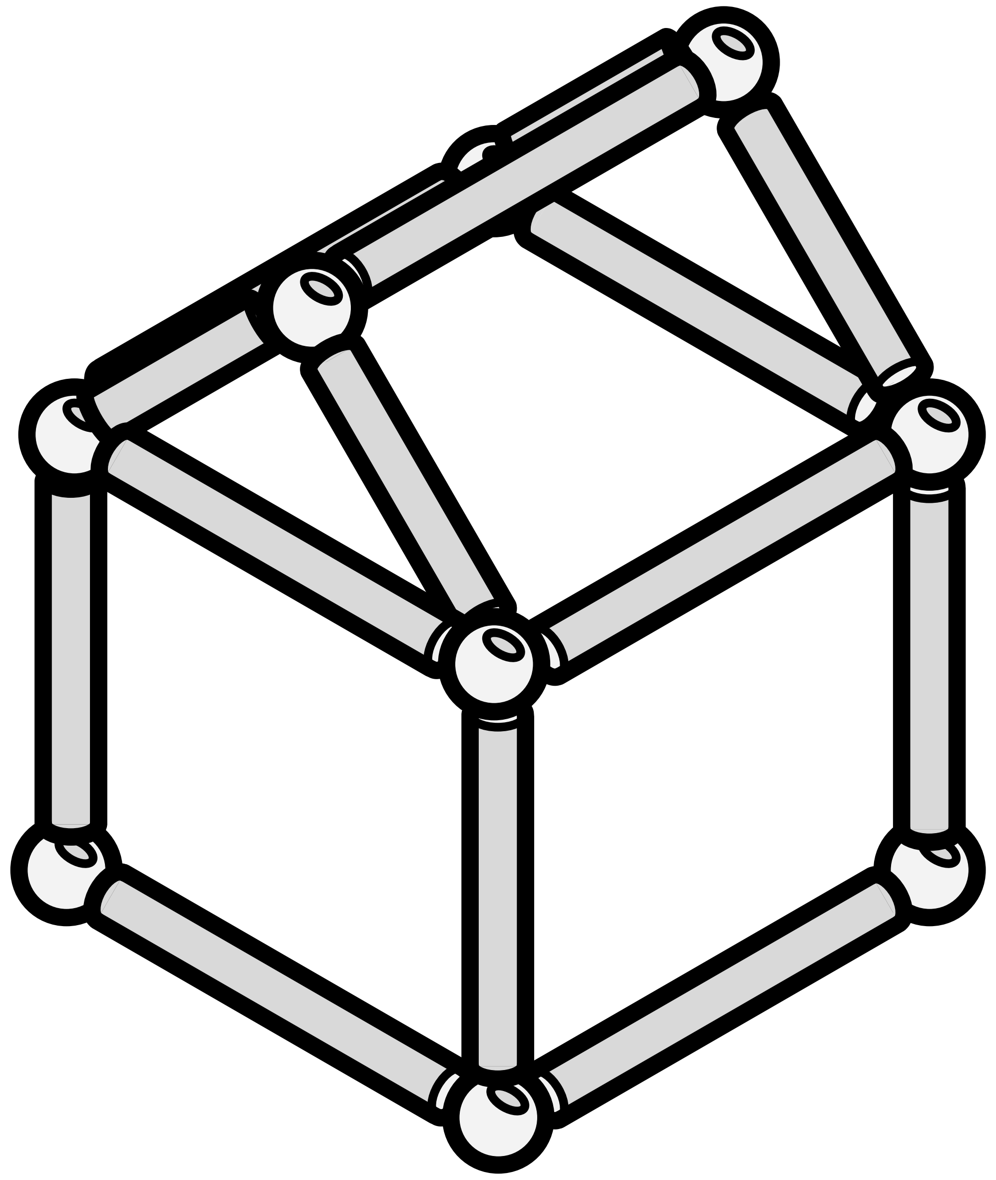
Voxel



Layers



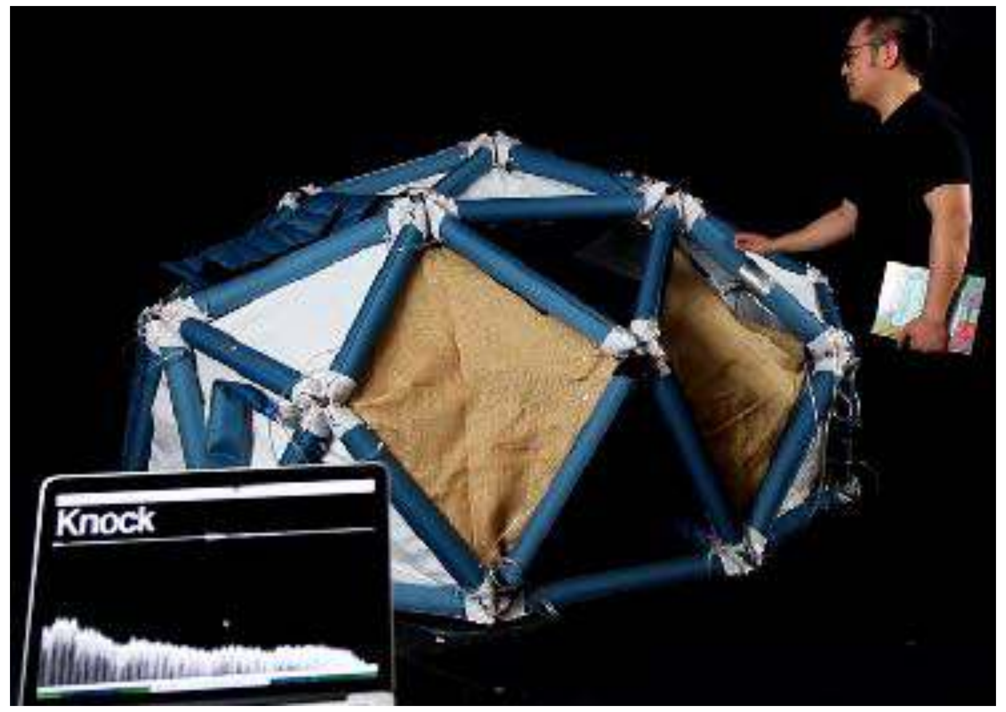
Surface



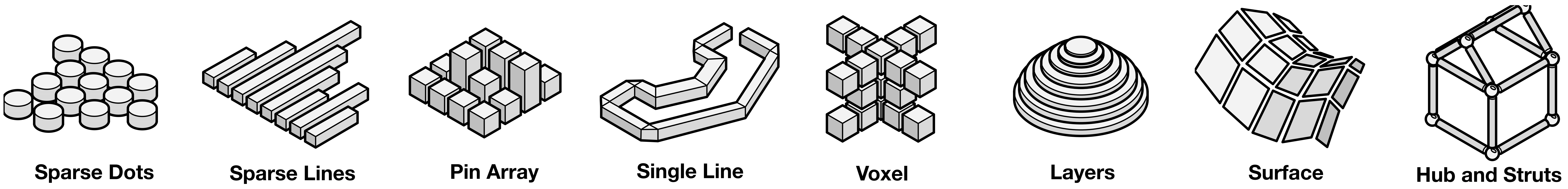
Hub and Struts

[Hammond 2020]

[KineReels, Takei 2011]



[Swaminathan 2019]


Sparse Dots
Sparse Lines
Pin Array
Single Line
Voxel
Layers
Surface
Hub and Struts


Sparse Dots
Sparse Lines
Pin Array
Single Line
Voxel
Layers
Surface
Hub and Struts
Active Elements
Passive Elements

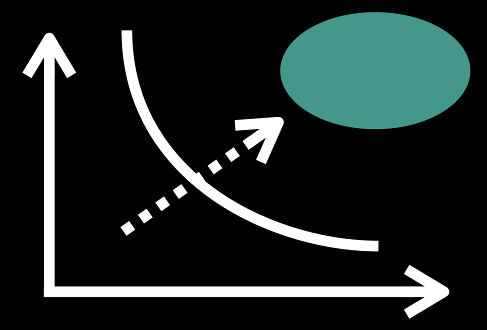
I demonstrate and explore new representations to expand the current scope

I demonstrate and explore new representations to expand the current scope

also discuss future research opportunities and exploration strategies to fill the gap

Background

Why This Approach?

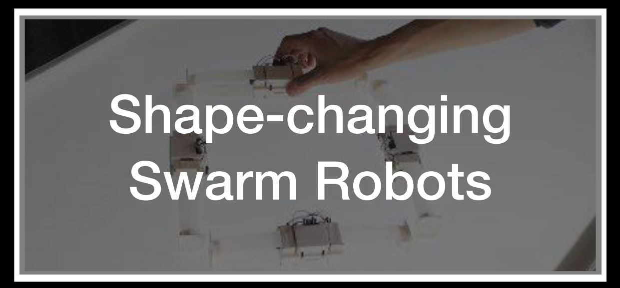


Concept

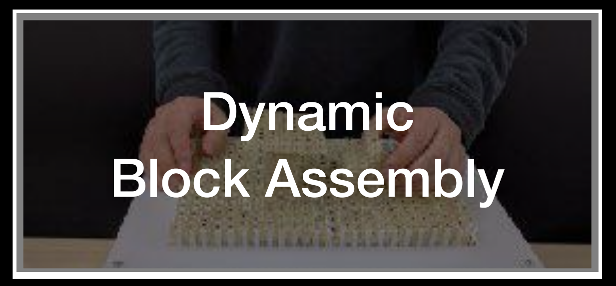
What is
Dynamic and Collective
Shape Construction?

Explorations

Shape Construction
with **Active** Elements



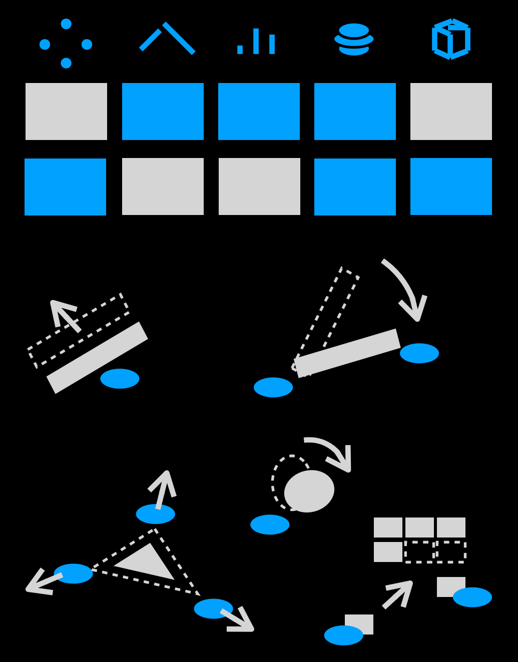
Shape Construction
with **Passive** Elements



Interaction with
Collective Elements

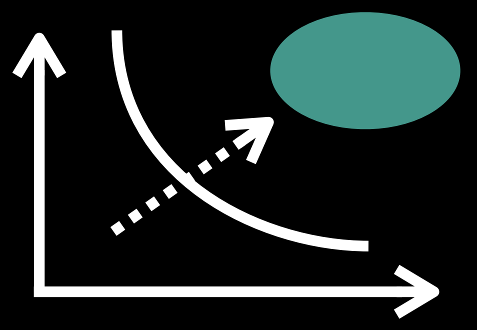
Discussion

What's Next?



Background

Why This Approach?



Concept

What is
Dynamic and Collective
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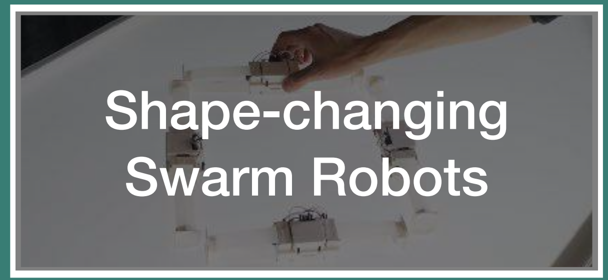
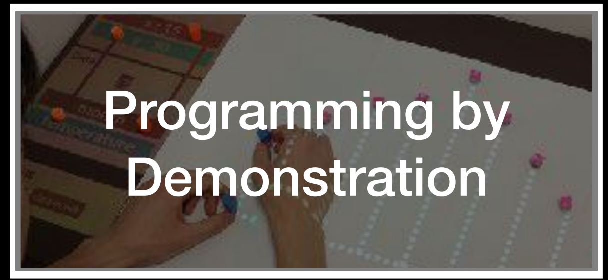
Explorations

Shape Construction
with **Active** Elements



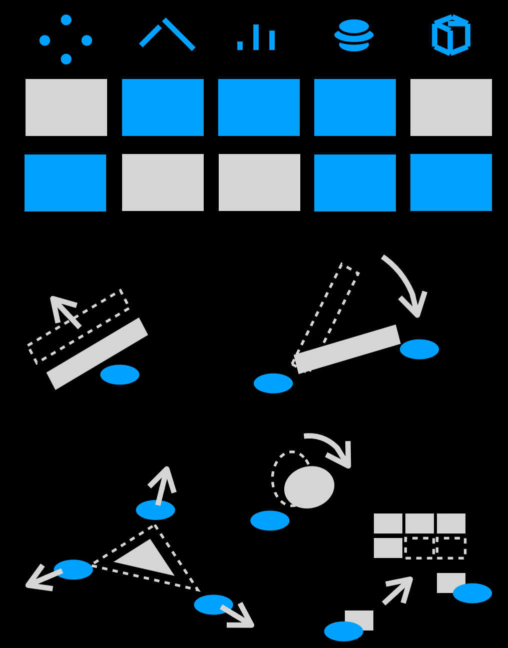
Shape Construction
with **Passive** Elements

Interaction with
Collective Elements



Discussion

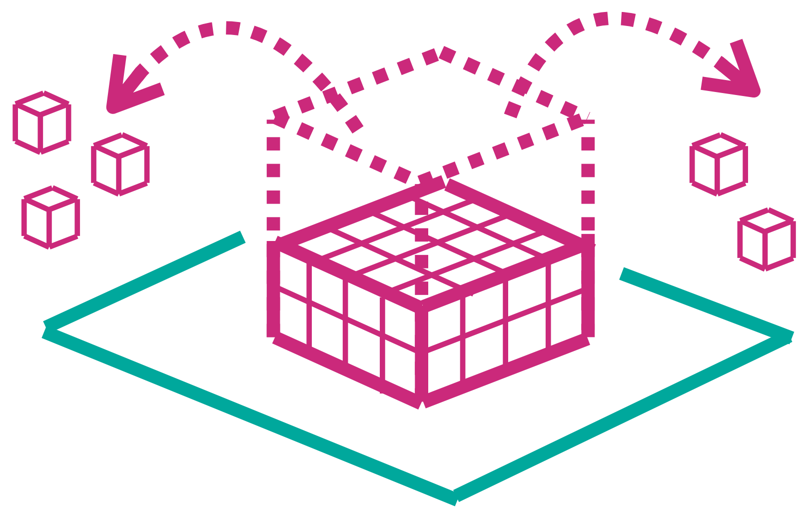
What's Next?



The focus of this thesis

Dynamic and **collective** shape construction

Dynamic Physical UI

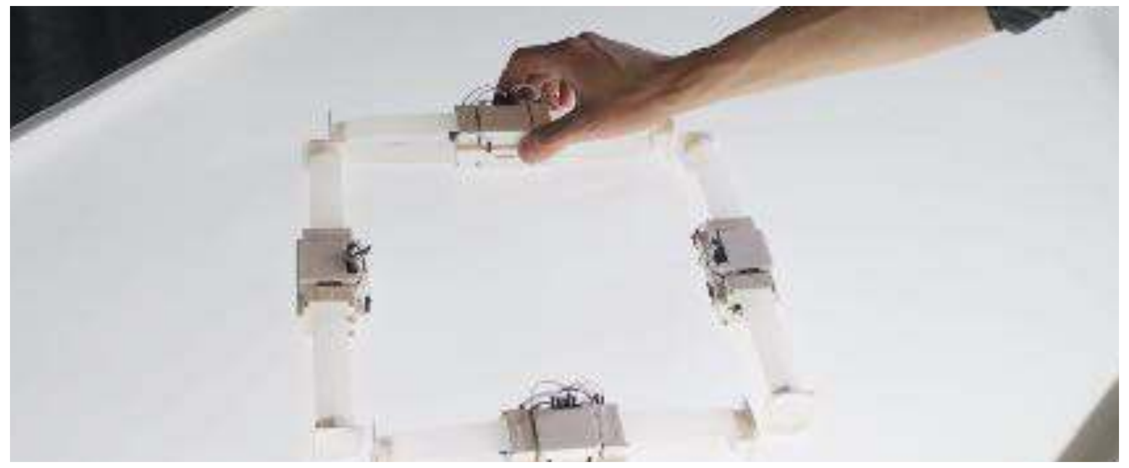


Shape Change with **Collective Elements**

Active collective elements

||

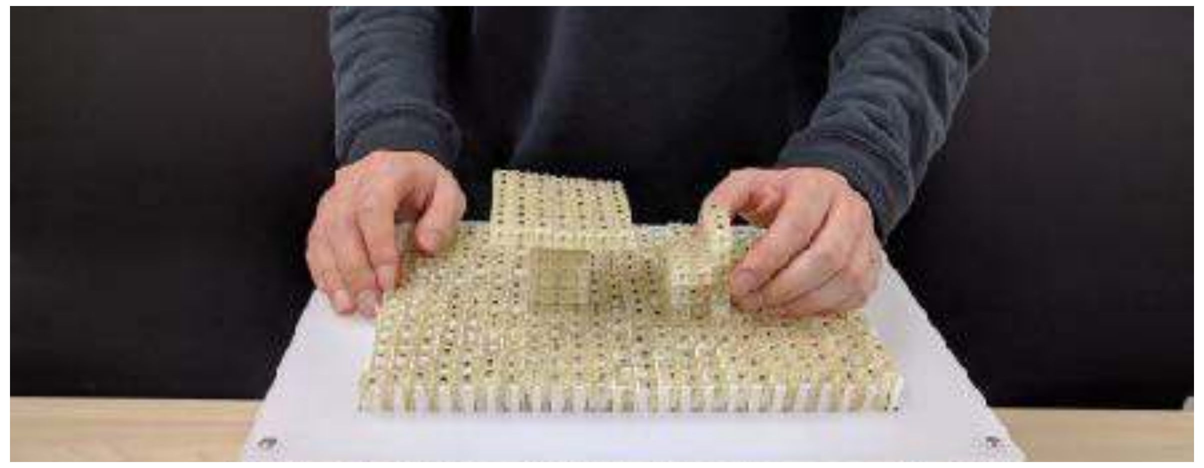
self-actuated elements that can move or reconfigure themselves with internal actuation



Passive collective elements

||

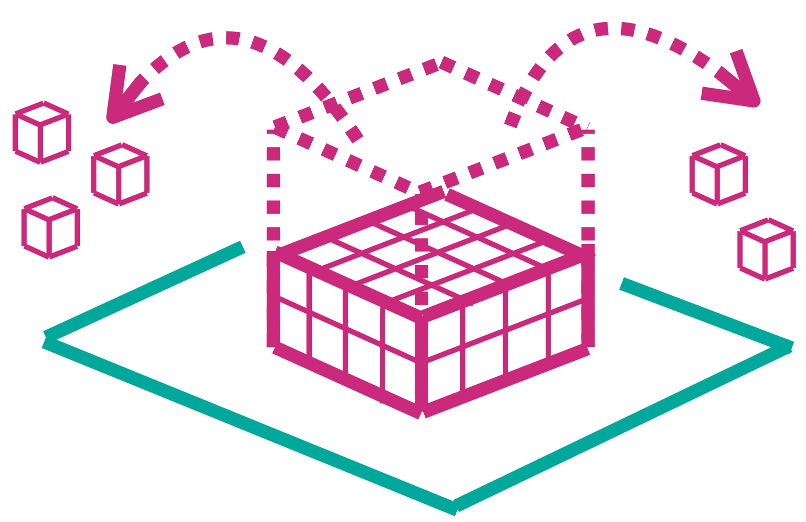
externally-actuated elements that can move or reconfigure through external actuation



The focus of this thesis

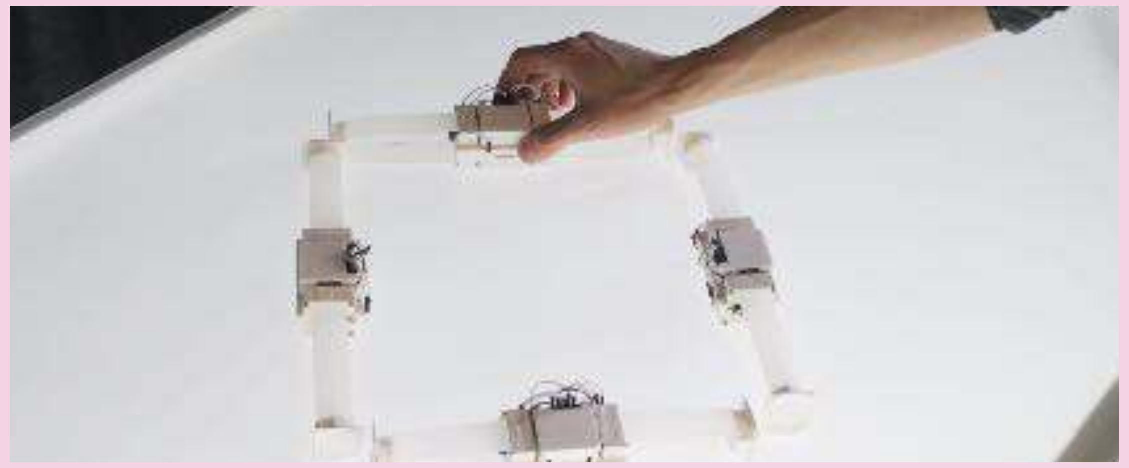
Dynamic and **collective** shape construction

Dynamic Physical UI

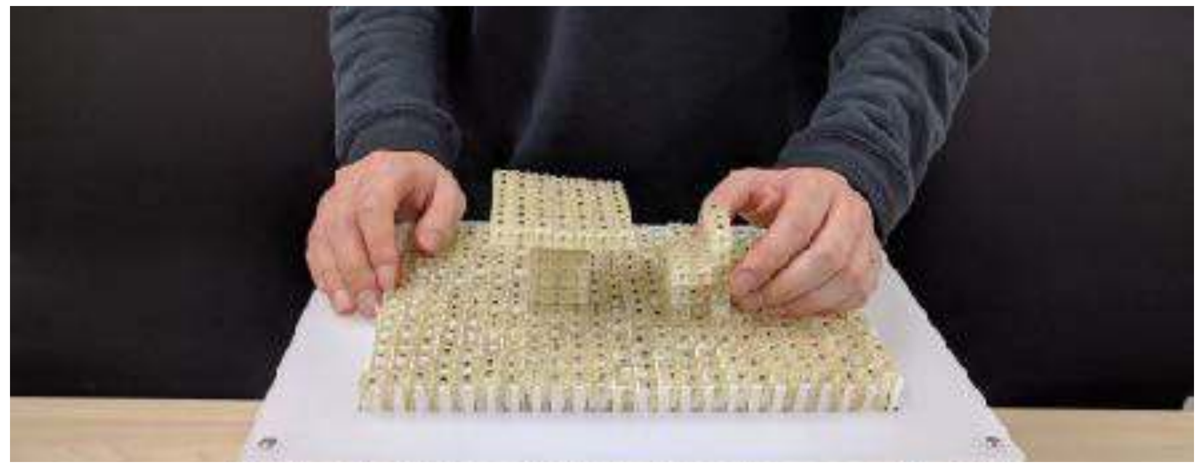


Shape Change with **Collective Elements**

Active collective elements
||
self-actuated elements that can move or reconfigure themselves with internal actuation



Passive collective elements
||
externally-actuated elements that can move or reconfigure through external actuation



Active

collective elements

self-actuated elements
that can move or reconfigure
themselves with internal actuation

Zooids
[Le Goc UIST 2016]

UbiSwarm
[Kim UbiComp 2017]

GridDrones
[Braley UIST 2018]

Rovables
[Dementyev UIST 2016]

PICO
[Patten CHI 2007]

Rolling Pixels
[Lee TEI 2020]

Swarm User Interfaces: Using Swarm Robots as Displays and Tangible User Interfaces

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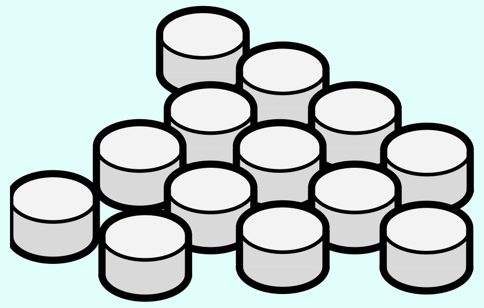
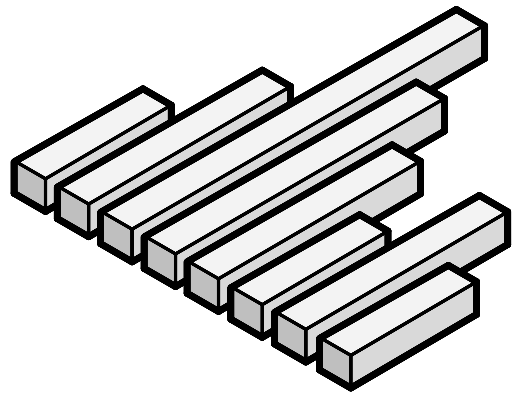
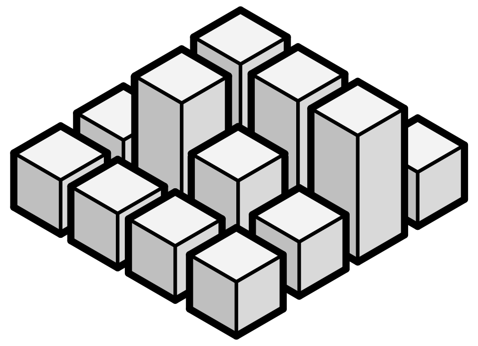


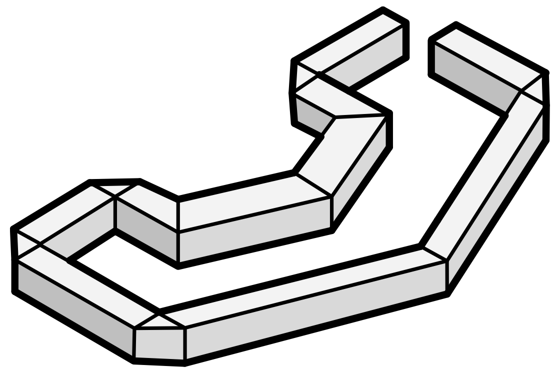
Sparse Dots



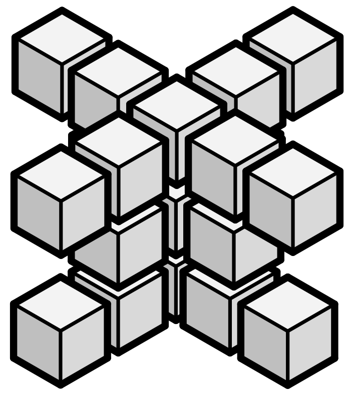
Sparse Lines



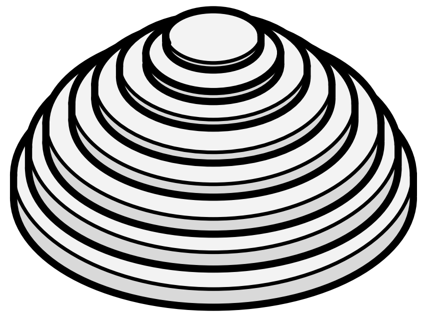
Pin Array



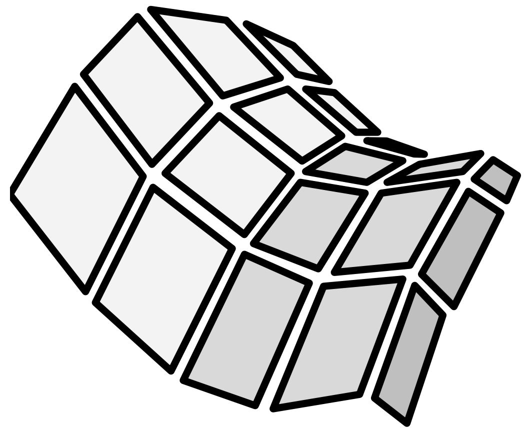
Single Line



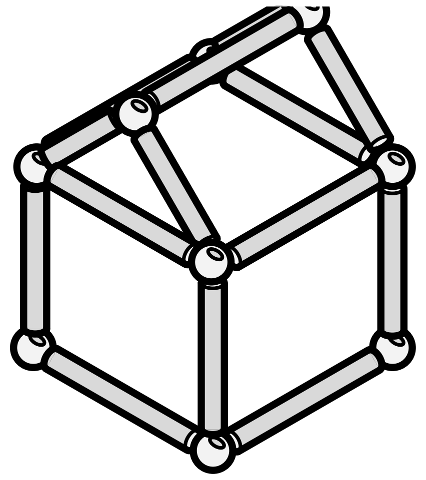
Voxel



Layers



Surface



Hub and Struts

Swarm User Interfaces: Using Swarm Robots as Displays and Tangible User Interfaces

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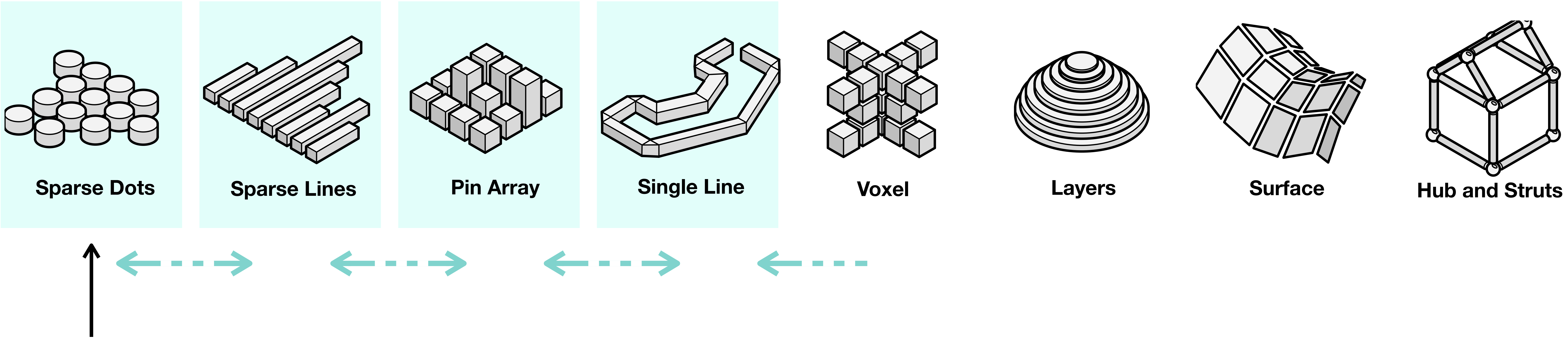
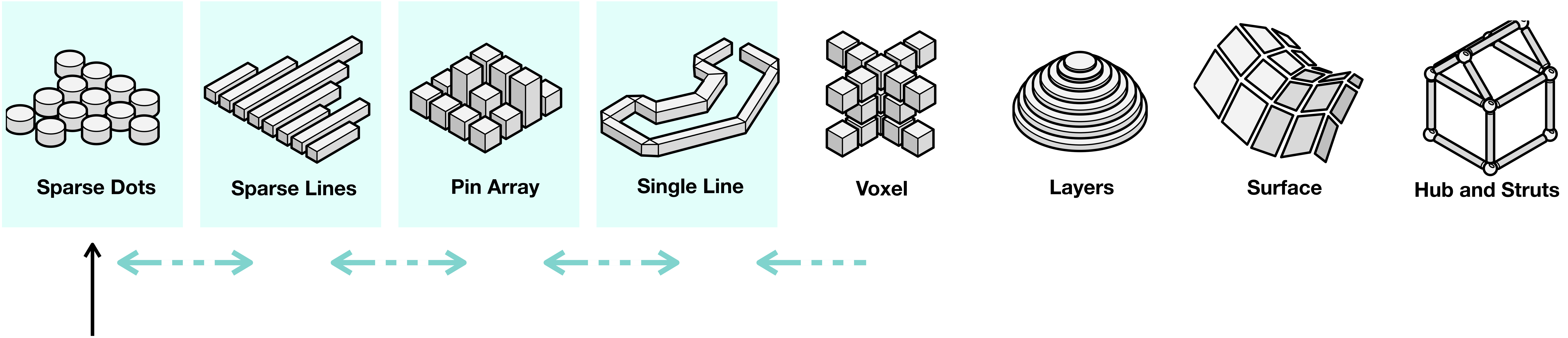


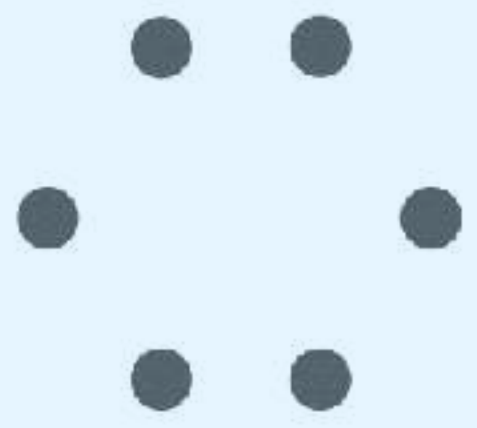
What if these swarm robotic elements can not only represent a shape with sparse dots but also through lines, or pins, or connected lines to expand a range of expressions?

This new type of representations can not only improve expressions but also expand a range of applications and interaction space



What if these swarm robotic elements can not only represent a shape with spatially aligned dots but also through lines, or pins, or connected lines to expand a range of expressions?

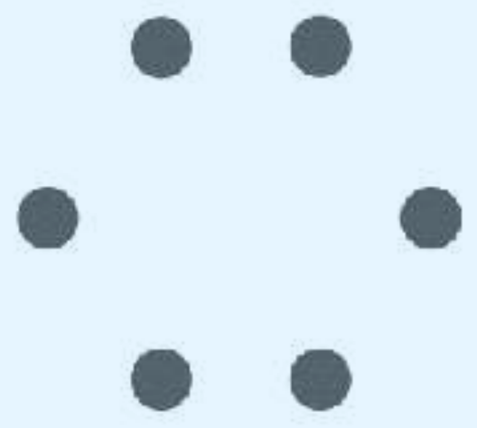
Swarm Robots



Collective

Shape Transformation

Swarm Robots



Shape-changing UI

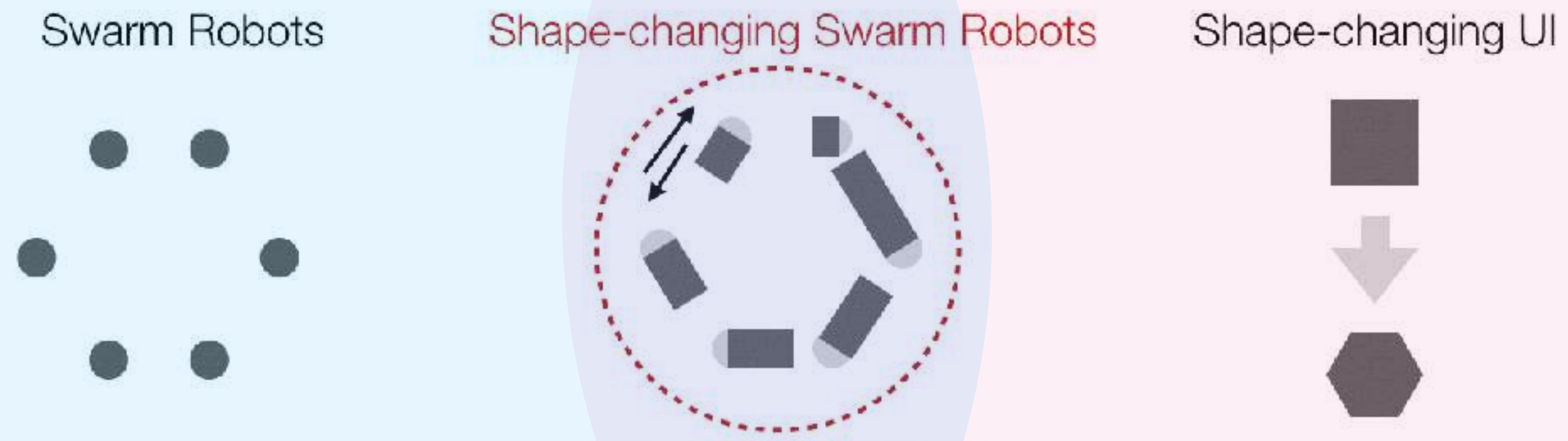
Collective

Shape Transformation

Individual

Shape Transformation

Collective and Individual
Shape Transformation



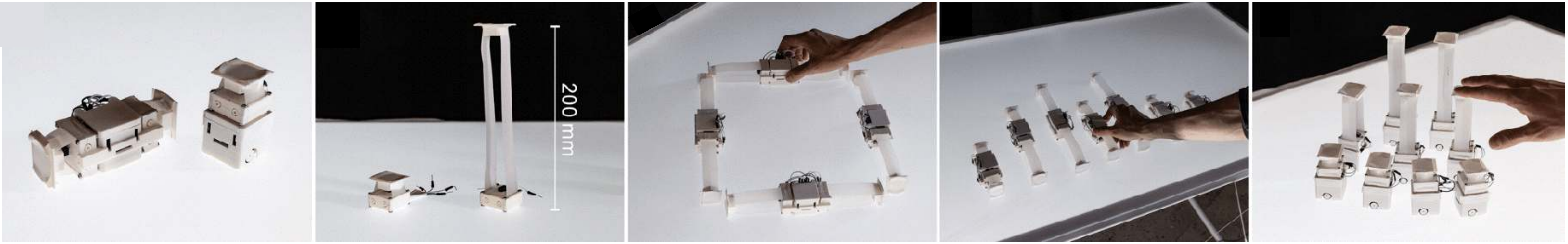
Collective
Shape Transformation

Individual
Shape Transformation

[UIST 2019]

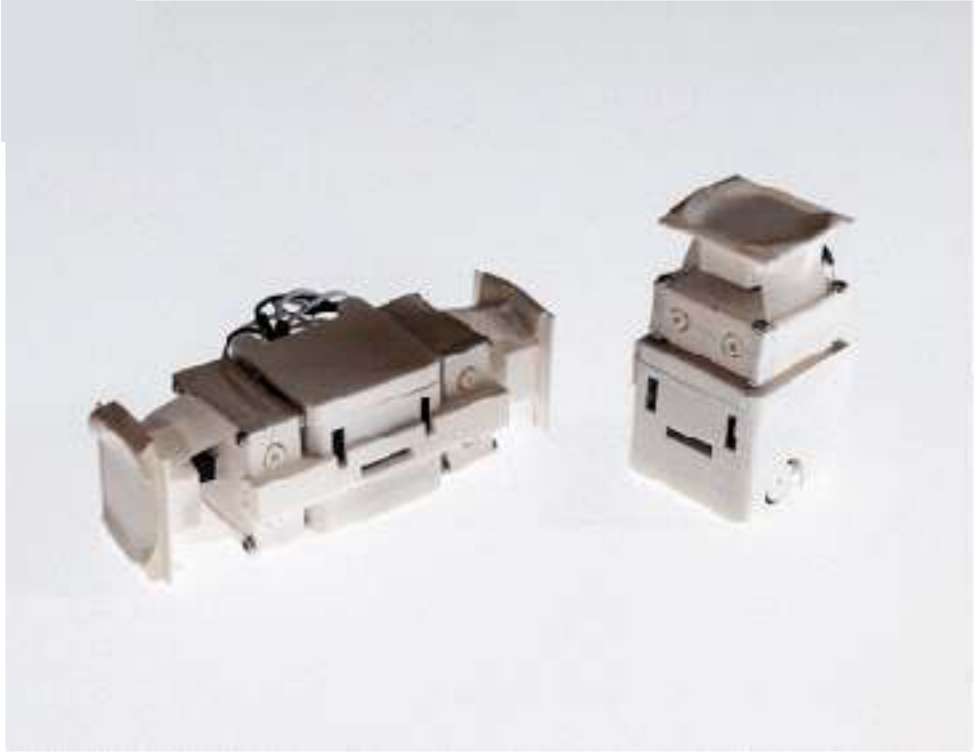
ShapeBots: Shape-changing Swarm Robots

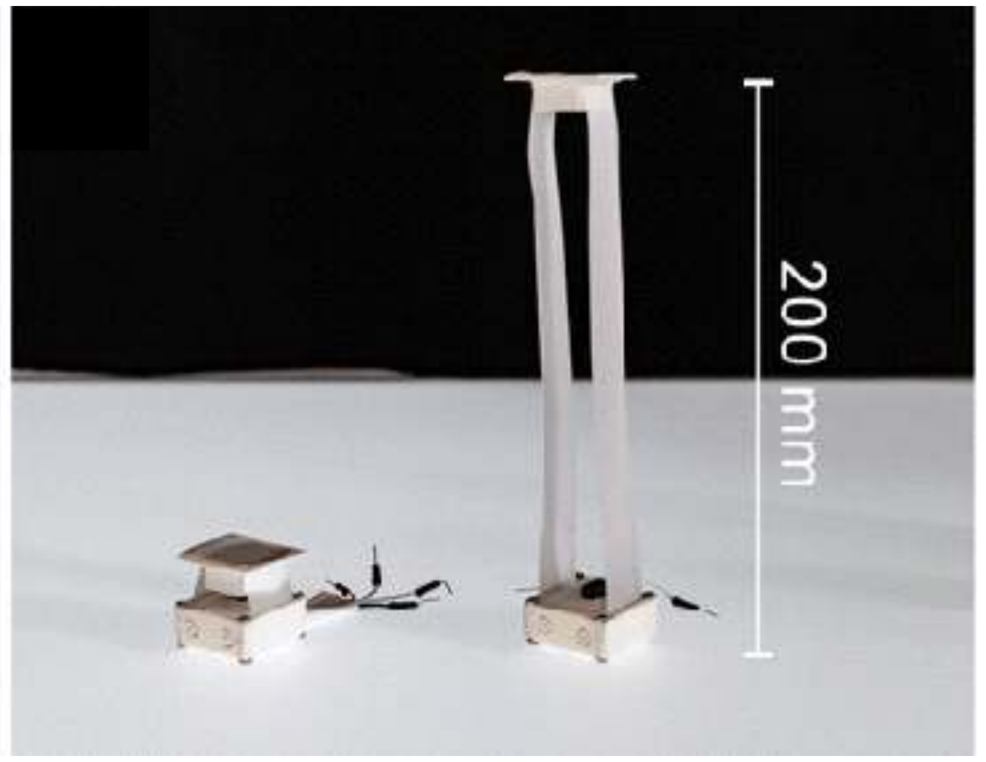
by Suzuki, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger



[UIST 2019] *ShapeBots: Shape-changing Swarm Robots* by **Suzuki**, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger

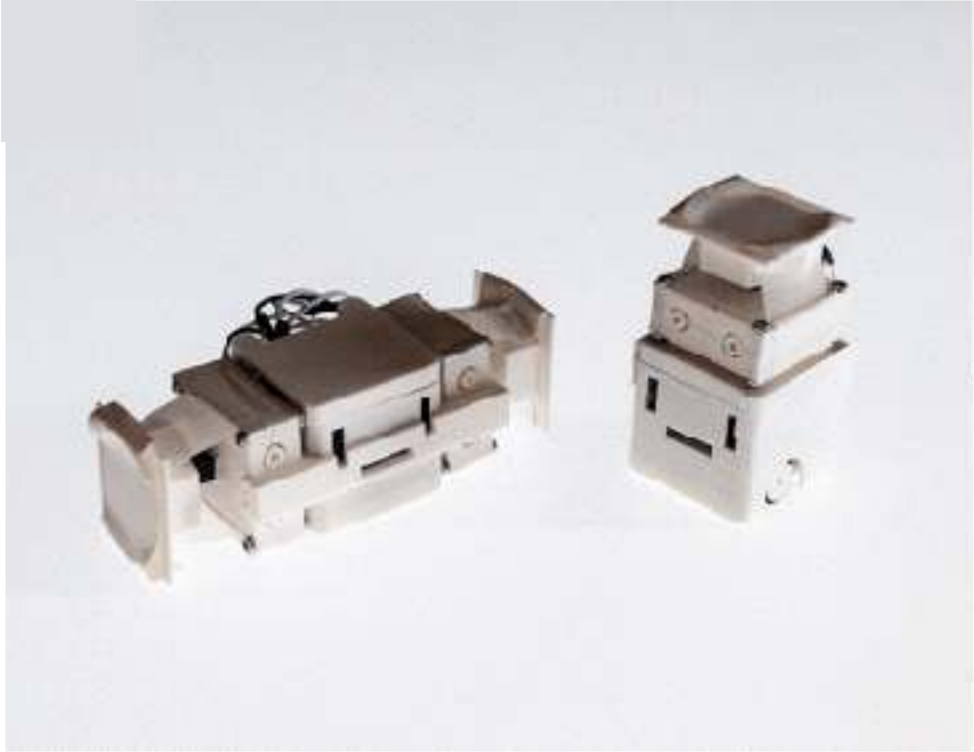
ShapeBots is a demonstration of **swarm robots** that can **both individually and collectively** transform their shape.
We explore how **shape-changing swarm robots** can expand a range of expressions for information display as well as application space for tangible user interfaces

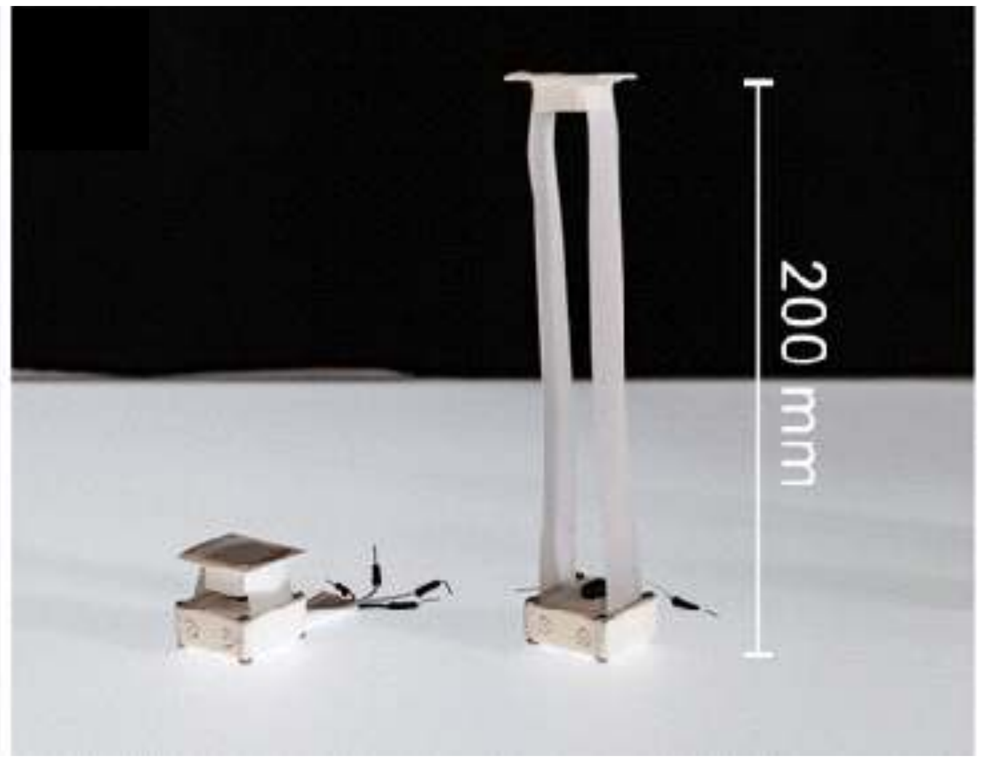


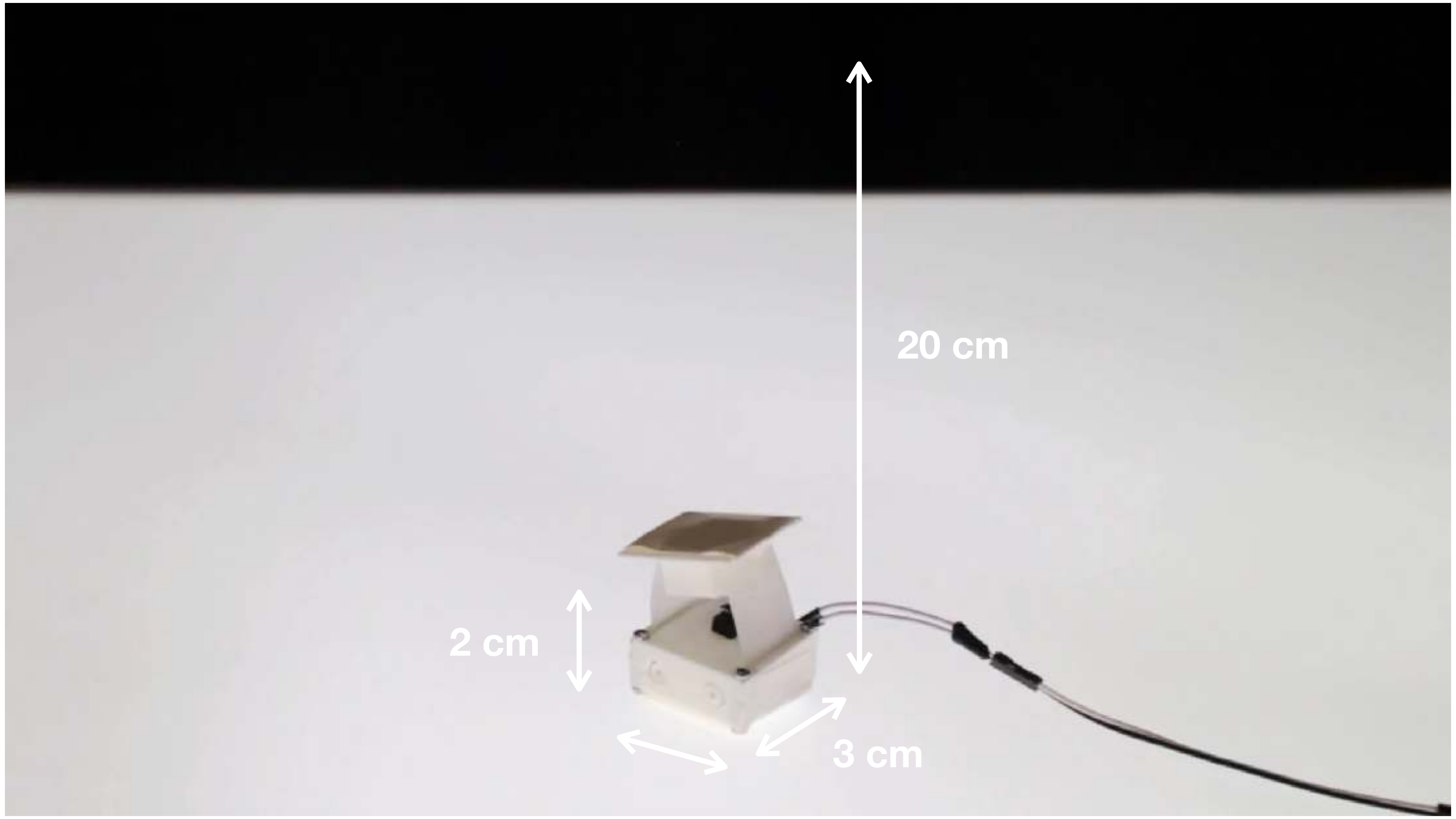


[UIST 2019] *ShapeBots: Shape-changing Swarm Robots* by **Suzuki**, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger

Miniature Reel Actuator

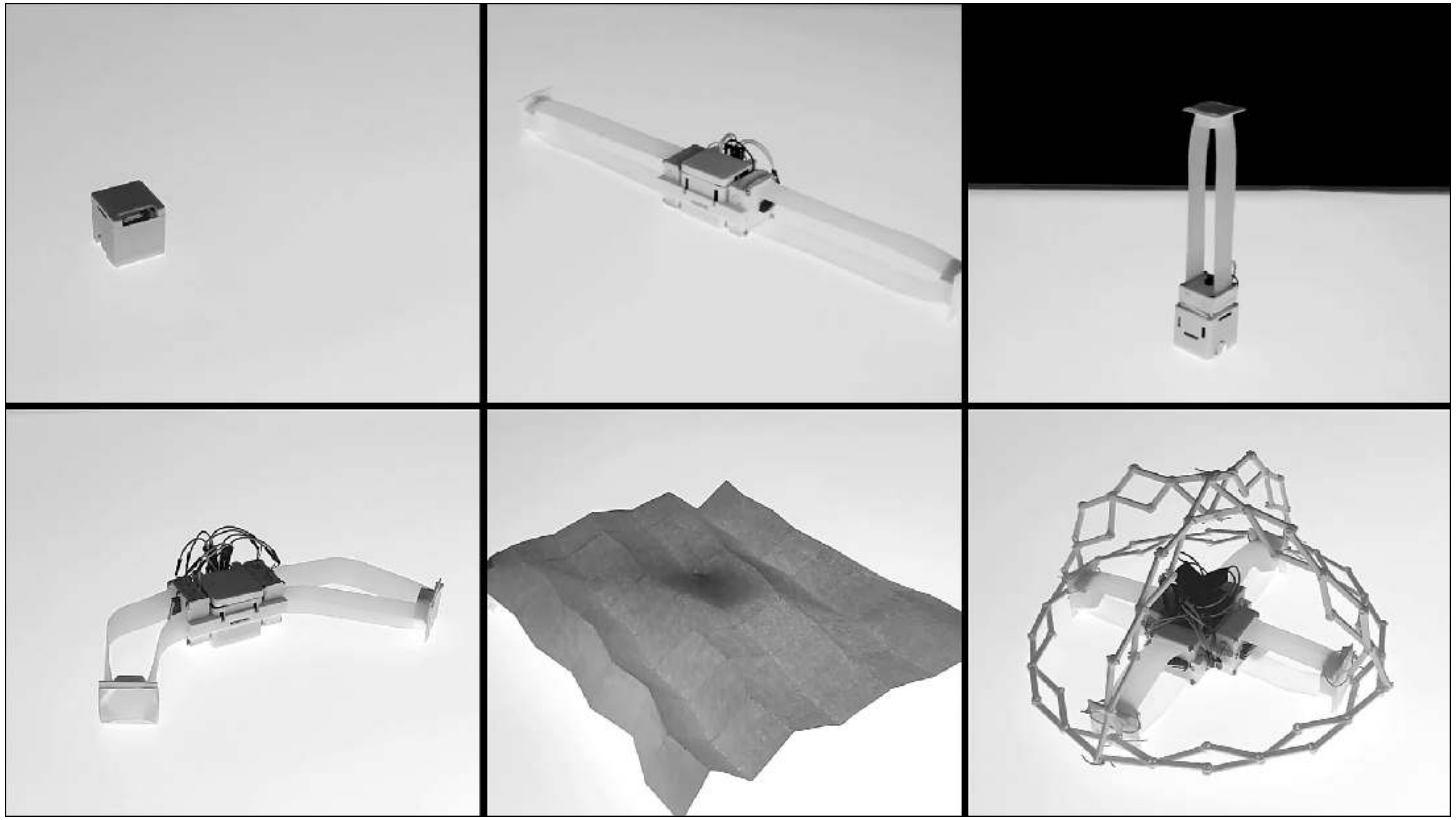






[UIST 2019] *ShapeBots: Shape-changing Swarm Robots* by **Suzuki**, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger

Types of Transformation

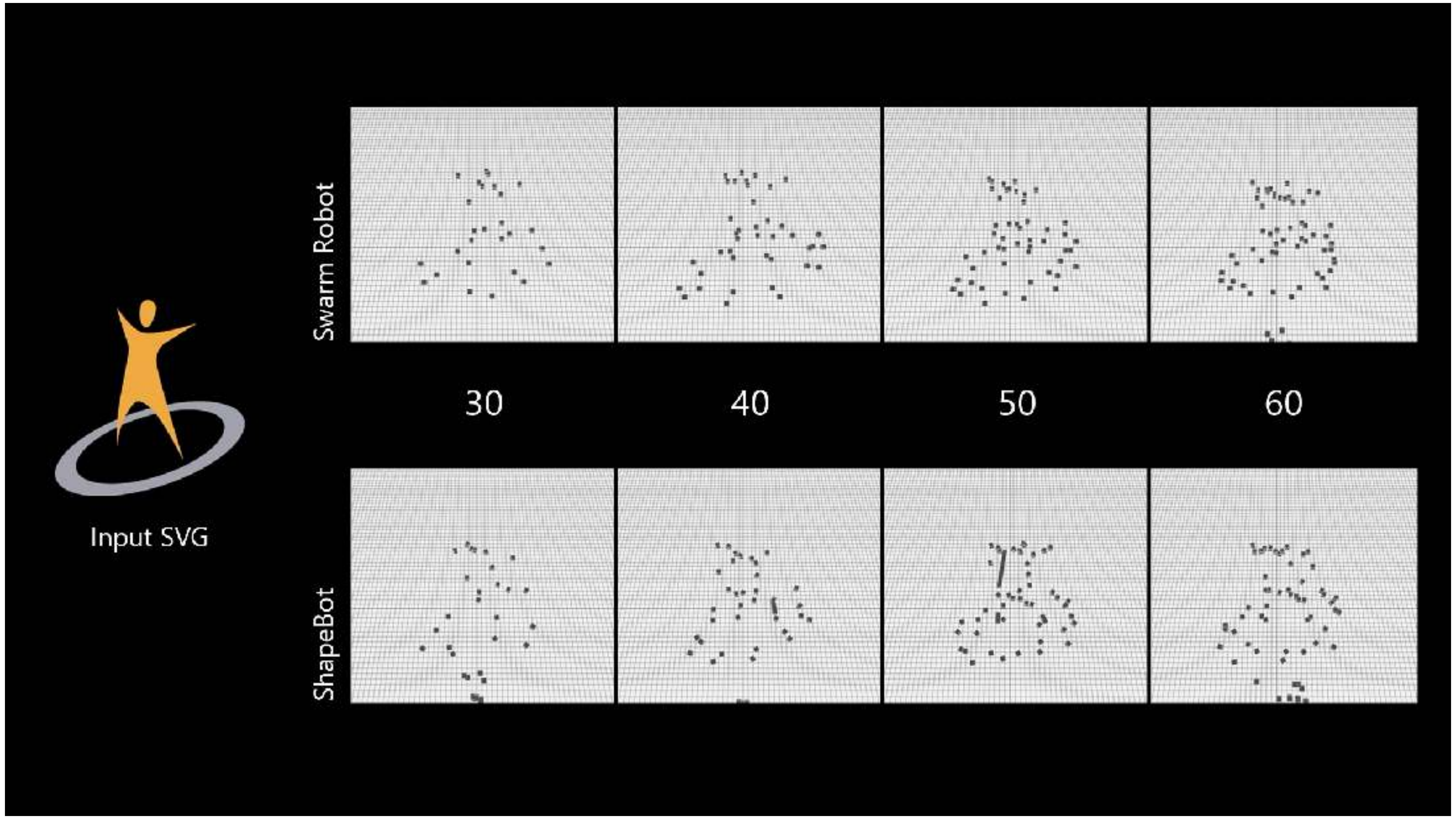


[UIST 2019] *ShapeBots: Shape-changing Swarm Robots* by **Suzuki**, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger

Interactive Information Display

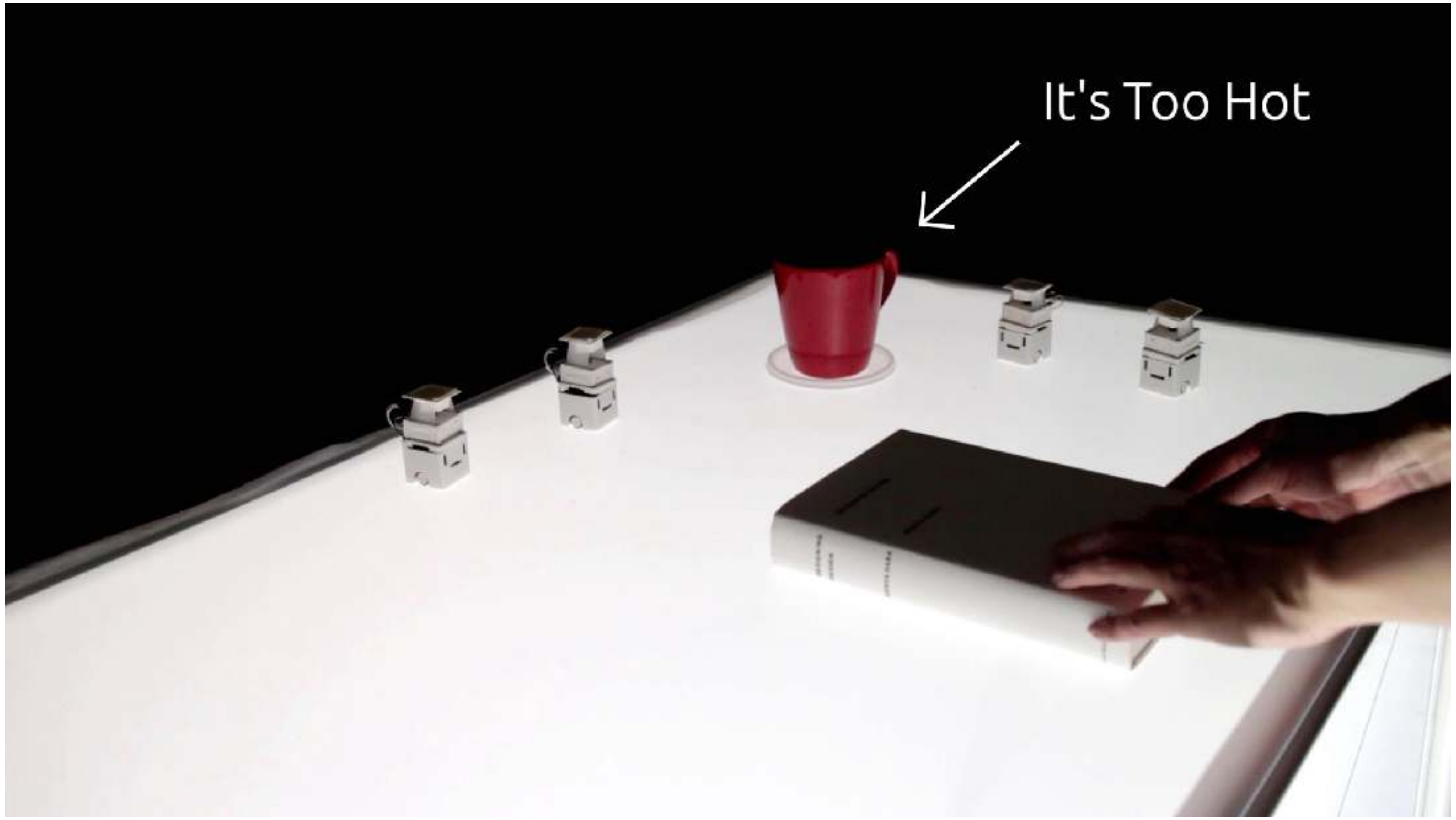
[UIST 2019] *ShapeBots: Shape-changing Swarm Robots* by **Suzuki**, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger

Interactive Information Display



[UIST 2019] *ShapeBots: Shape-changing Swarm Robots* by **Suzuki**, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger

Dynamic Physical Affordances

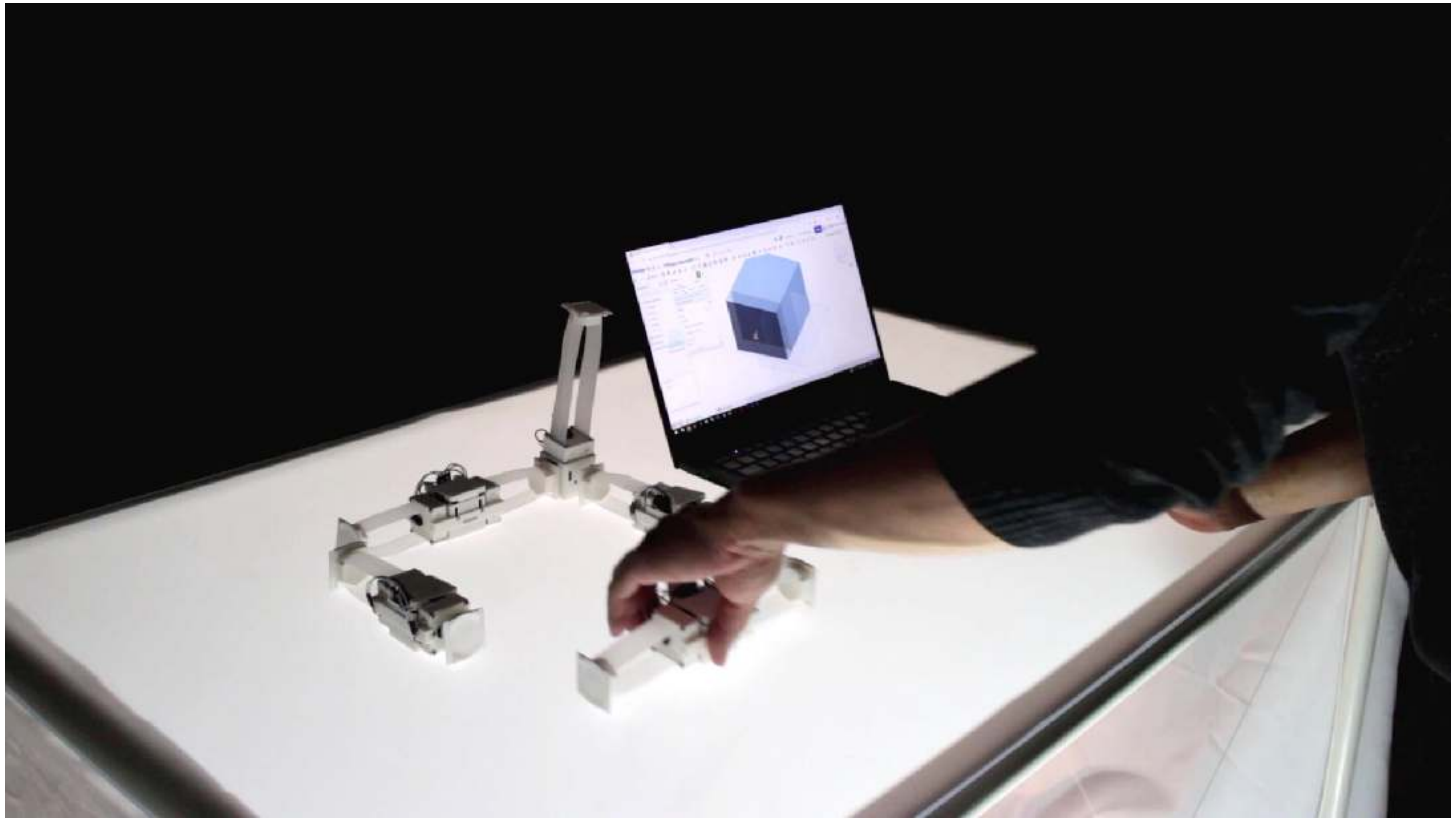


[UIST 2019] *ShapeBots: Shape-changing Swarm Robots* by **Suzuki**, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger

Object Actuation

[UIST 2019] *ShapeBots: Shape-changing Swarm Robots* by **Suzuki**, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger

Adaptive Physical Tools



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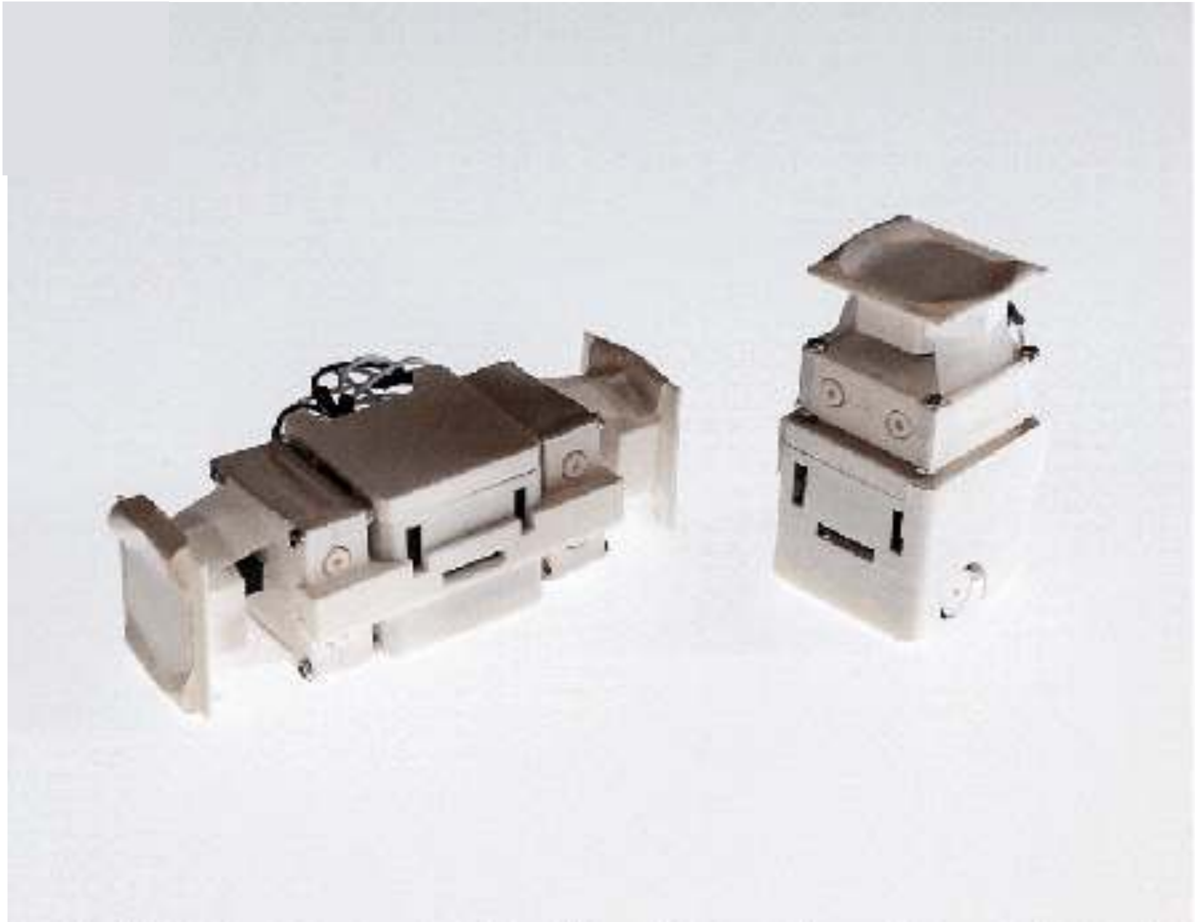
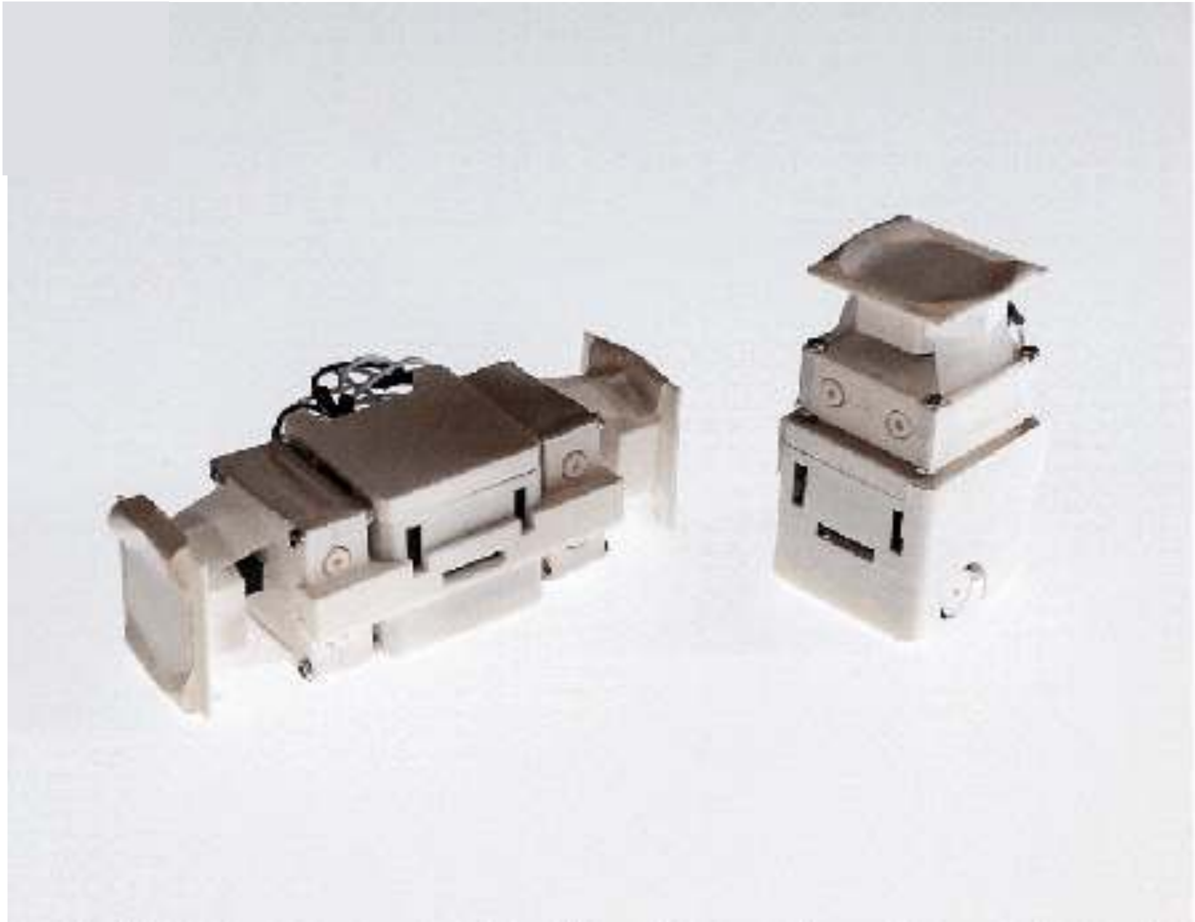
Tabletop-scale



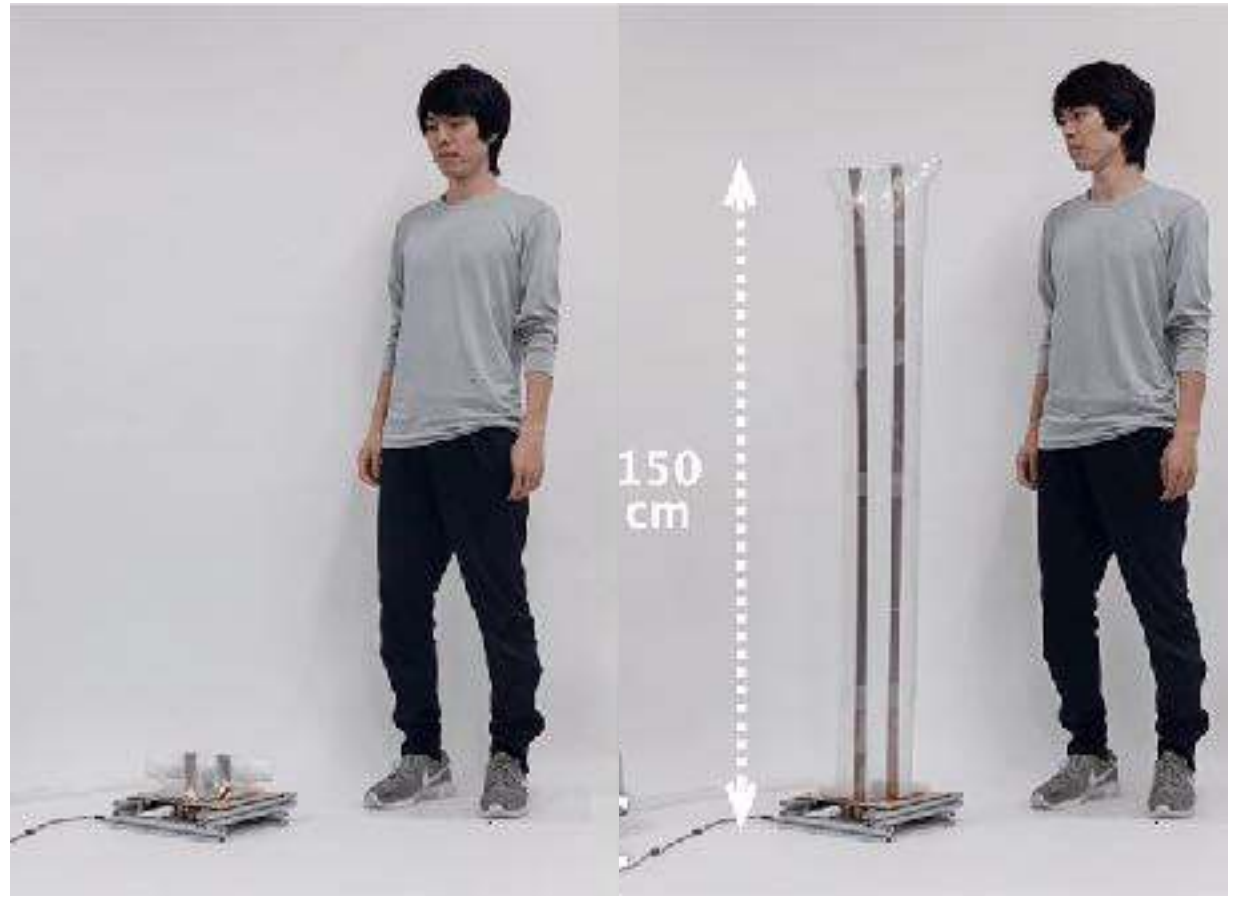
ShapeBots

Tabletop-scale



ShapeBots

Room-scale



[TEI 2020]

LiftTiles: Modular Inflatable Tiles

by Suzuki, Nakayama, Liu, Kakehi, Gross, and Leithinger

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Reconfigurable Modular Inflatable Tiles
for Room-scale Shape Transformation

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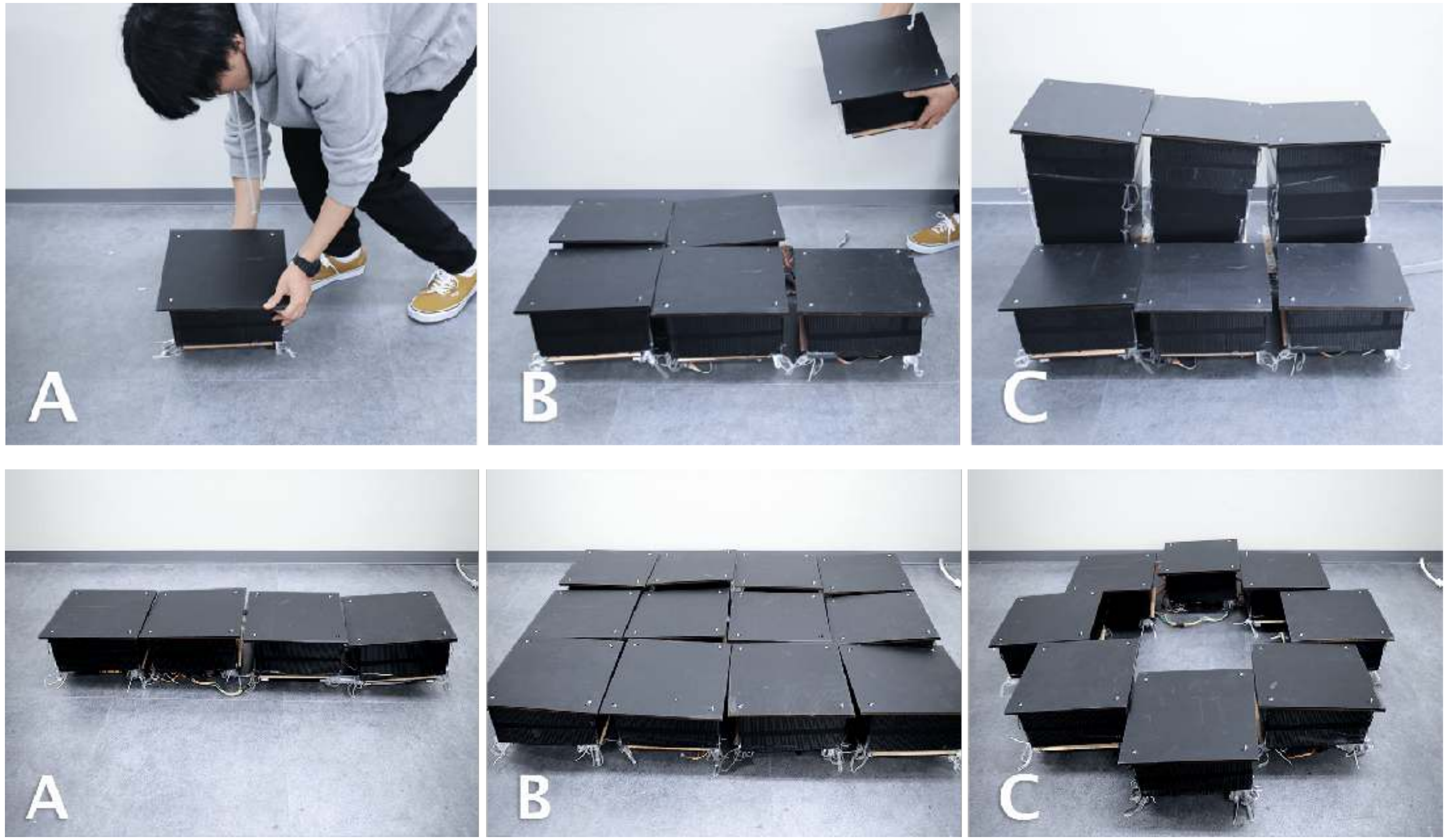
User-customizable and **-reconfigurable**
Shape-changing Elements



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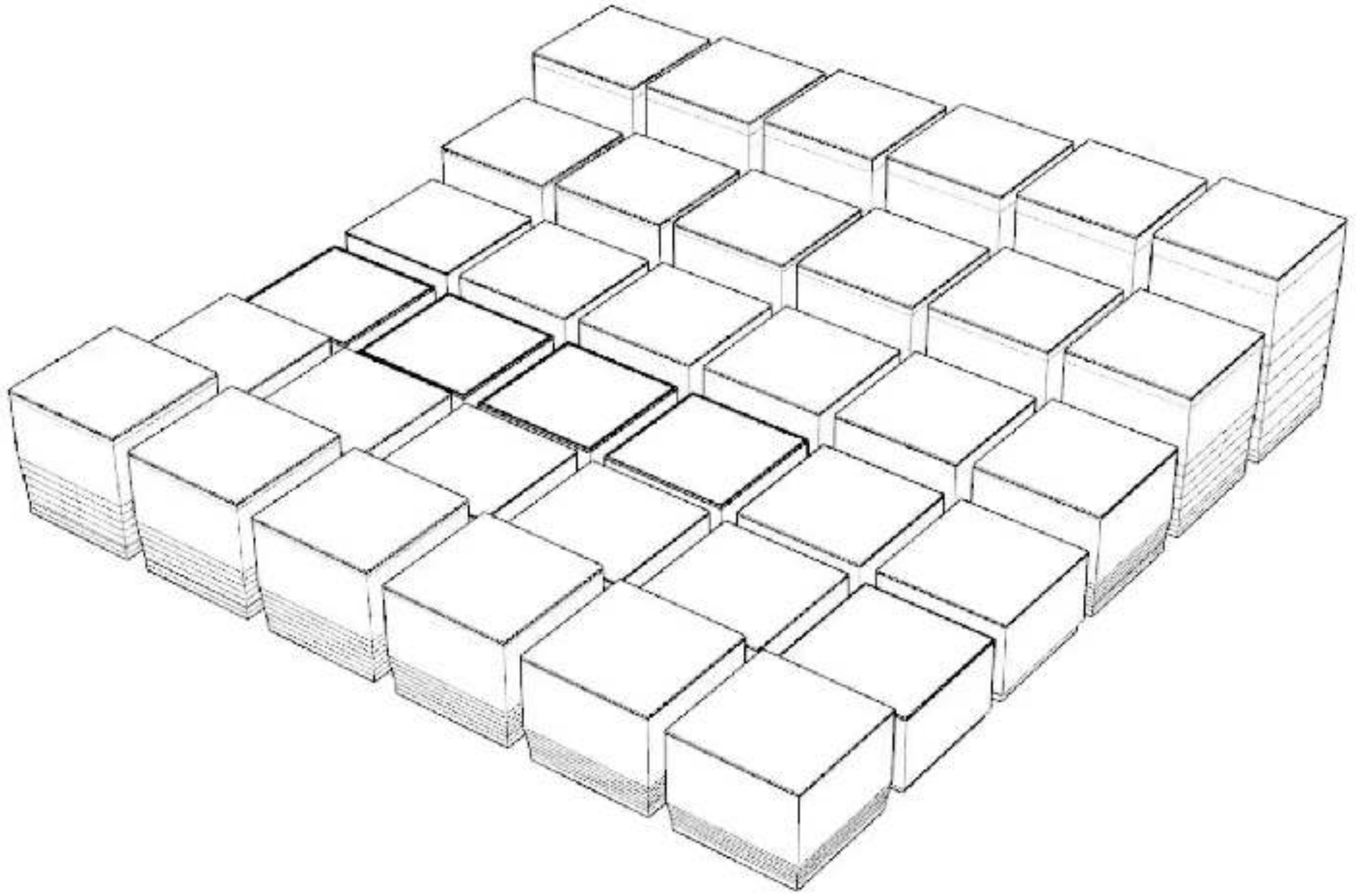

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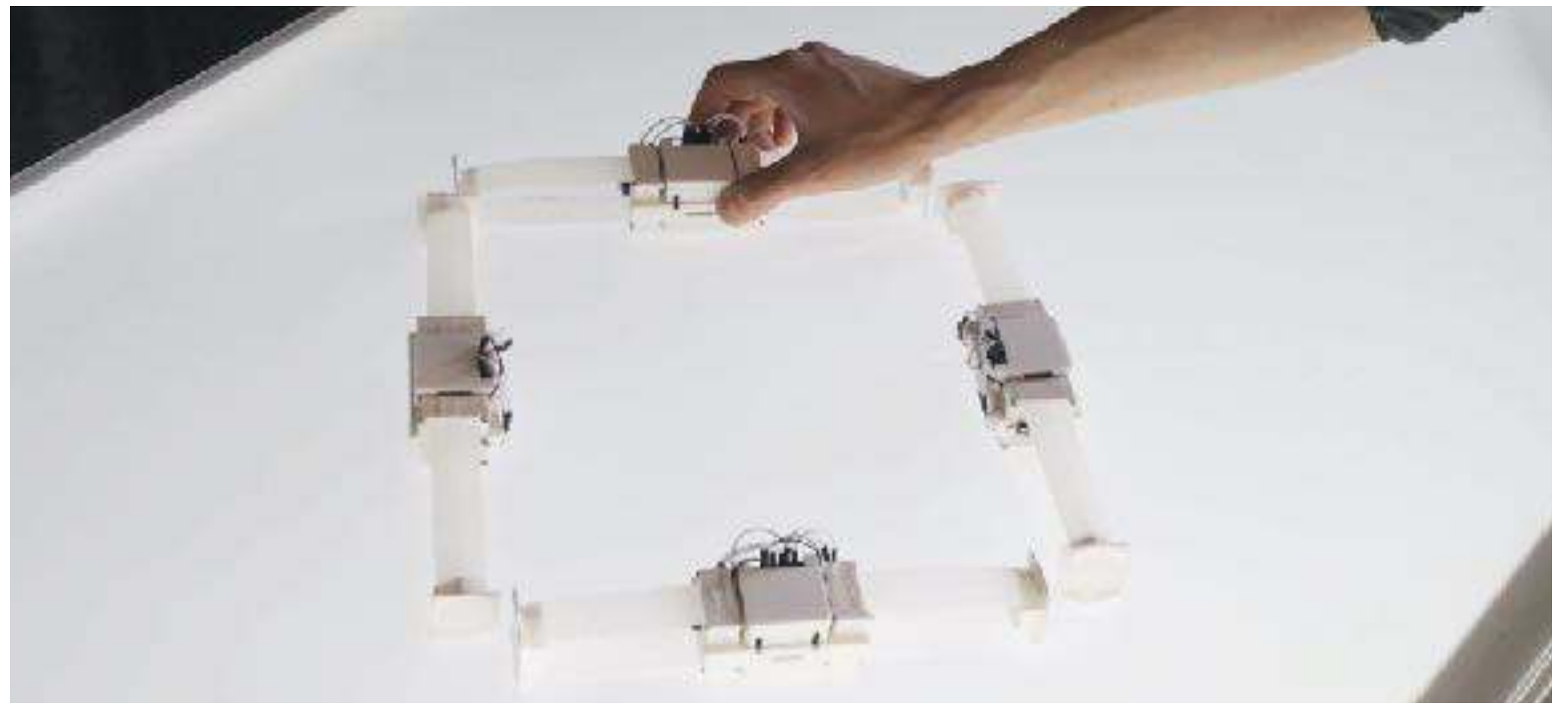
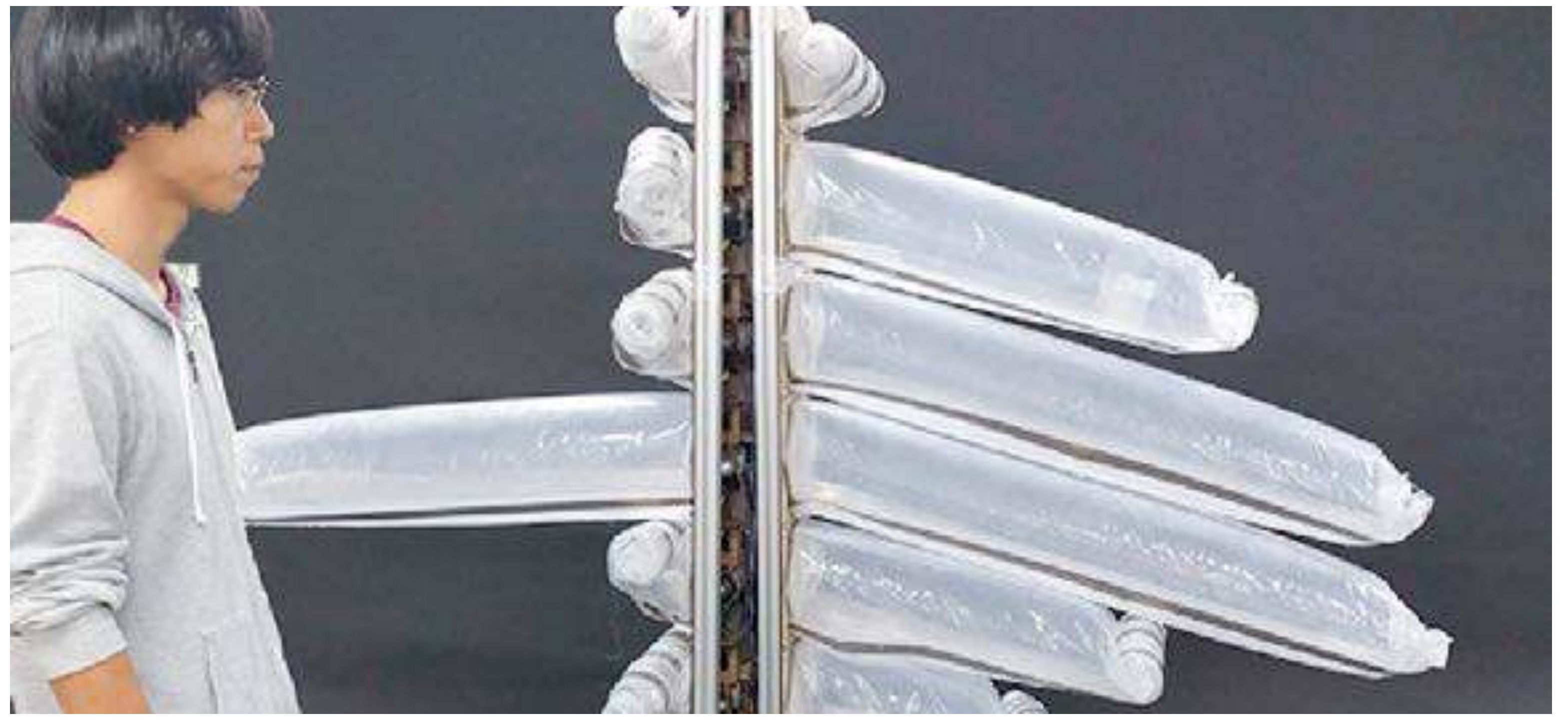
Dynamic Shape Construction with **Active** Collective Elements



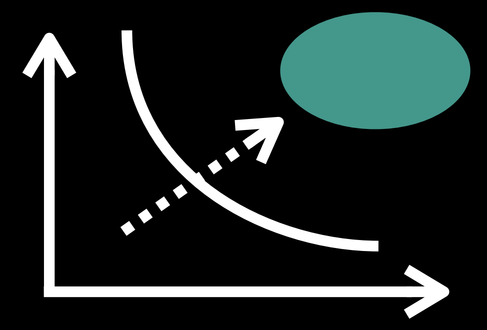
Dynamic Shape made of
Shape-changing Swarm Robots
[Suzuki et al., UIST 2019]



Dynamic Shape made of
Modular Inflatable Tiles
[Suzuki et al., TEI 2020]

Background

Why This Approach?

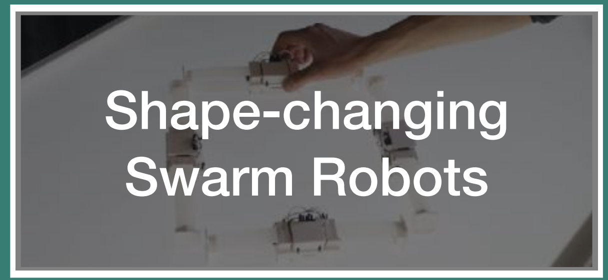


Concept

What is
Dynamic and Collective
Shape Construction?

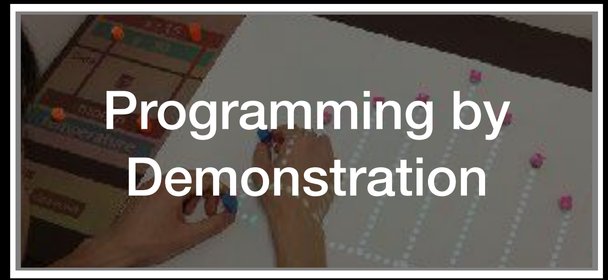
Explorations

Shape Construction
with **Active** Elements



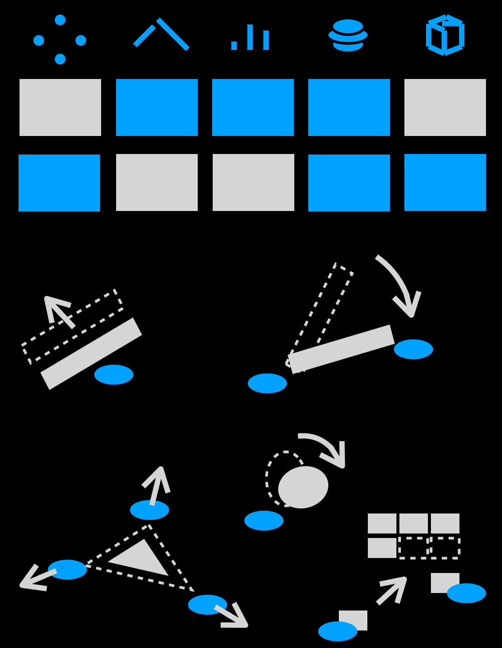
Shape Construction
with **Passive** Elements

Interaction with
Collective Elements



Discussion

What's Next?



Background

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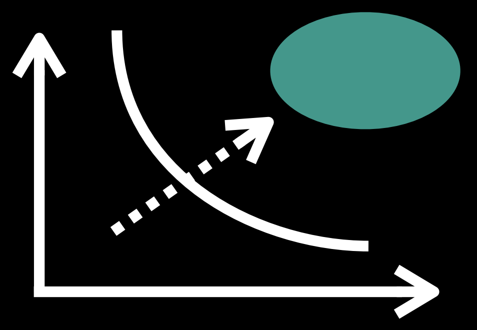

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Explorations

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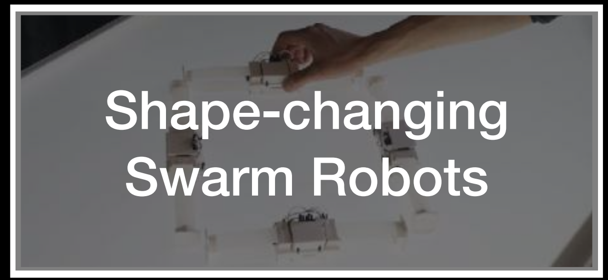

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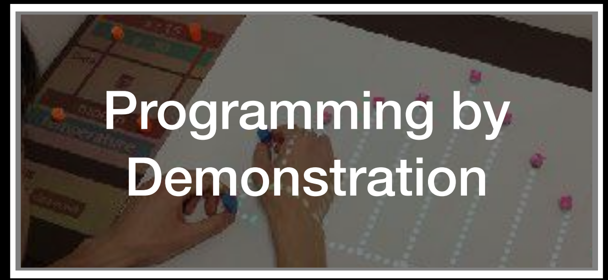
Collective Elements



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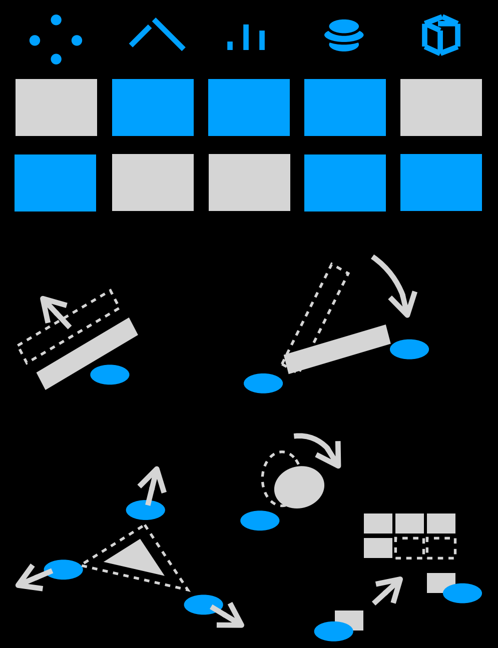
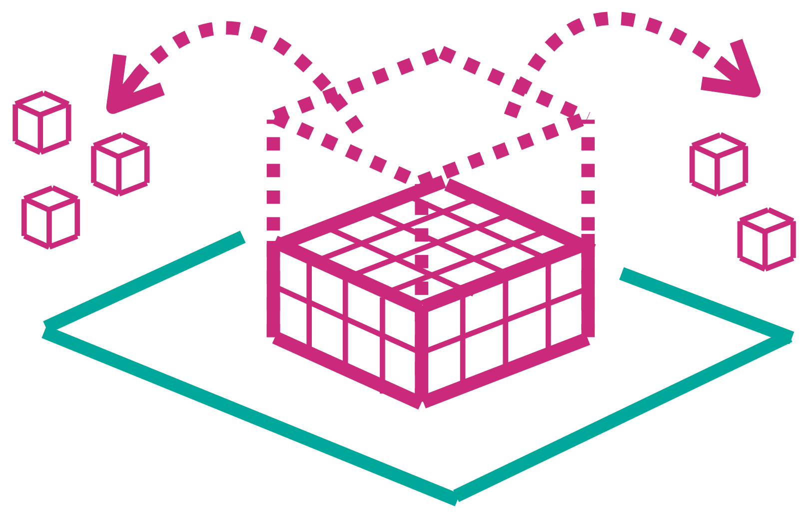


Dynamic Physical UI

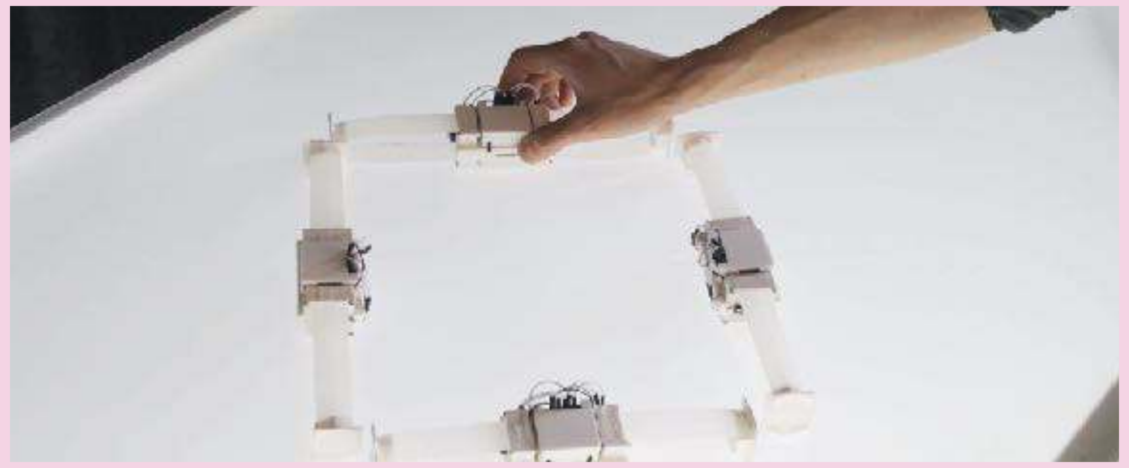


Shape Change with
Collective Elements

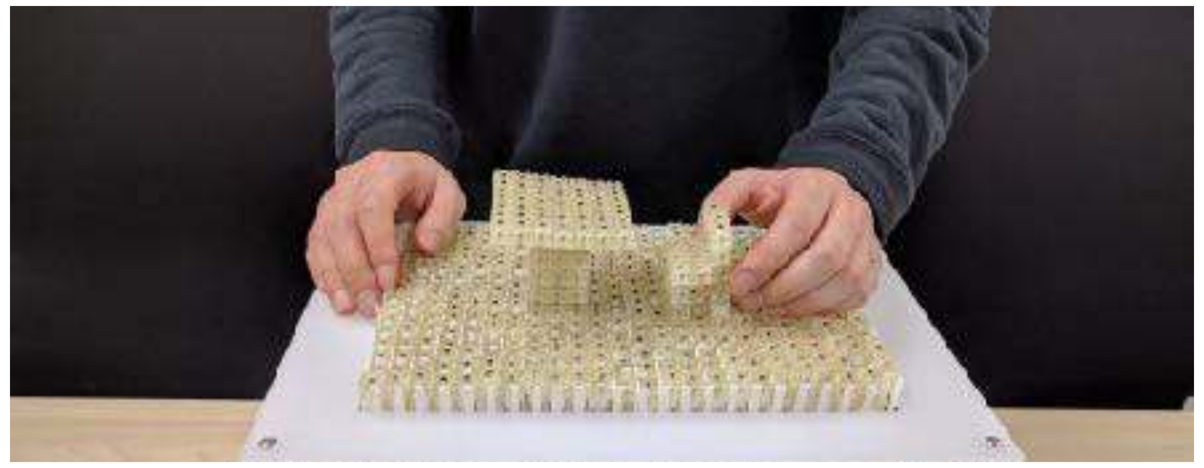
<u>The focus of this thesis</u>

Dynamic shape made of
discrete collective elements

Active
collective elements
||
self-actuated elements
that can move or reconfigure
themselves with internal actuation



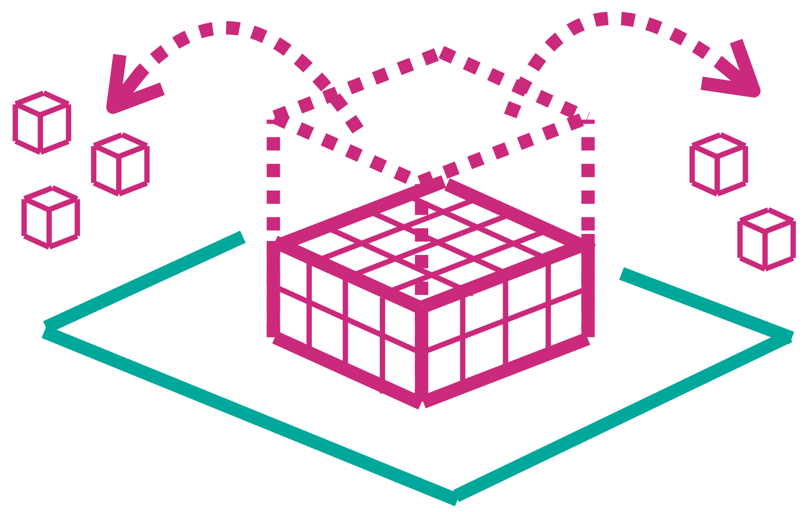
Passive
collective elements
||
externally-actuated elements
that can move or reconfigure
through external actuation



The focus of this thesis

Dynamic shape made of **discrete** collective elements

Dynamic Physical UI



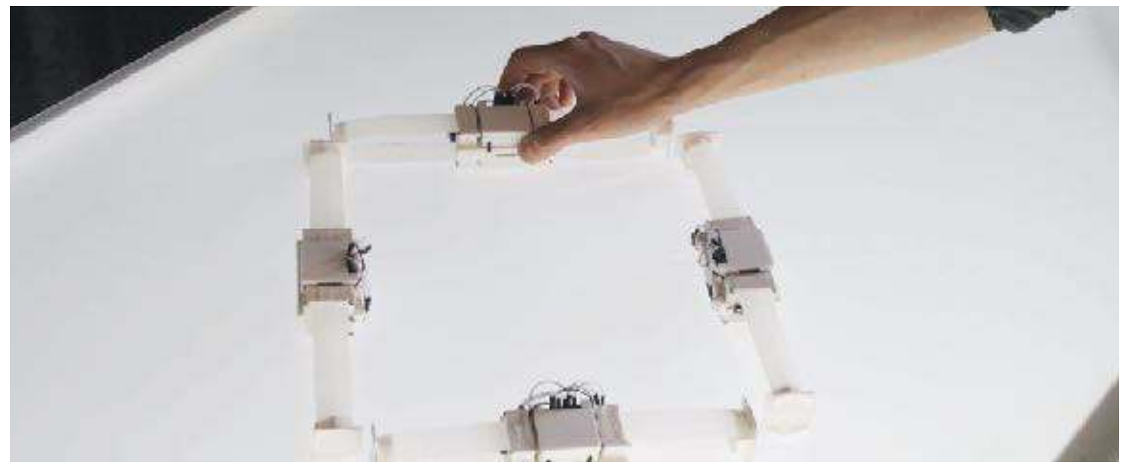
Shape Change with **Collective Elements**

Active

collective elements

||

self-actuated elements that can move or reconfigure themselves with internal actuation

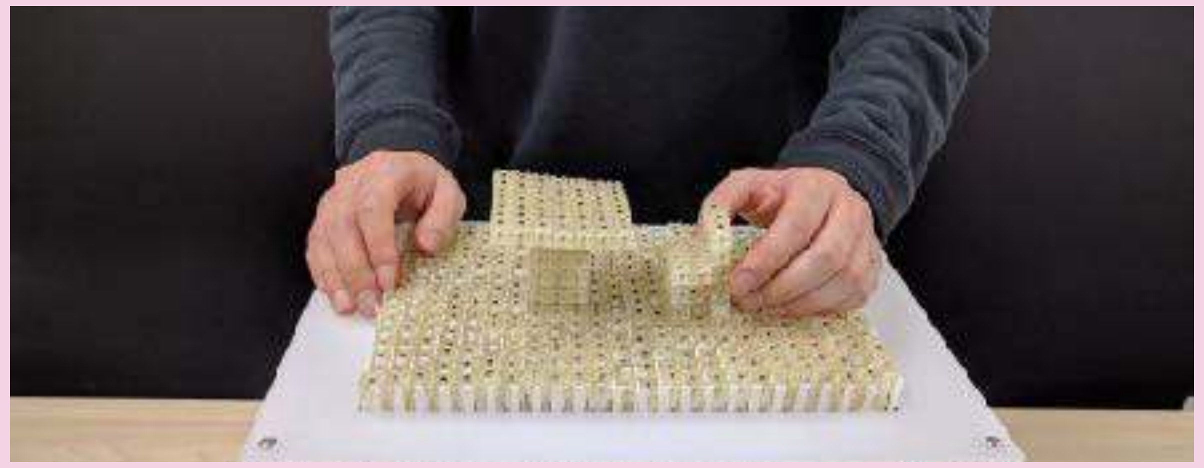


Passive

collective elements

||

externally-actuated elements that can move or reconfigure through external actuation



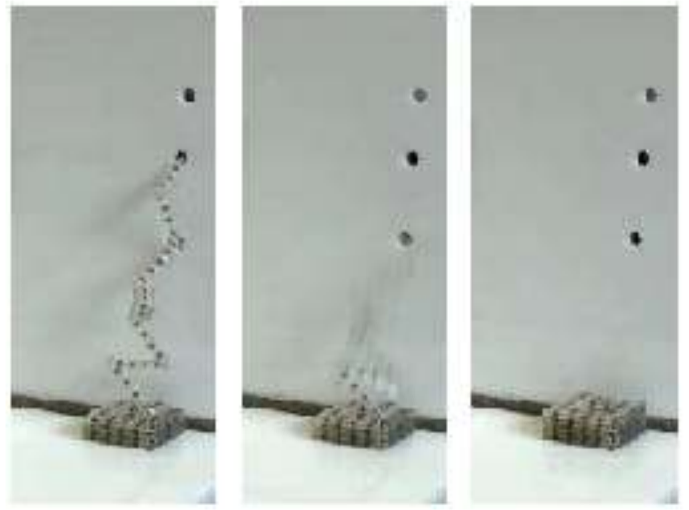
Passive

collective elements

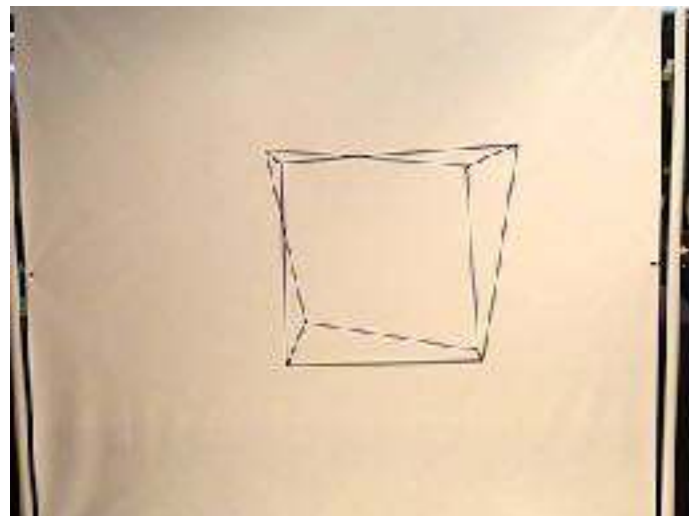
externally-actuated elements
that can move or reconfigure
through external actuation

PixieDust
[Ochiai 2014]

Aerial Assembly
[Tibbits 2014]

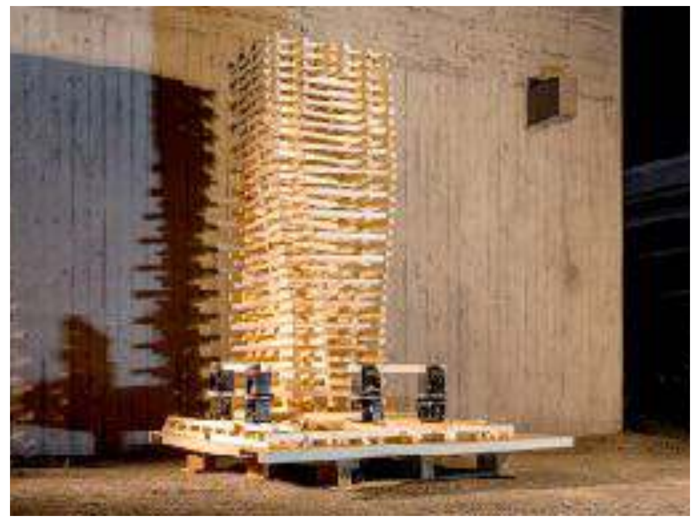


SoftCubes
[Yim 2014]



Morphing Cube
[Yamaoka 2014]

Actuated Lattice
[Torres 2014]



Timber Construction
[Leder 2018]

Passive
collective elements

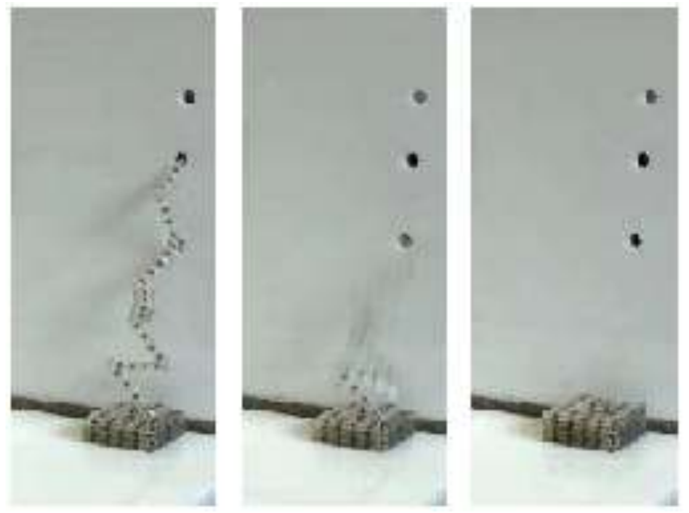
externally-actuated elements
that can move or reconfigure
through external actuation

Three Benefits

1. **Scalability**
   does not require electro-mechanical components, thus become simple inexpensive
2. **Resolution**
   overall size can become small and support large number of elements
3. **Robustness**
   provide structural stability that can decrease mechanical breakdown

PixieDust
[Ochiai 2014]

Aerial Assembly
[Tibbits 2014]



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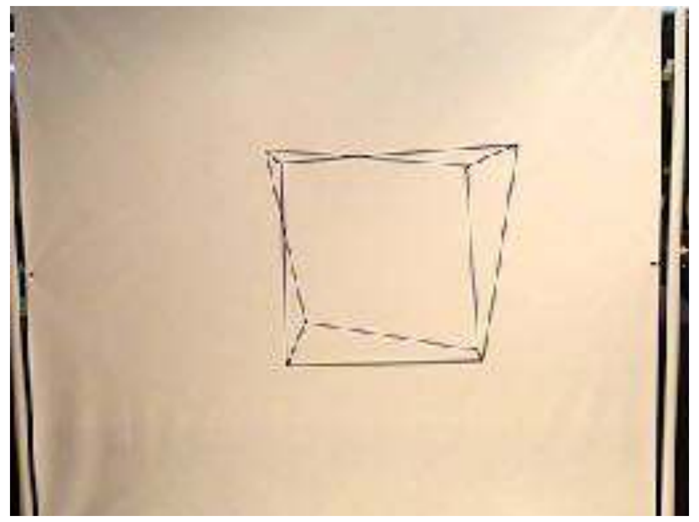

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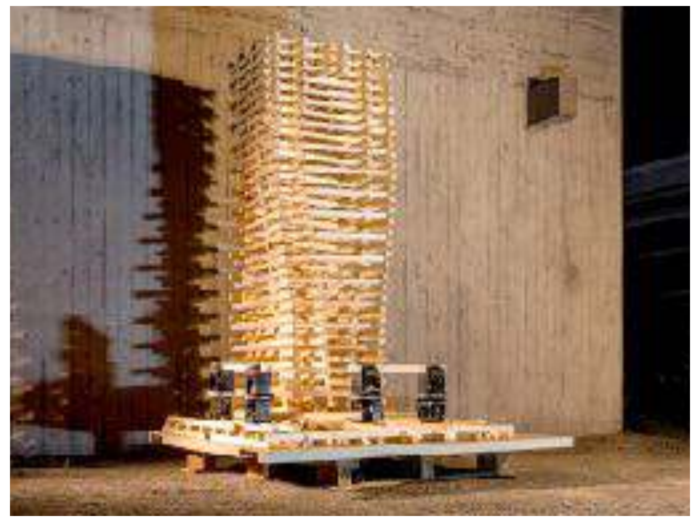

Timber Construction
[Leder 2018]

Challenges:

How can we dynamically construct a shape?

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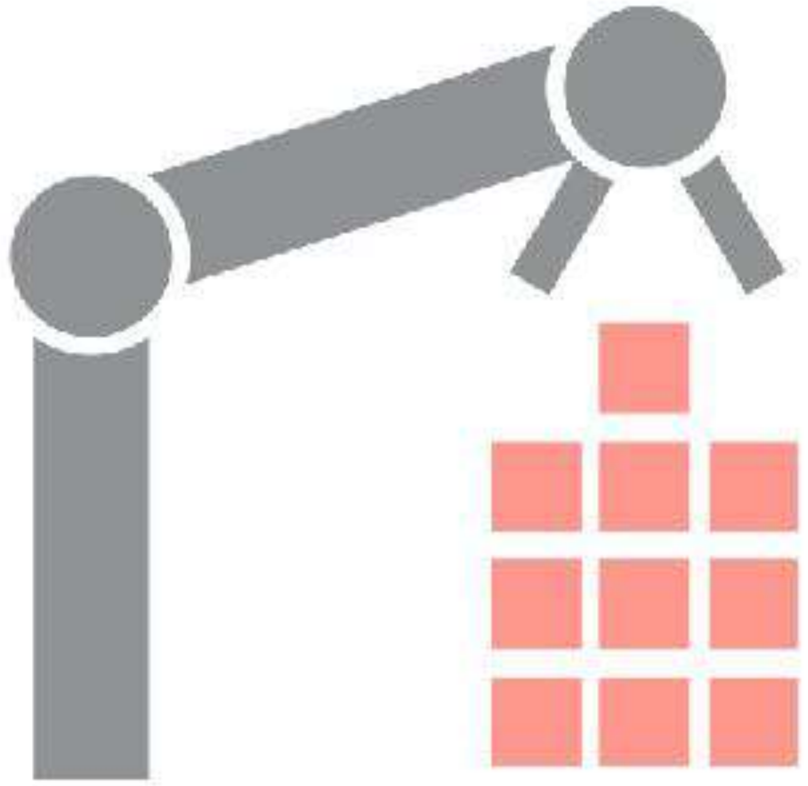
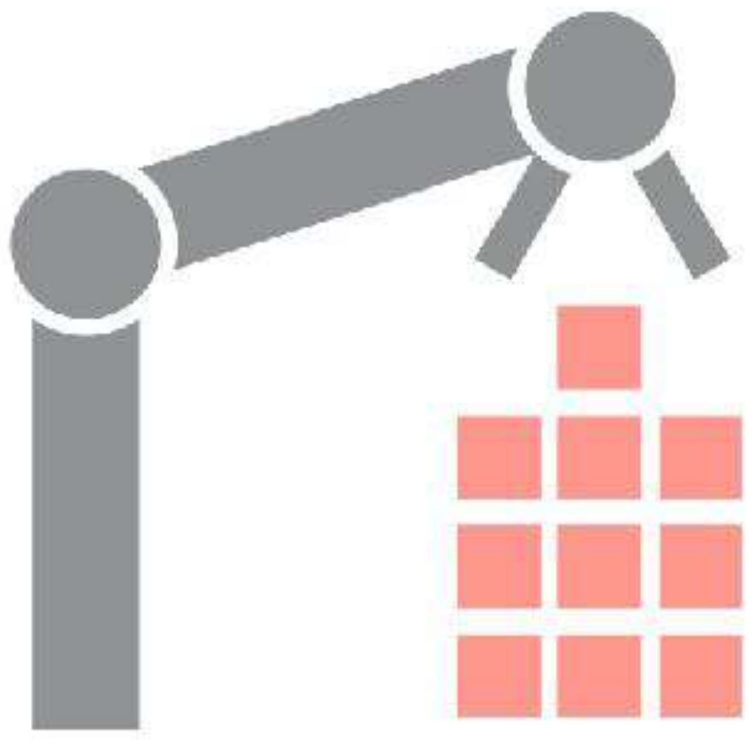
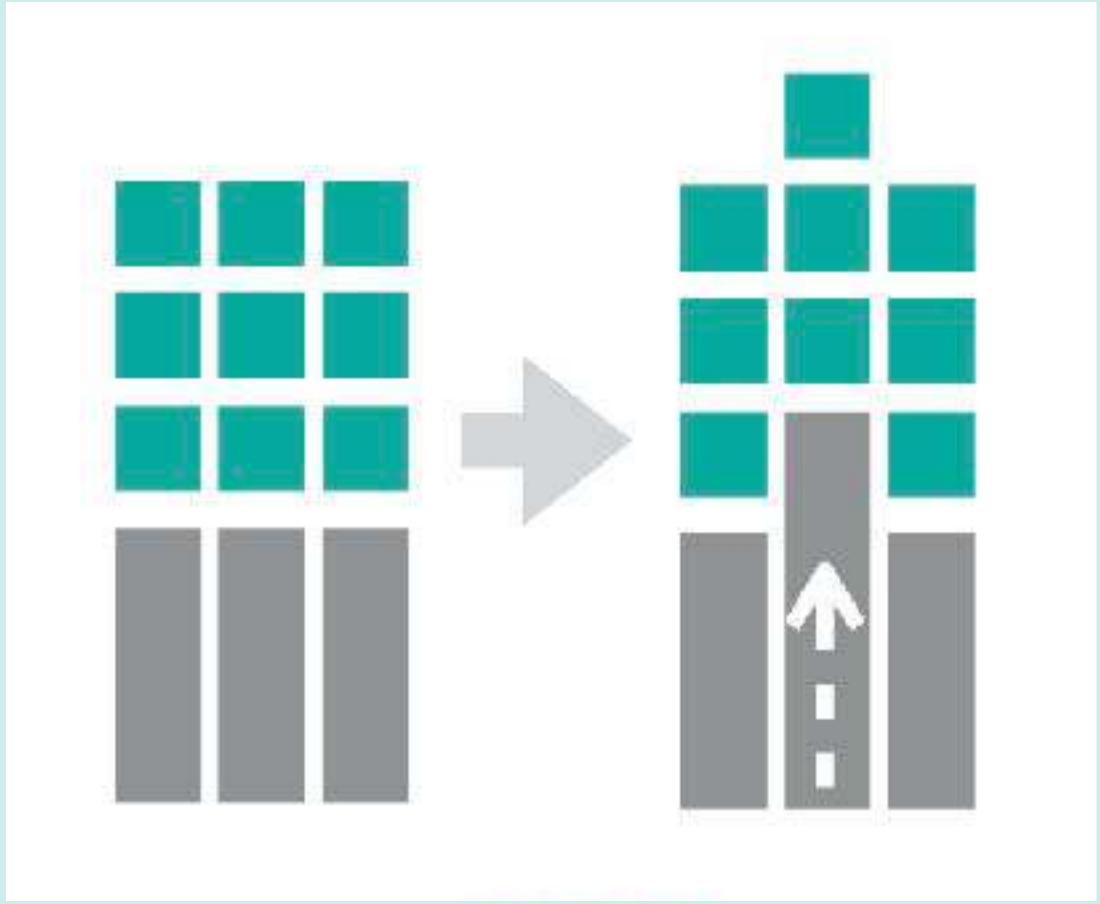


Example:
Assembling blocks with a robotic is **slow**
because it is **Serial** process

Challenges:

How can we dynamically construct a shape?





Serial ⟷ **Parallel**

only one element is dynamically moving

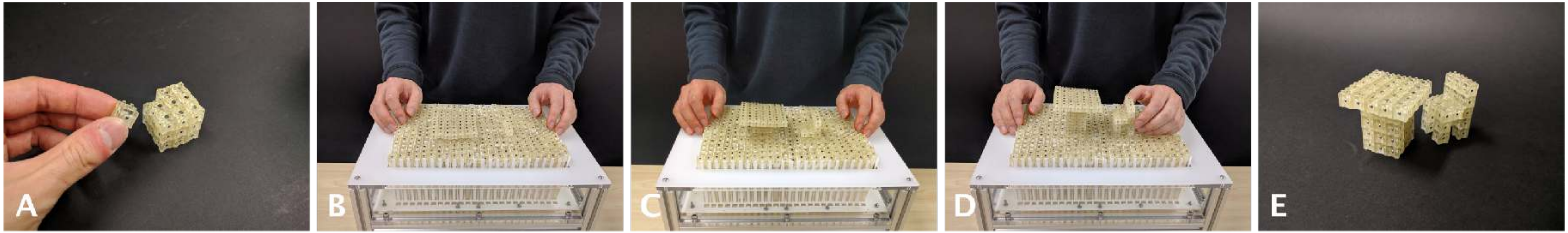
all elements are dynamically moving

how can we apply this for
collective shape construction of an arbitrary **3D shape**?

[UIST 2018]

Dynablock: Dynamic 3D Printing

by Suzuki, Yamaoka, Leithinger, Yeh, Gross, Kawahara, Kakehi

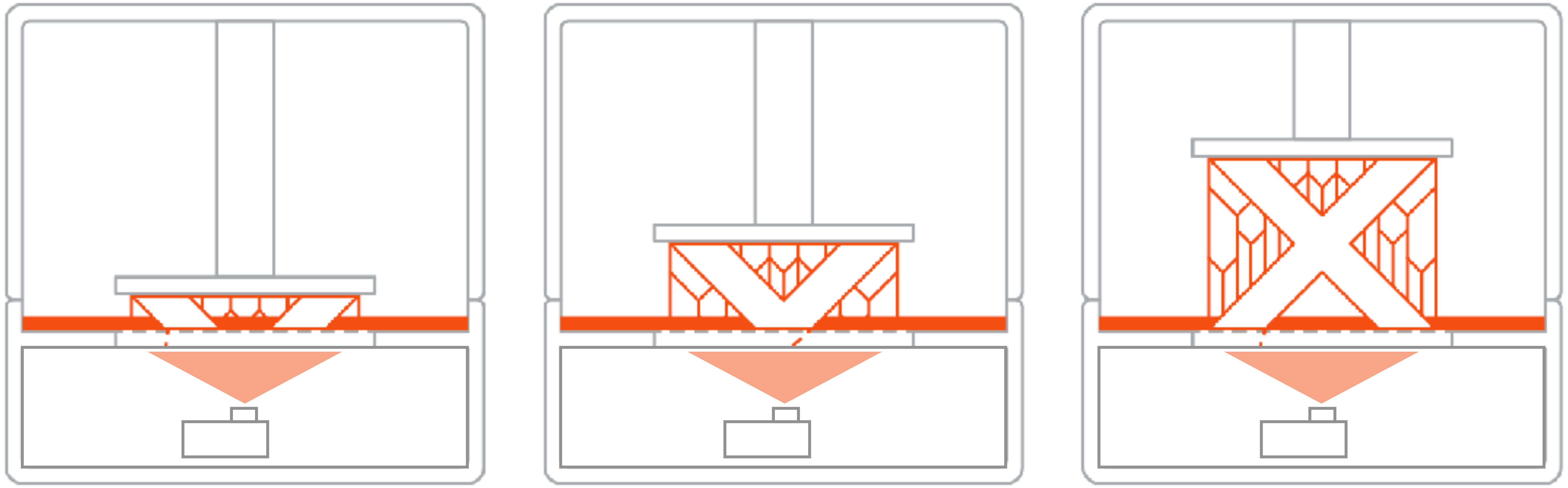


[UIST 2018] *Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation*

by **Suzuki**, Yamaoka, Leithinger, Yeh, Gross, Kawahara, and Kakehi

Inspiration

Parallel Material Solidification
of DLP 3D Printer



[UIST 2018] *Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation*
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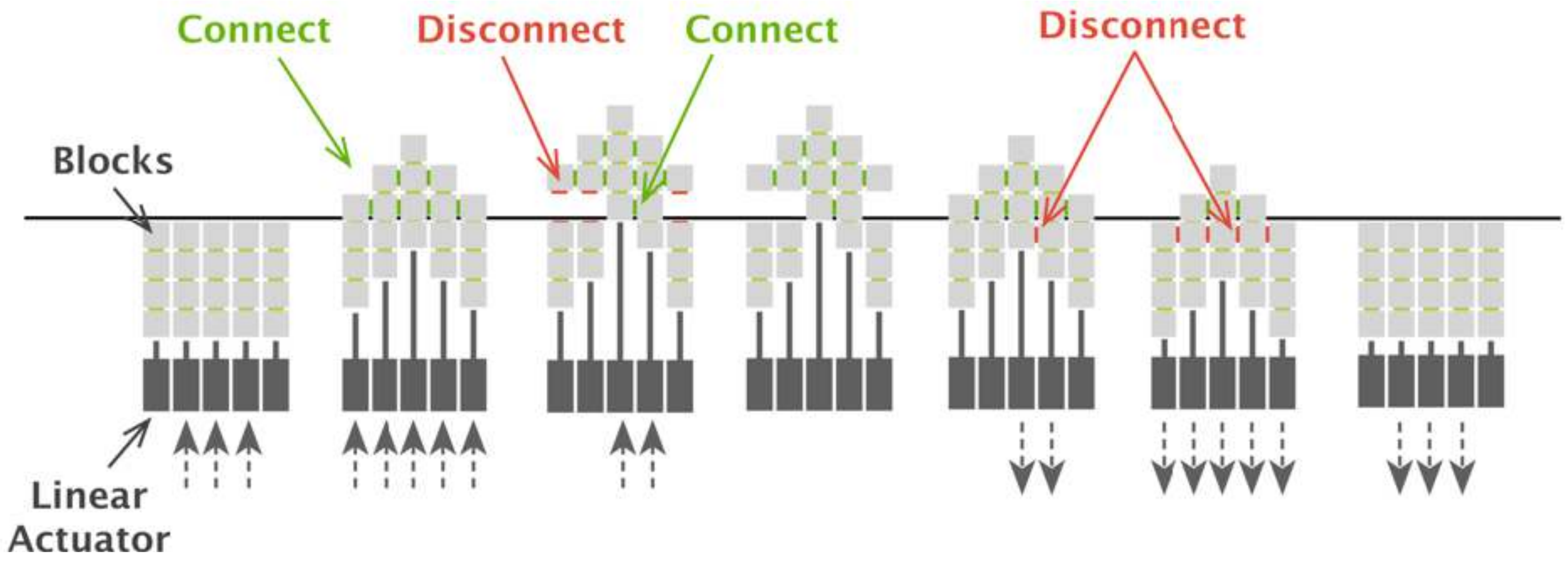
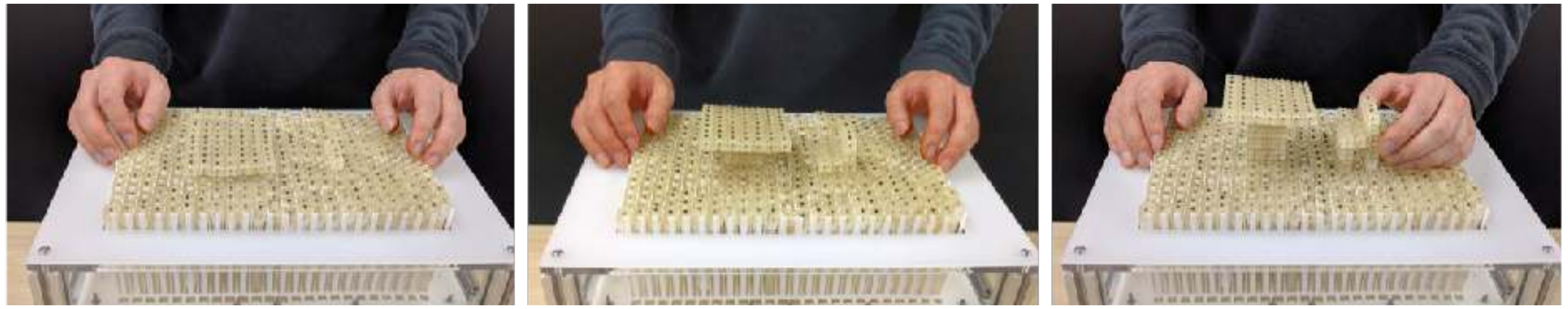
Proposed Approach

Parallel Block Assembly with Shape Display
assemble each layer at once





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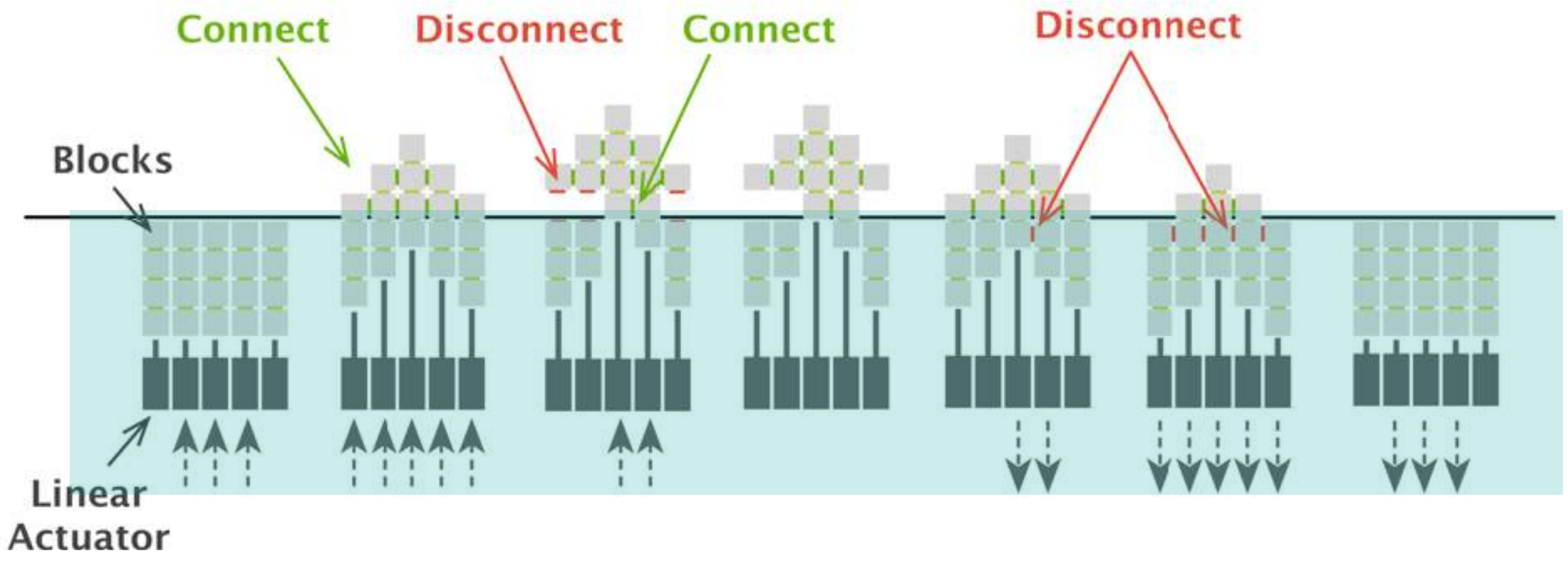

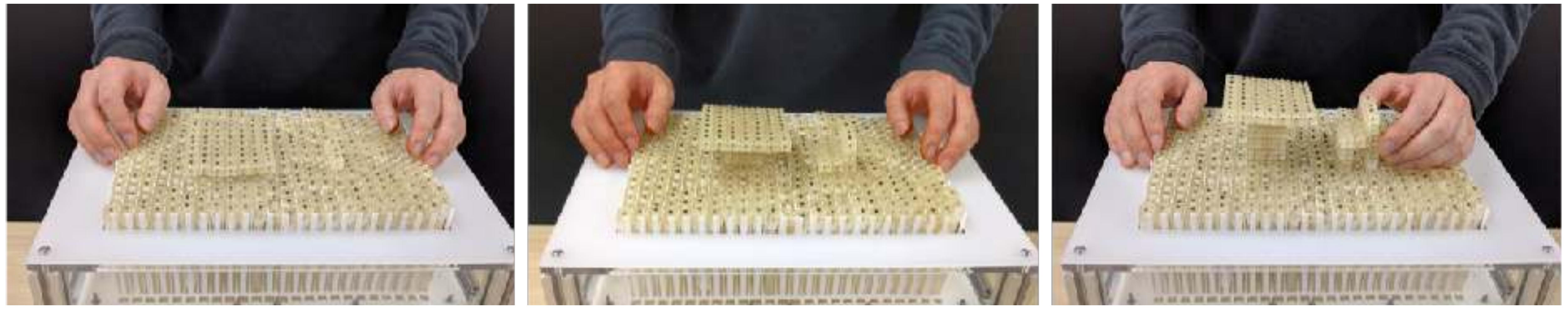

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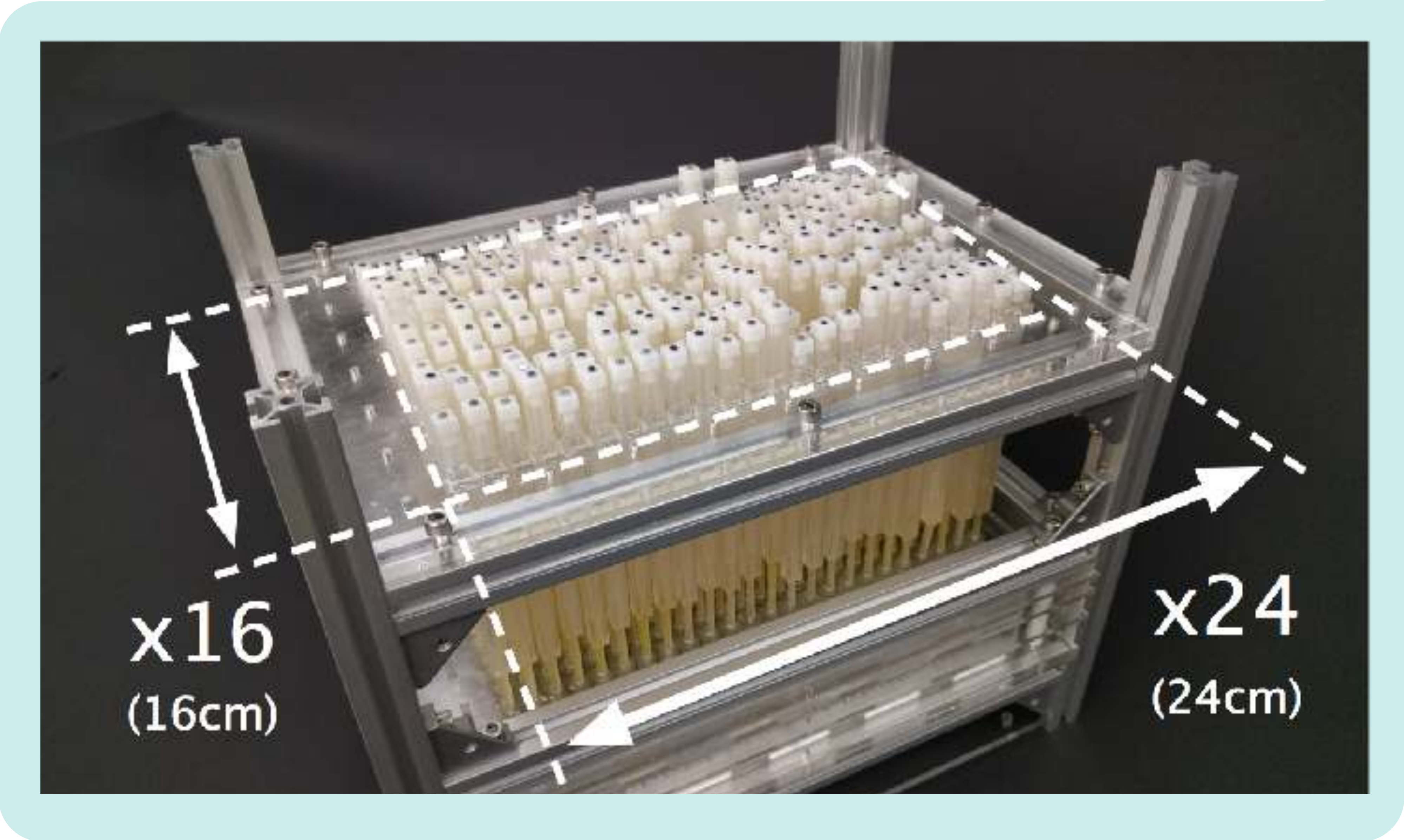

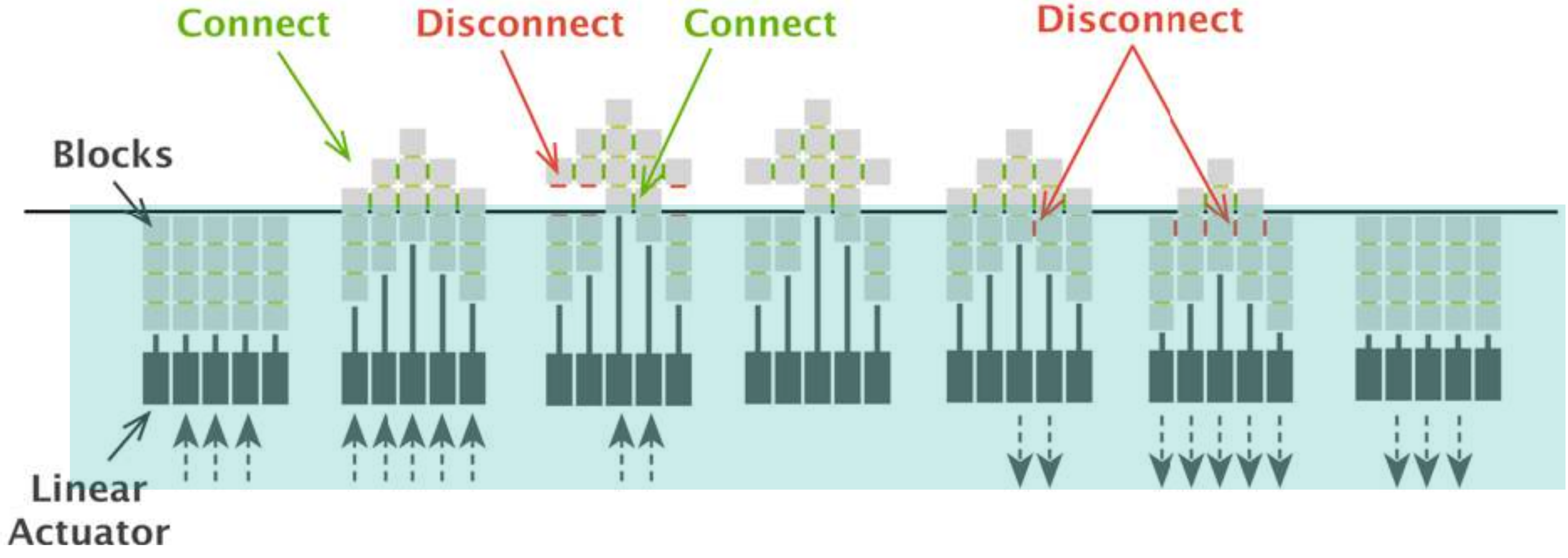

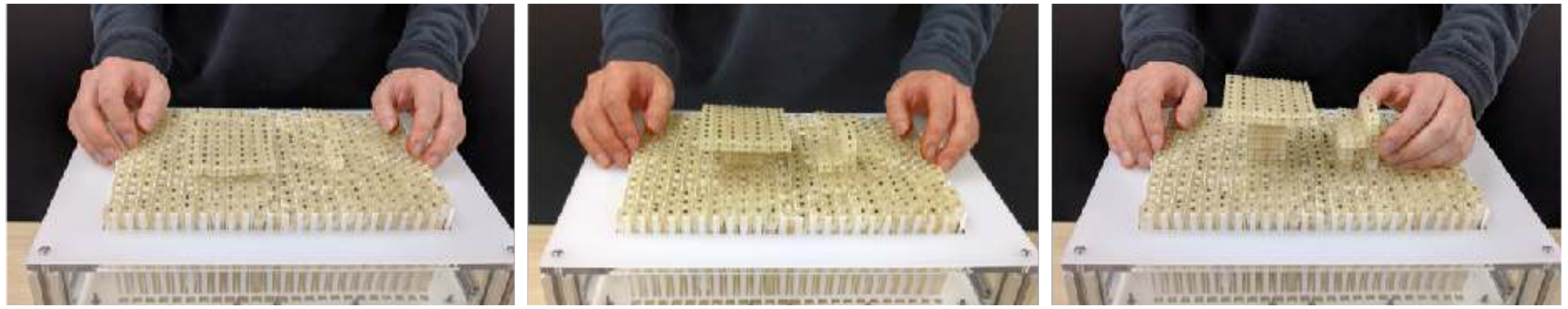

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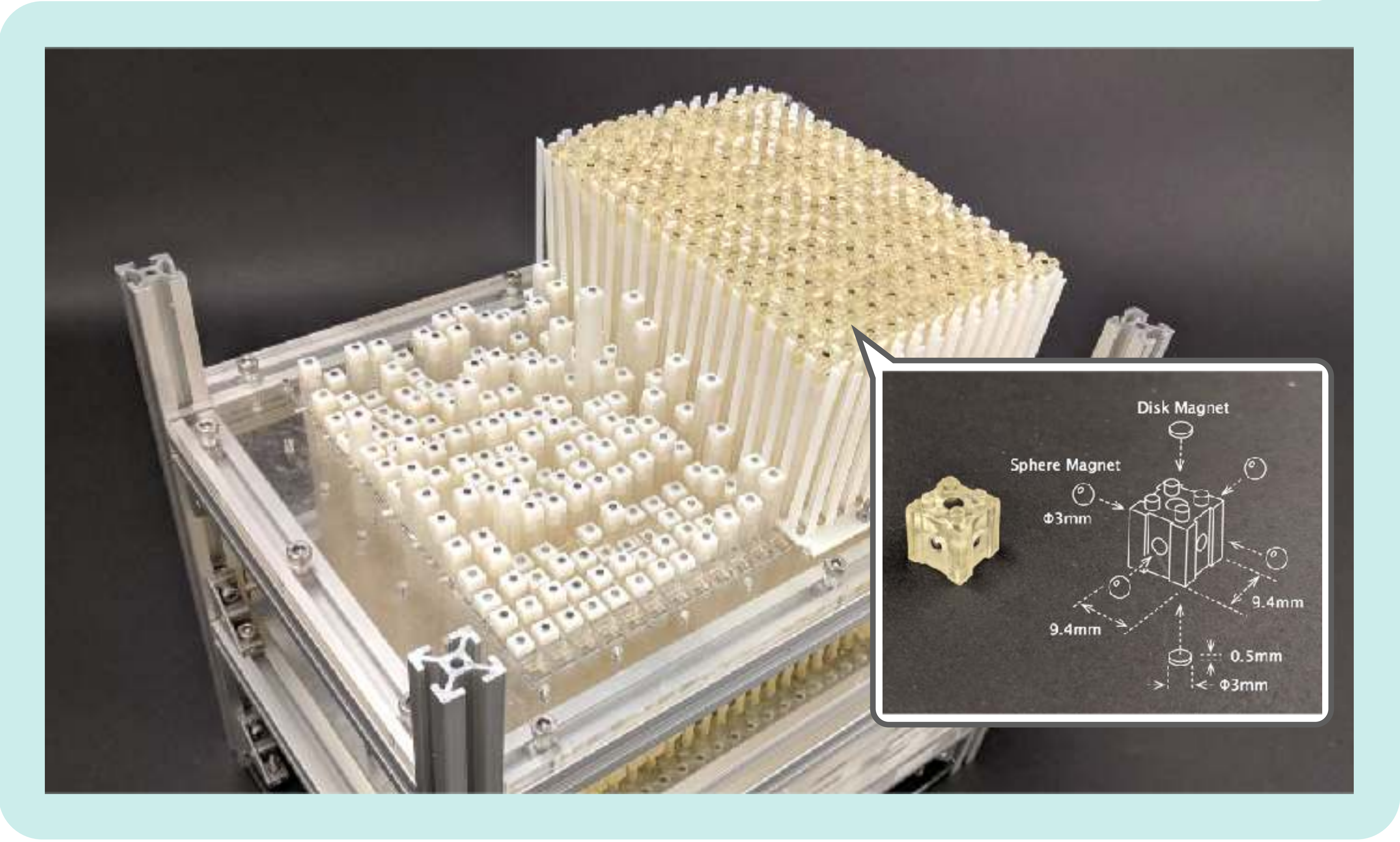

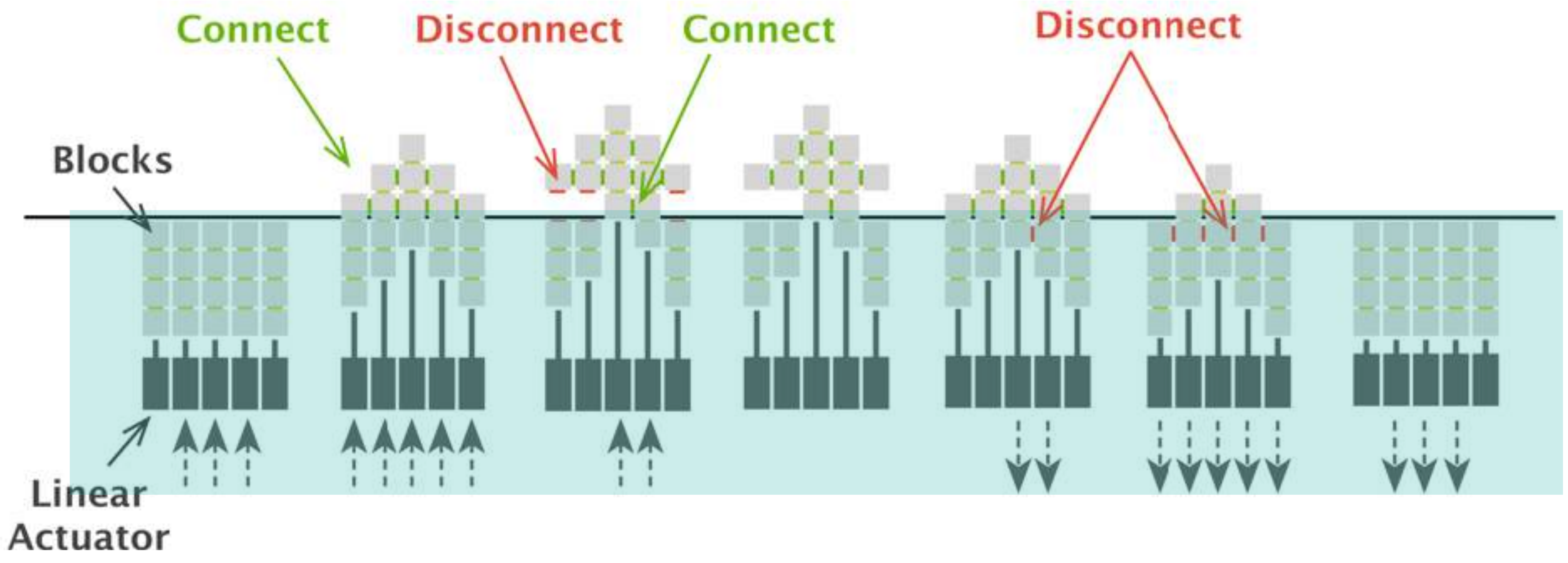

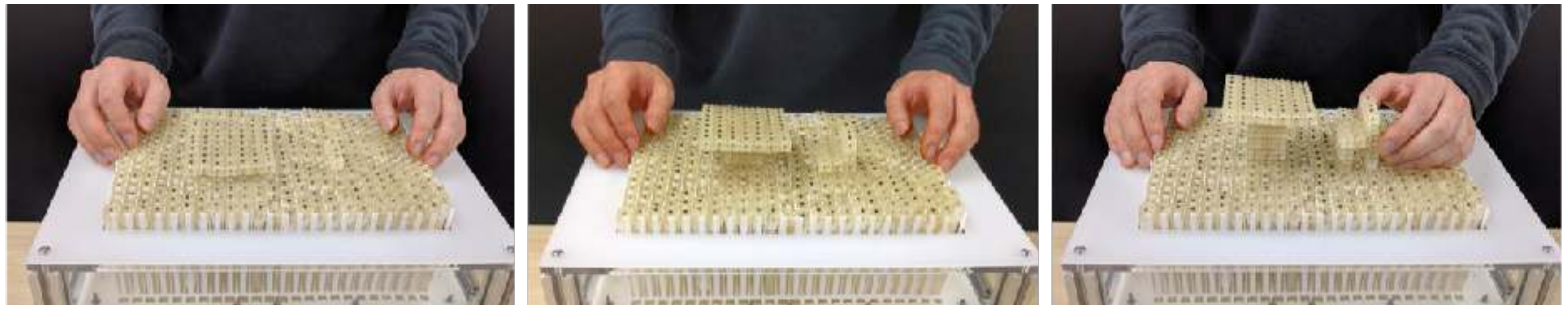

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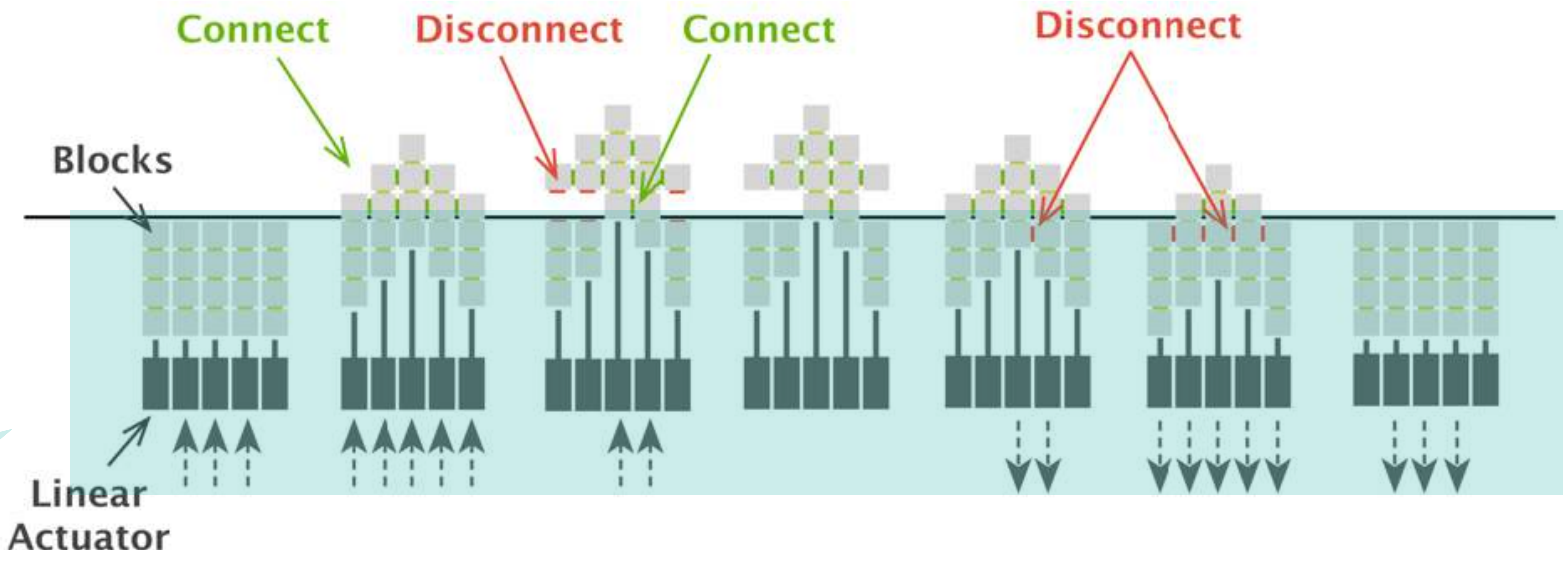

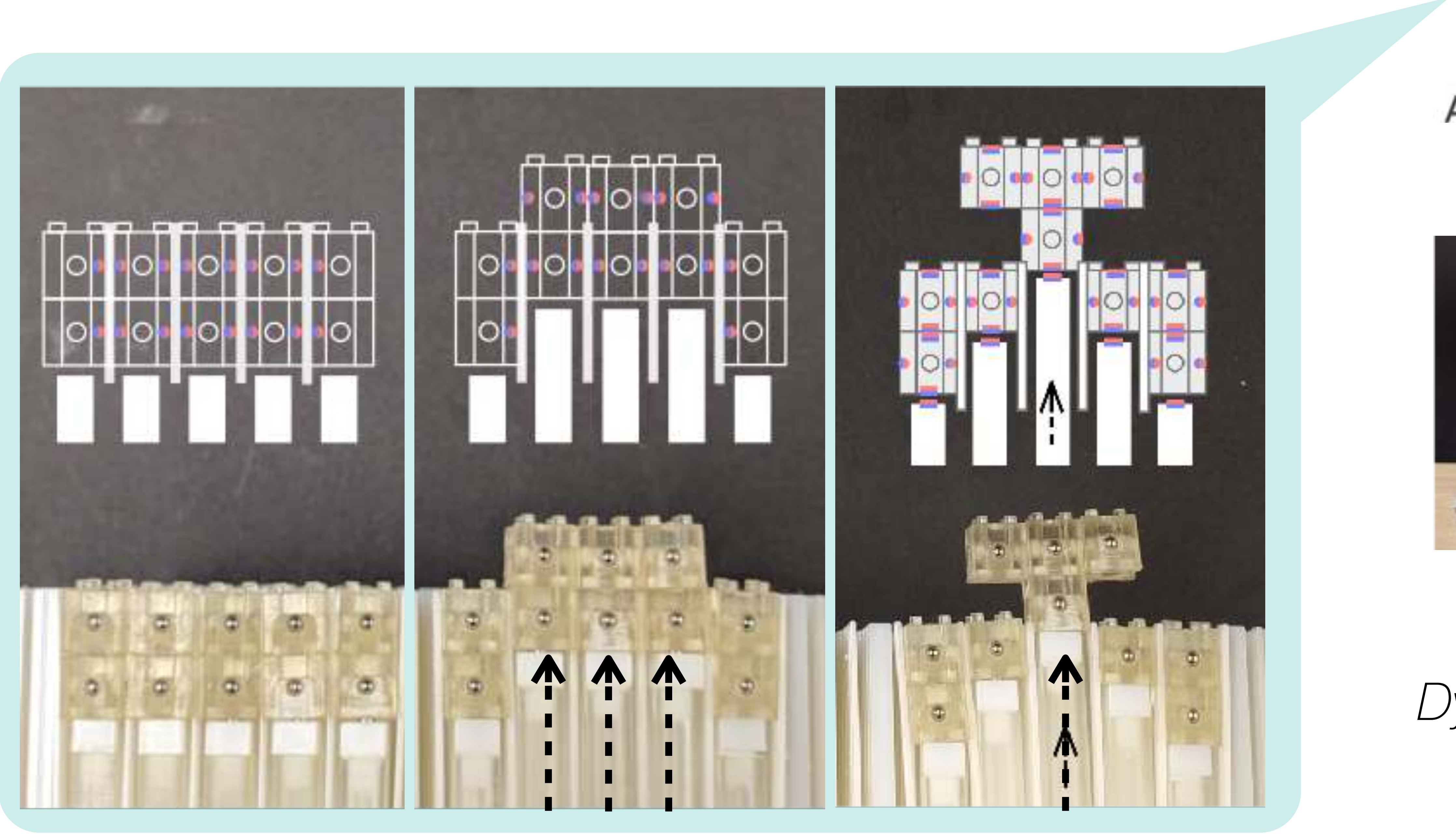

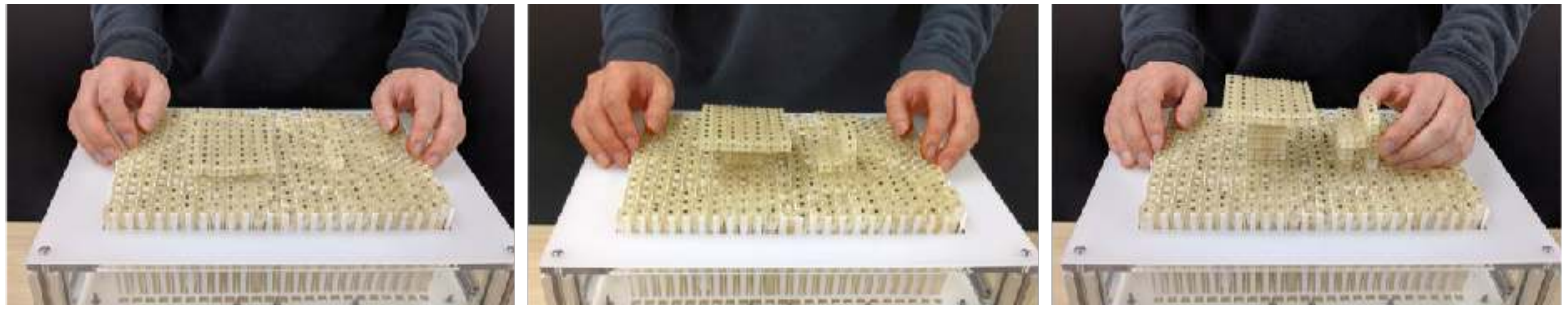

Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation
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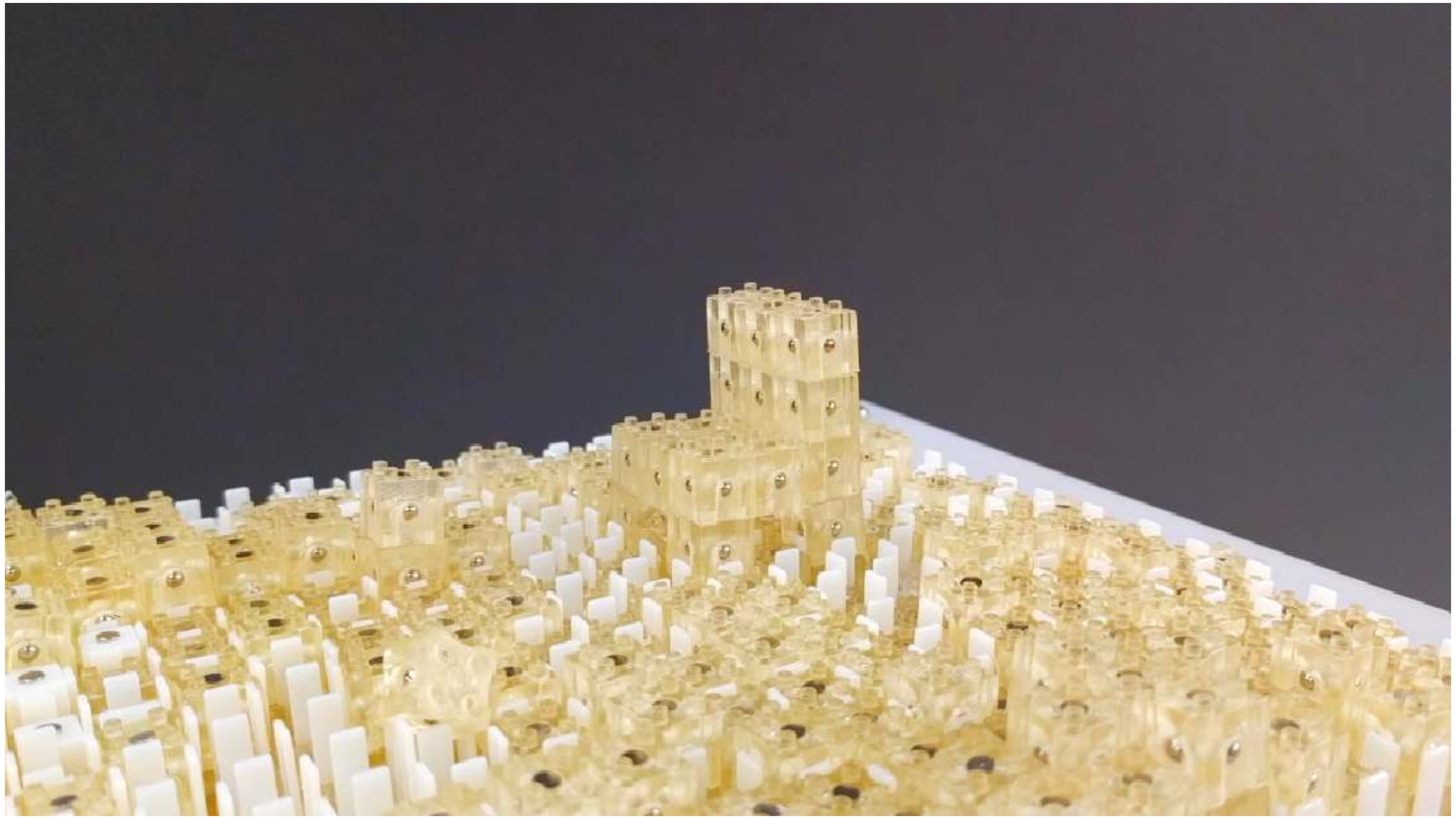
Dynablock: Dynamic 3D Printing

Parallel assembly of collective passive blocks



[UIST 2018] *Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation*

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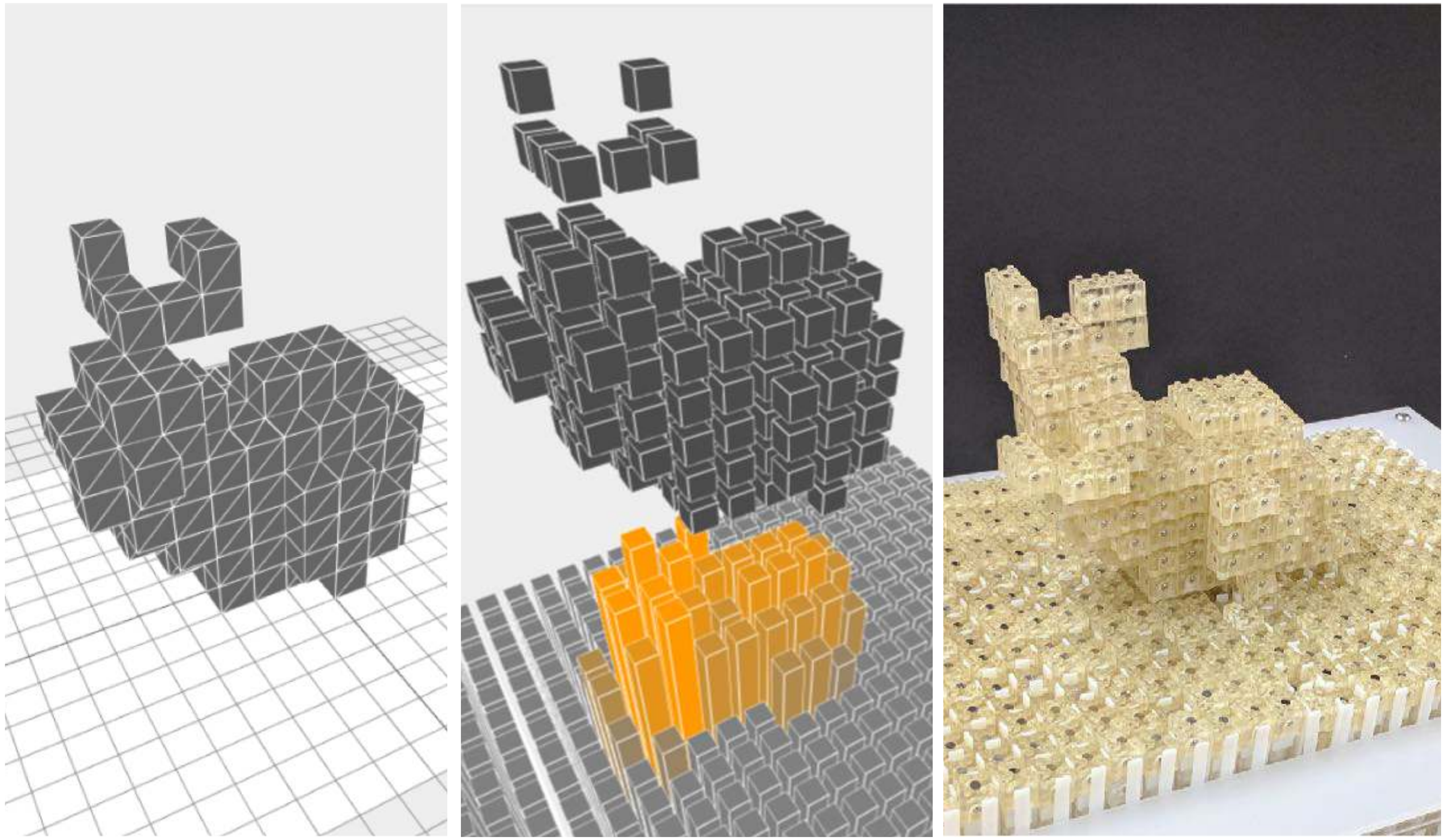
3D Shape Construction
by Selectively Actuating the Pins



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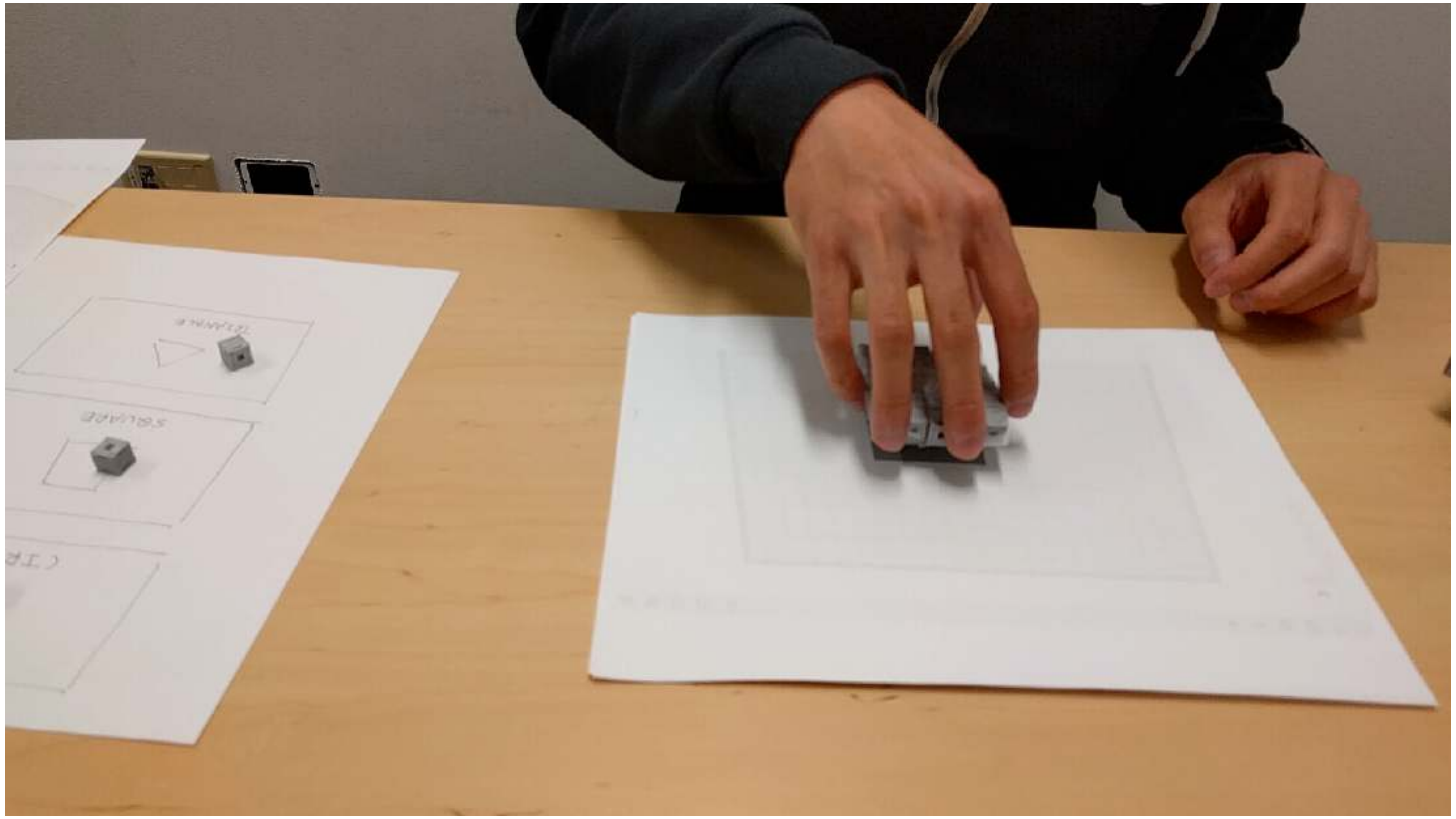
Vision



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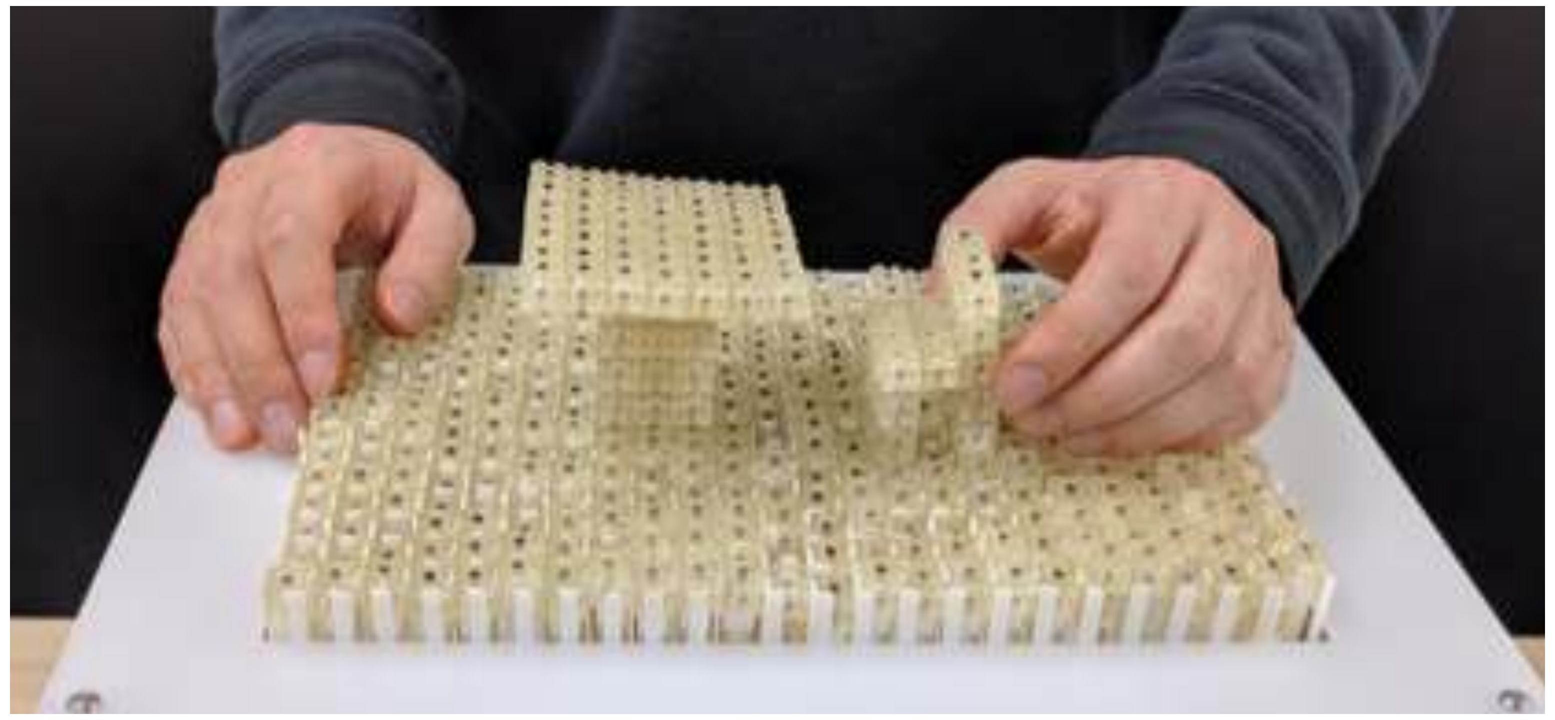
Dynamic Shape Construction with **Passive** Collective Elements

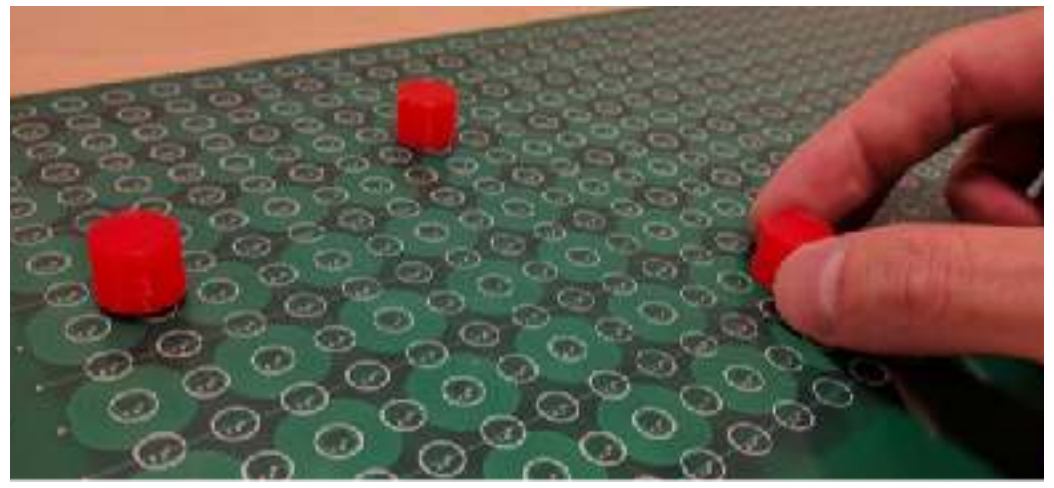


Parallel actuation of passive building blocks for **voxel** representation

[Suzuki et al., UIST 2018]

Dynamic Shape Construction with **Passive** Collective Elements

Parallel actuation of
passive building blocks for
voxel representation



Parallel actuation of
passive swarm markers for
sparse dots representation

Dynamic Shape Construction with **Passive** Collective Elements

Parallel actuation of
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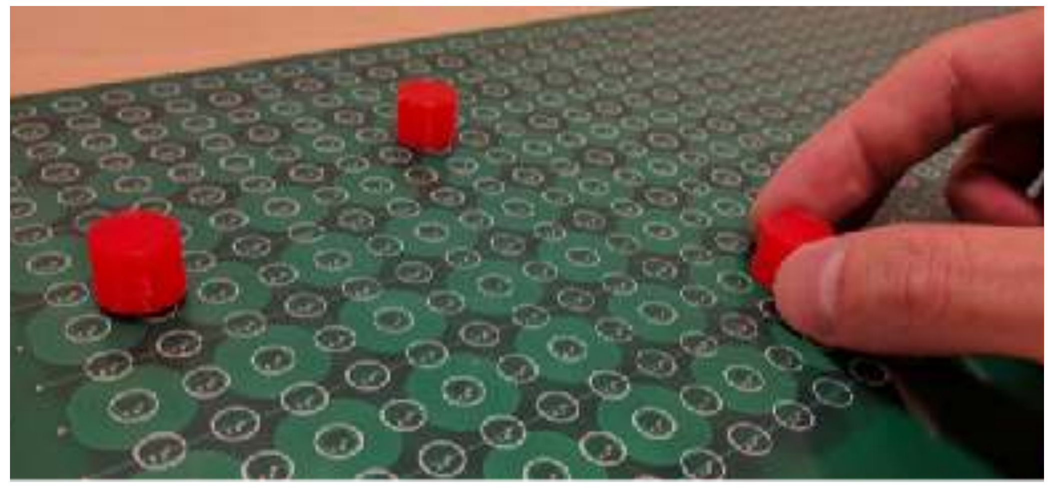
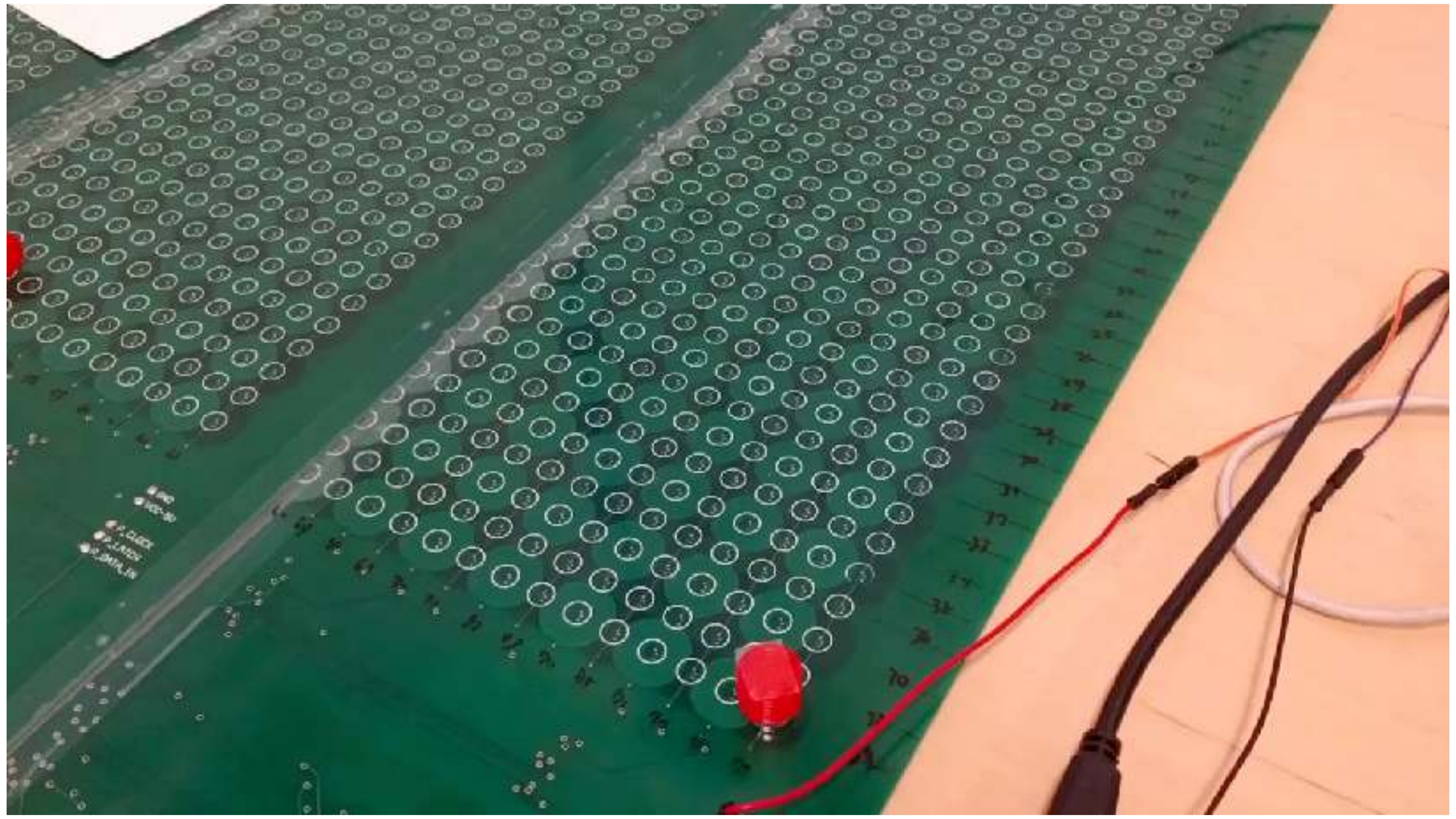


Parallel actuation of
passive swarm markers for
sparse dots representation

Externally actuated collective elements
with **electromagnetic coil arrays**



[ASSETS 2017] *FluxMarker: Enhancing Tactile Graphics with Dynamic Tactile Markers* by **Suzuki**, Stangl, Gross, and Yeh

[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

Dynamic Shape Construction with **Passive** Collective Elements

Parallel actuation of
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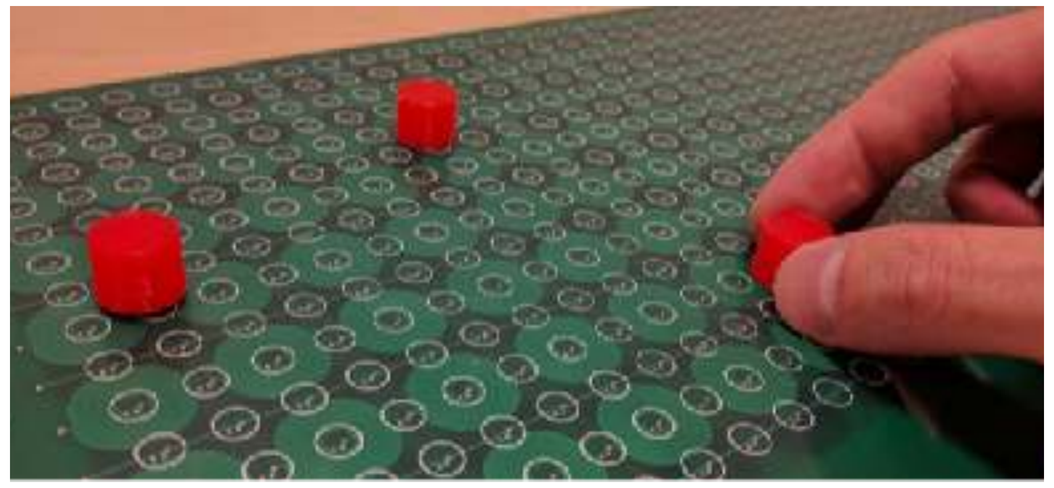
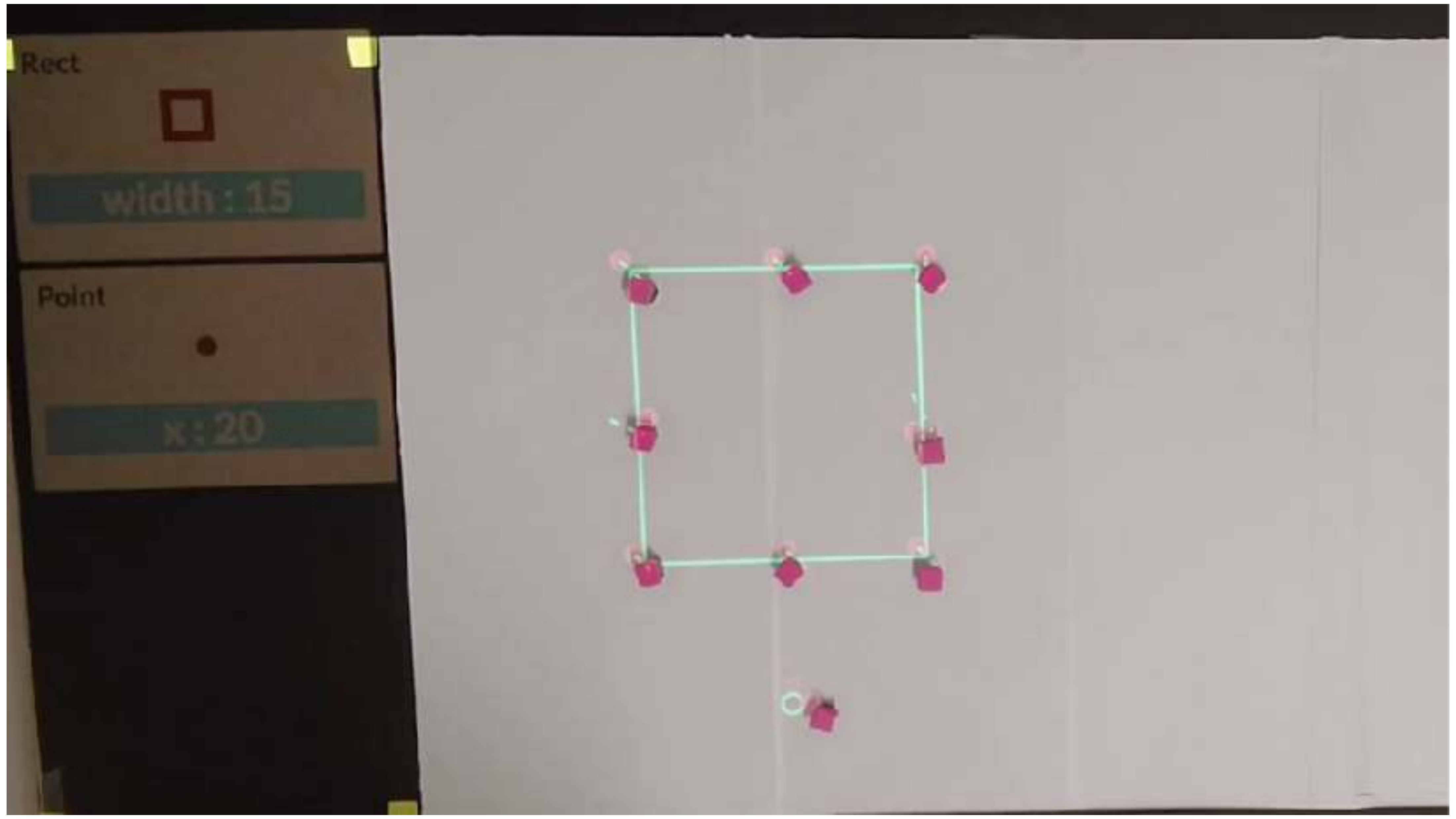


Parallel actuation of
passive swarm markers for
sparse dots representation

Externally actuated collective elements
with **electromagnetic coil arrays**



[ASSETS 2017] *FluxMarker: Enhancing Tactile Graphics with Dynamic Tactile Markers* by **Suzuki**, Stangl, Gross, and Yeh

[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

Dynamic Shape Construction with **Passive** Collective Elements

Parallel actuation of
passive building blocks for
voxel representation

Parallel actuation of
passive swarm markers for
sparse dots representation

Parallel actuation of
passive existing objects for
spatial reconfiguration

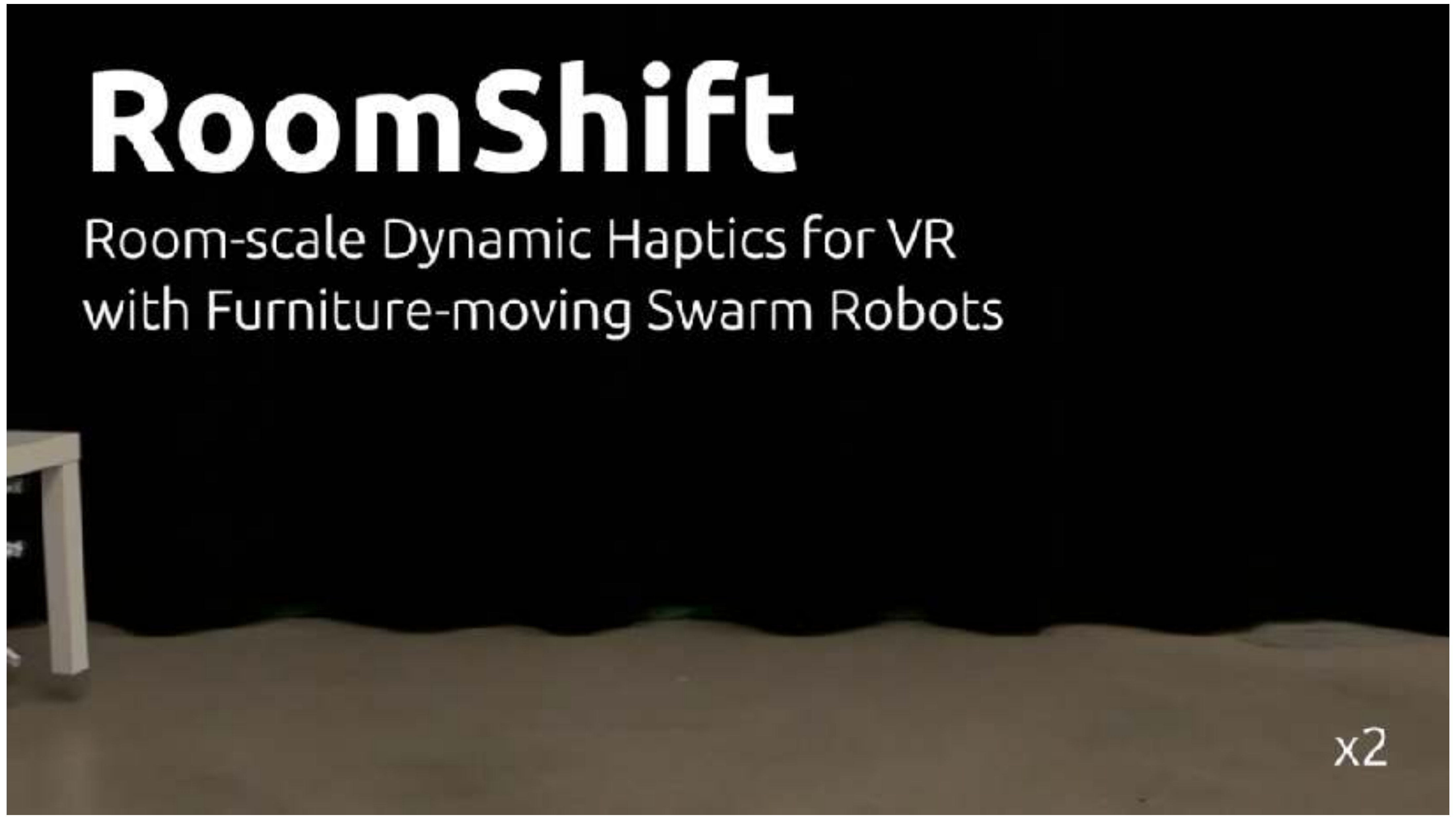
Dynamic Shape Construction with **Passive** Collective Elements

Parallel actuation of
passive building blocks for
voxel representation

Parallel actuation of
passive swarm markers for
sparse dots representation

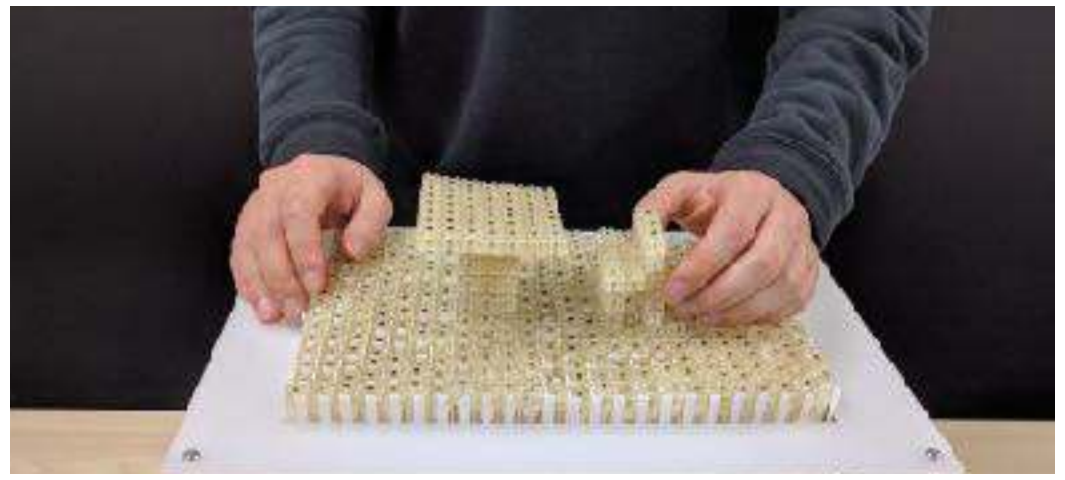
Parallel actuation of
passive existing objects for
spatial reconfiguration

Externally actuated existing static objects
with **swarm robotic actuation**

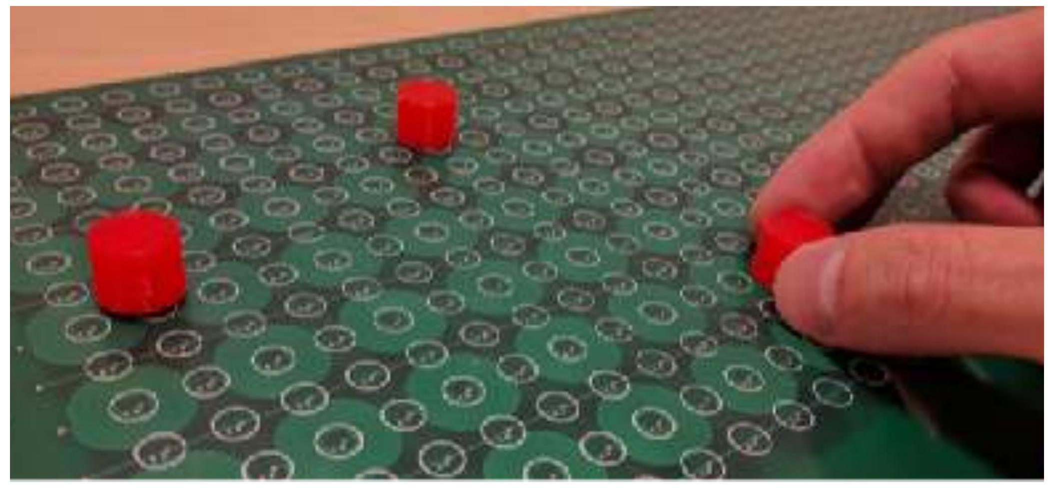


[CHI 2020] *RoomShift: Room-scale Dynamic Haptics for VR with Furniture-moving Swarm Robots*
by **Suzuki**, Hedayati, Zheng, Bohn, Szafir, Do, Gross, and Leithinger

Dynamic Shape Construction with **Passive** Collective Elements



Parallel actuation of
passive building blocks for
voxel representation

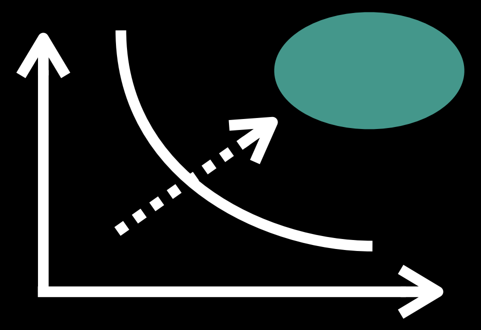


Parallel actuation of
passive swarm markers for
sparse dots representation

Parallel actuation of
passive existing objects for
spatial reconfiguration

Background

Why This Approach?

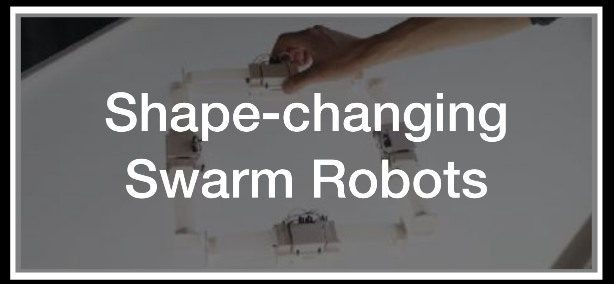


Concept

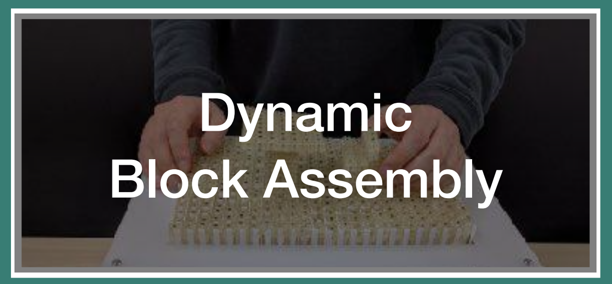
Introducing Dynamic and Collective Shape Construction

Explorations

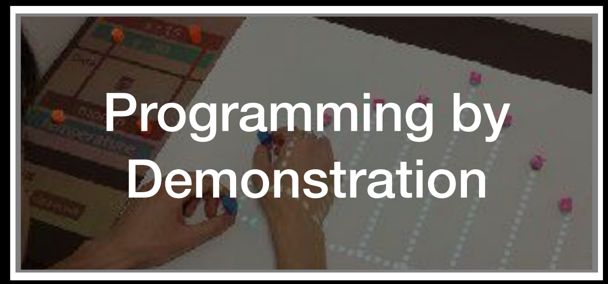
Shape Construction with **Active** Elements



Shape Construction with **Passive** Elements

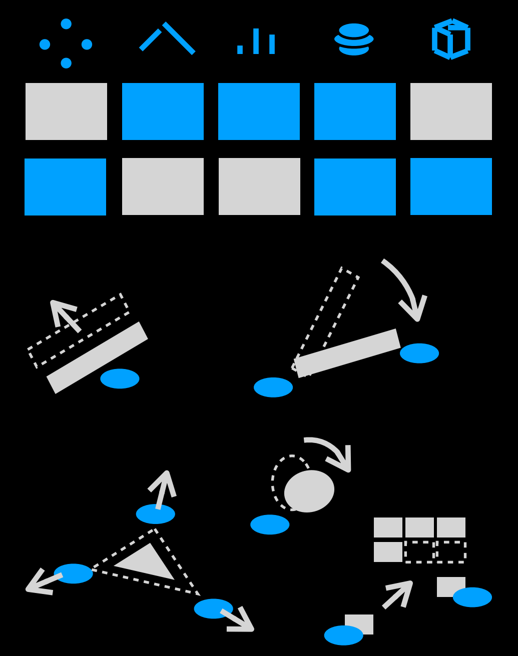


Interaction with Collective Elements



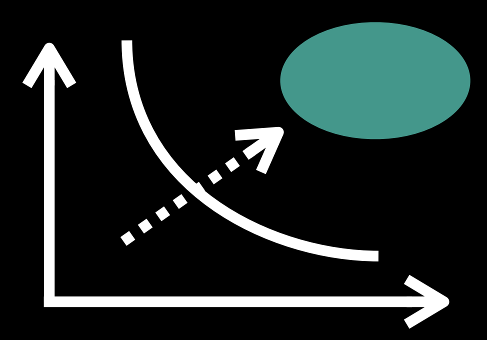
Discussion

What's Next?



Background

Why This Approach?



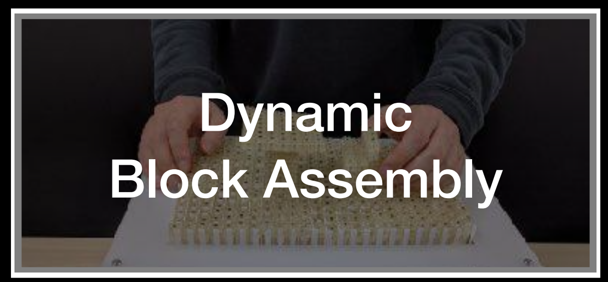
Concept

Introducing
Dynamic and Collective
Shape Construction

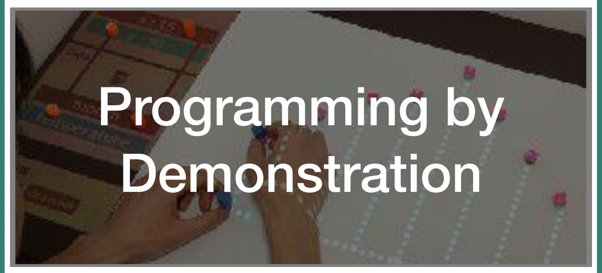
Explorations

Shape Construction
with **Active** Elements

Shape Construction
with **Passive** Elements

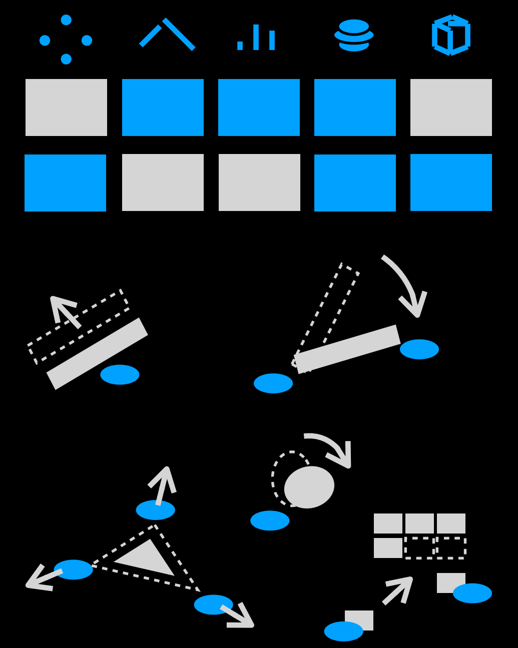


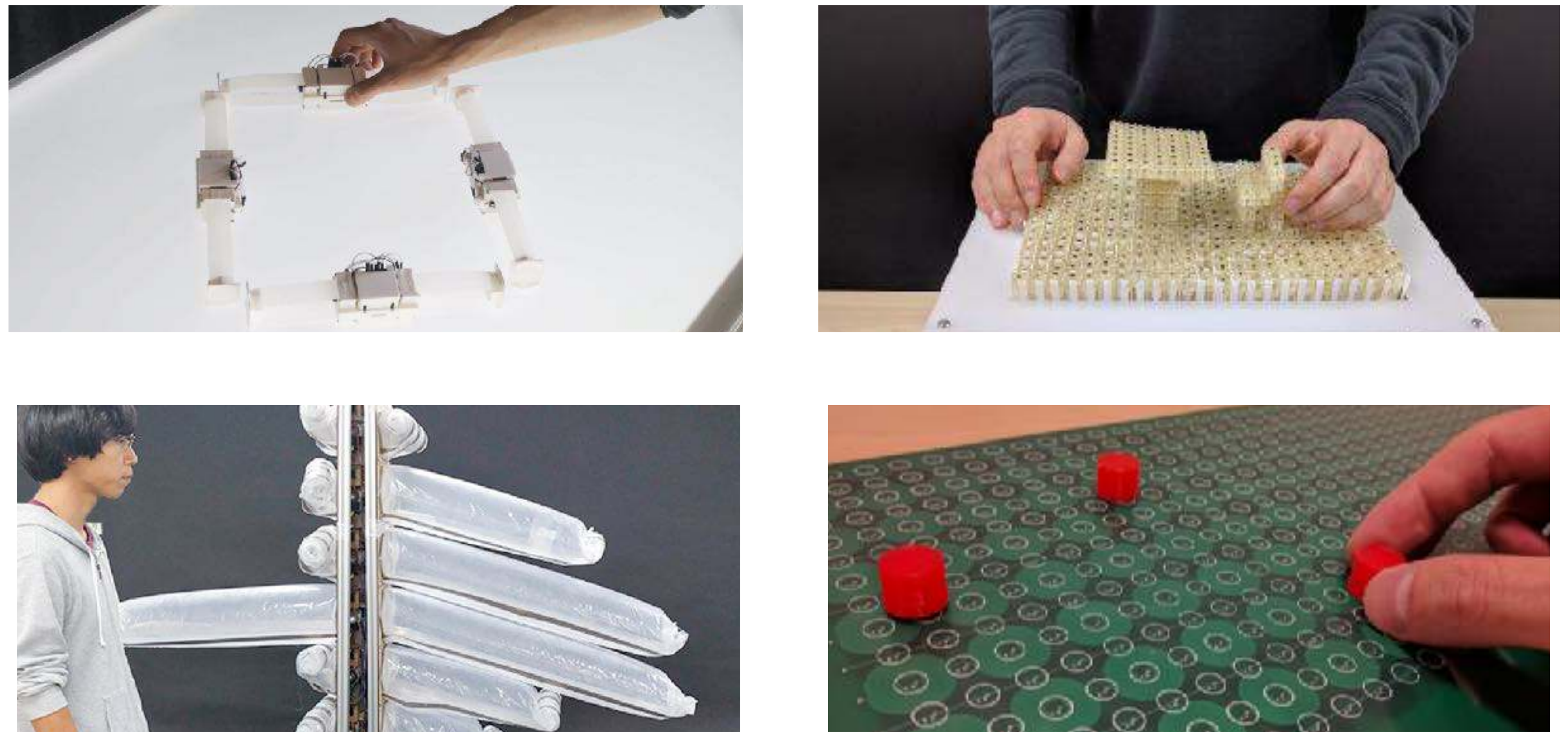
Interaction with
Collective Elements



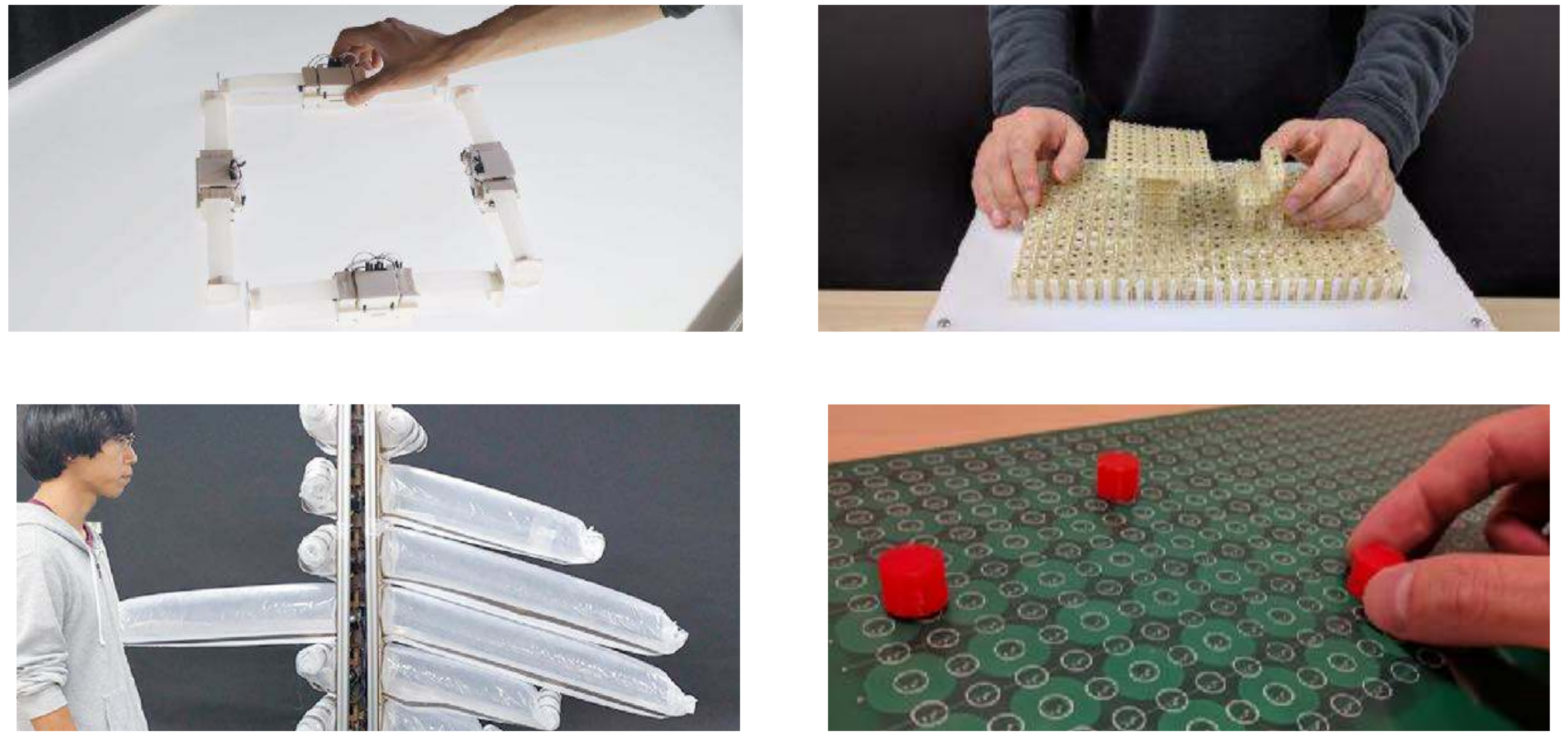
Discussion

What’s Next?





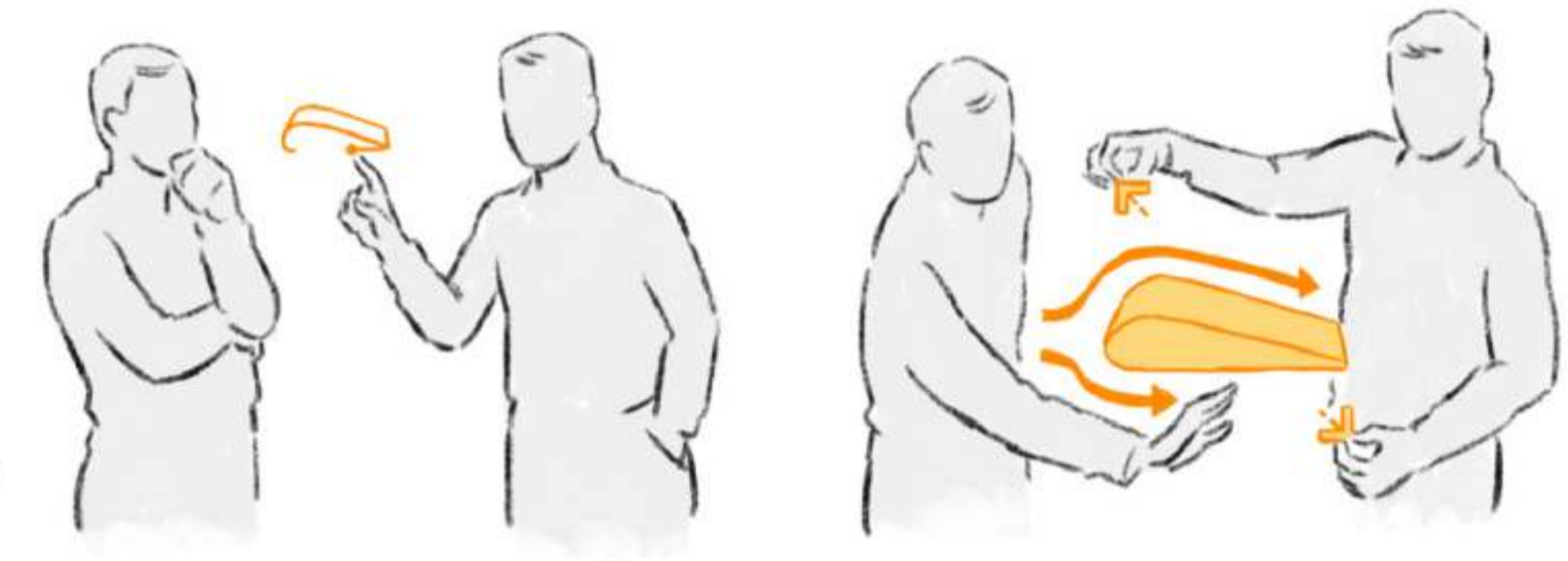
Using dynamic collective elements as
an **information display** or a **tool** to interact with.



Using dynamic collective elements as
an **information display** or a **tool** to interact with.

But, collective elements could be more than
just a tool or an information display,
but also a **medium** to create or animate
through exploration, like clay or building blocks

[Images from Bit Planner, LEGO, Zome Tools]



how can we use these collective elements
as a **medium** to create and explore dynamic motions?
what would be the interaction look like?

[Images from Victor 2014: Humane Representations of Thoughts] constructing dynamic motions often requires programming

interaction happens
in real world

programming happens
on a computer screen

[Image from Le Goc et al. 2016: Zooids: Building Blocks for Swarm User Interfaces]

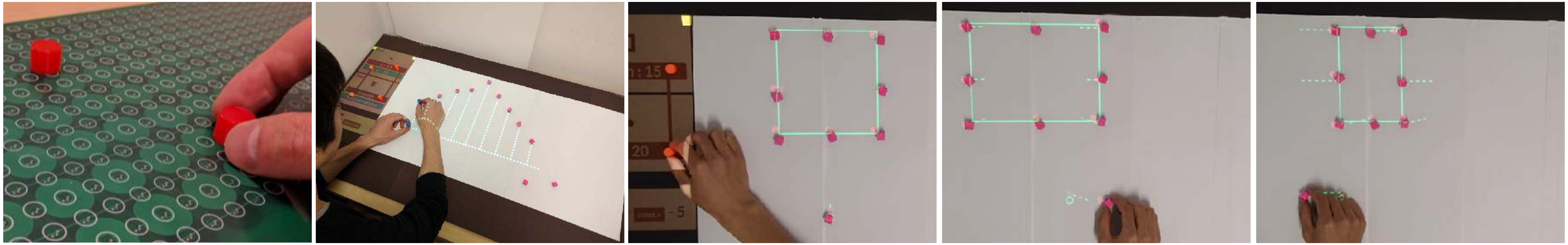
How can we enable the end user to create and explore dynamic motions, not through coding on a computer screen, but through direct physical manipulation in the real world?

[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

[CHI 2018]

Reactile:
Swarm UI Programming

by Suzuki, Kato, Gross, and Yeh



[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

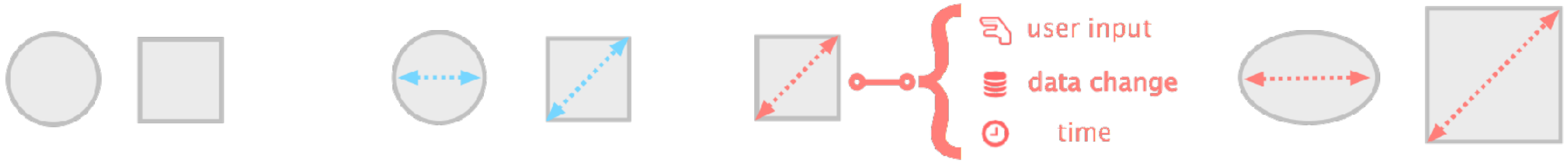
We propose the following workflow to program dynamic motions through direct physical manipulation

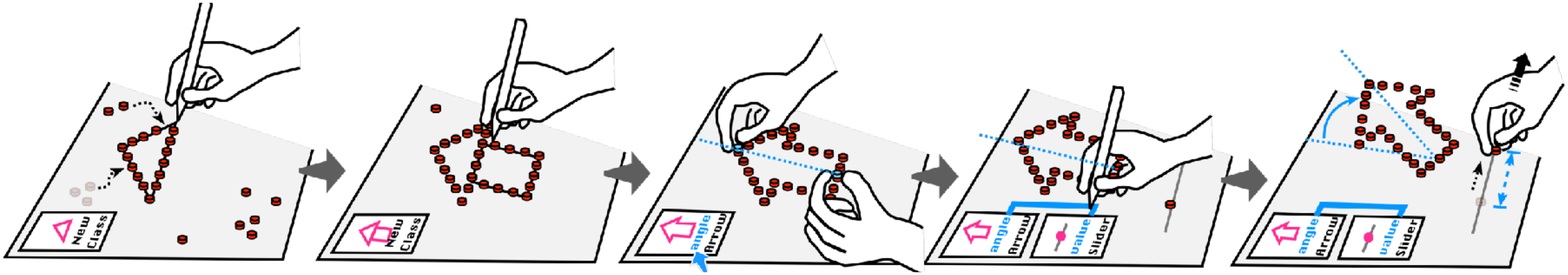
Step 1
Create Elements

Step 2
Abstract Attributes

Step 3
Specify Behaviors

Step 4
Propagate Changes



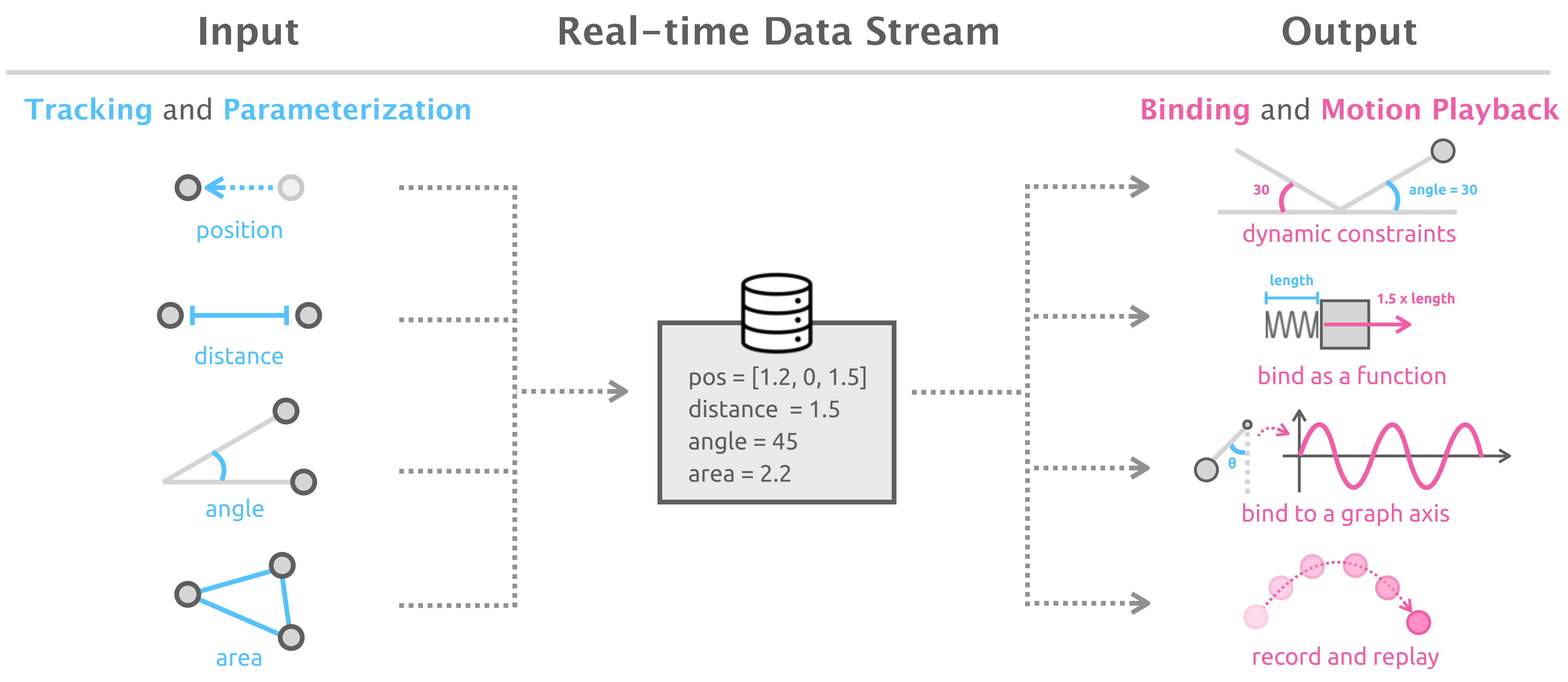


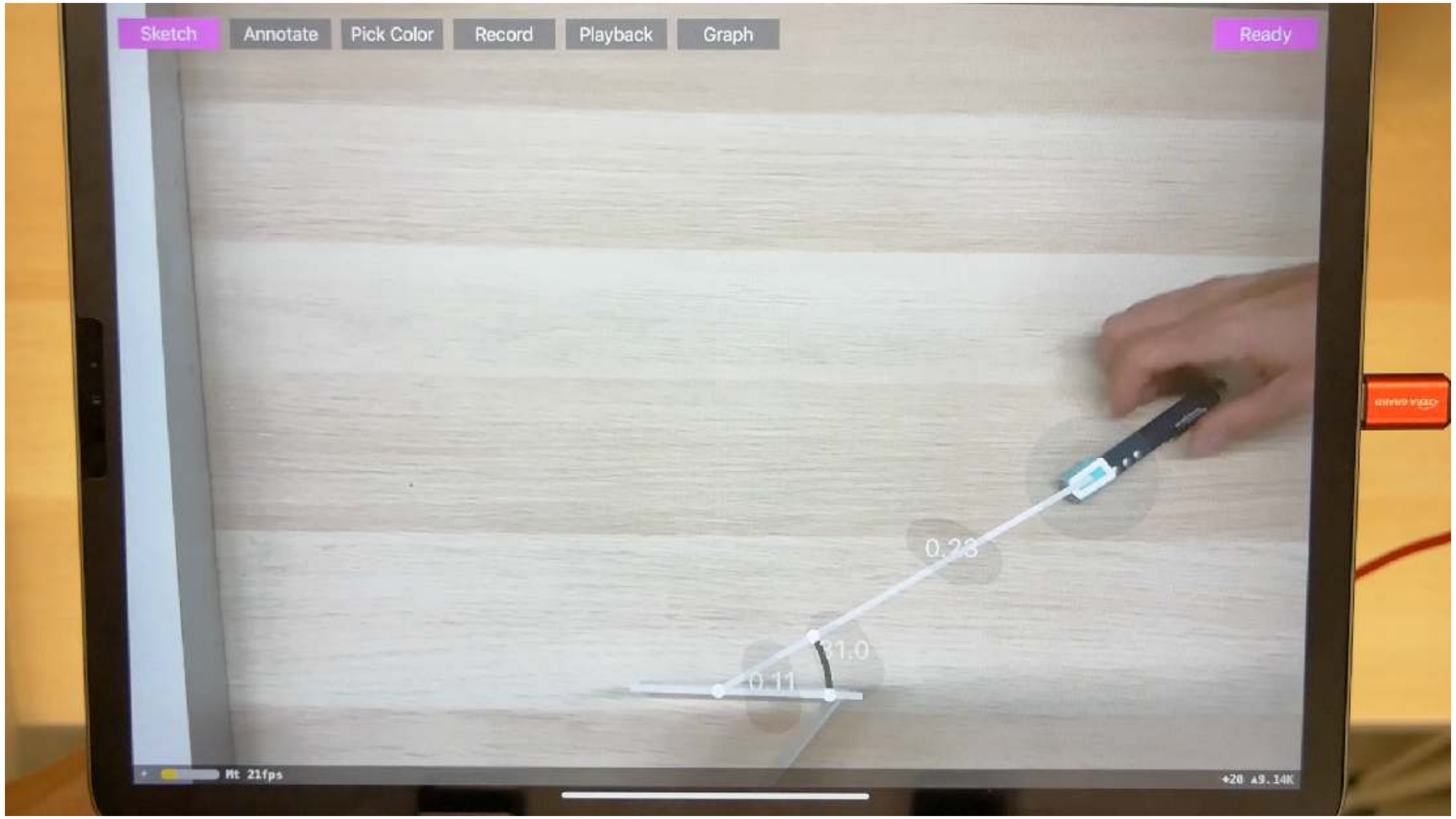
[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by Suzuki, Kato, Gross, and Yeh

Inspiration

Constraint-based Programming

1. Define
2. Bind
3. Propagate

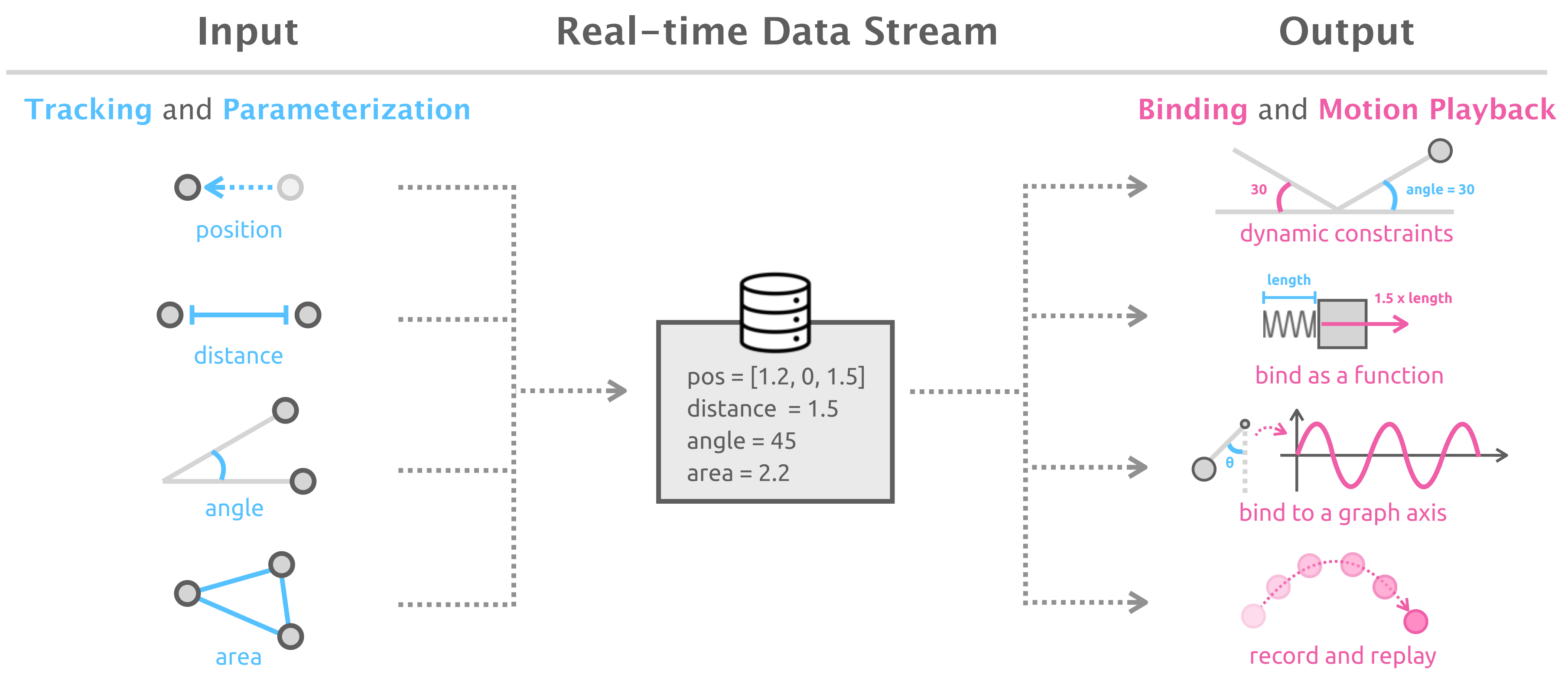


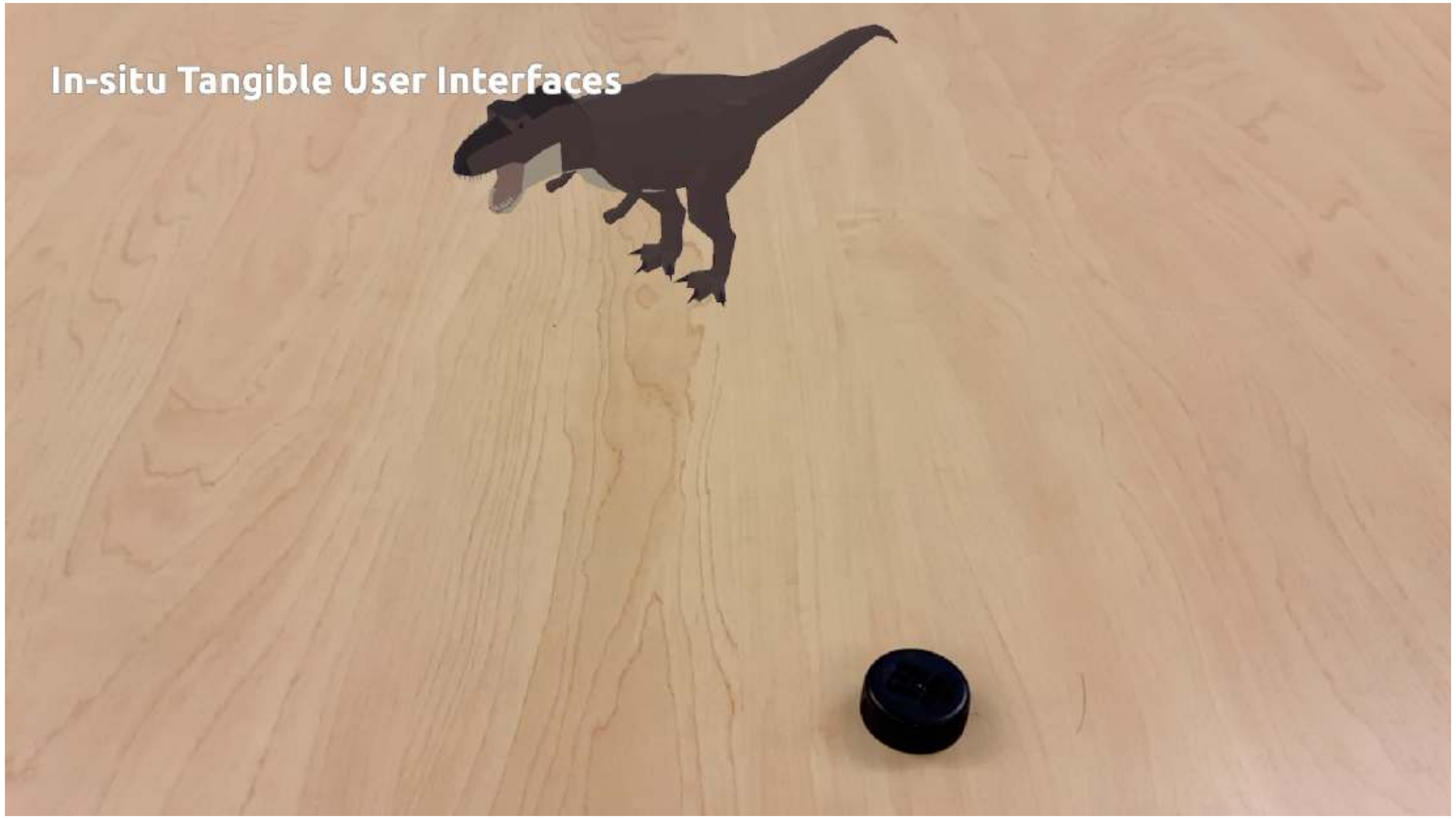


RealitySketch: Sketching Embedded and Responsive Graphics in Augmented Reality by **Suzuki**, Habib, Wei, Diverdi and Leithinger

Inspiration

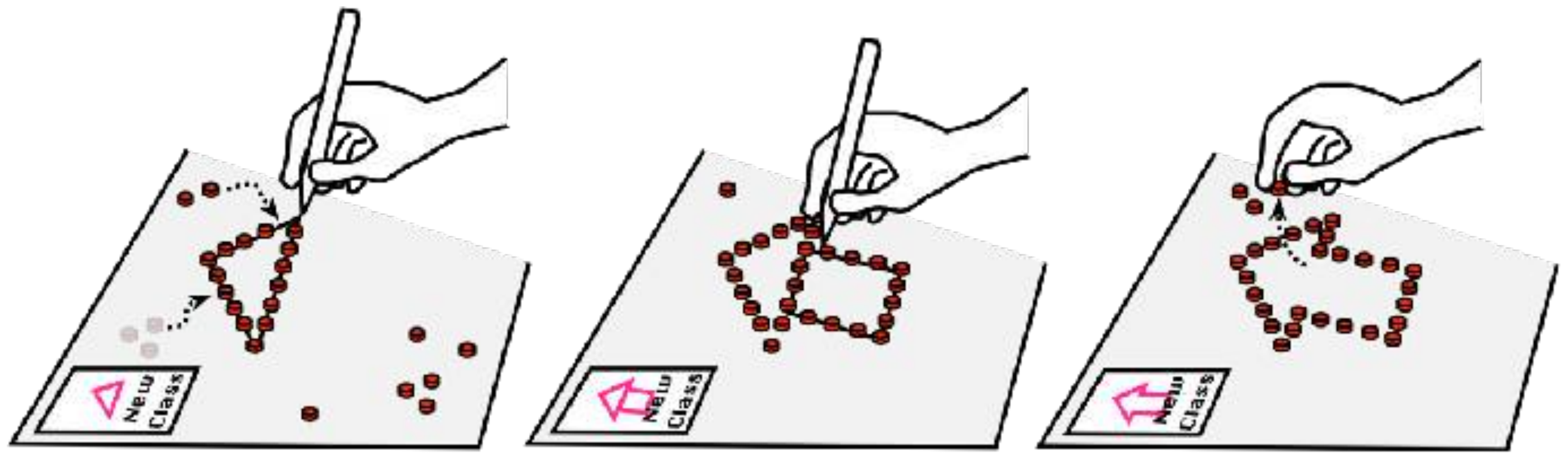
Constraint-based Programming
1. Define
2. Bind
3. Propagate

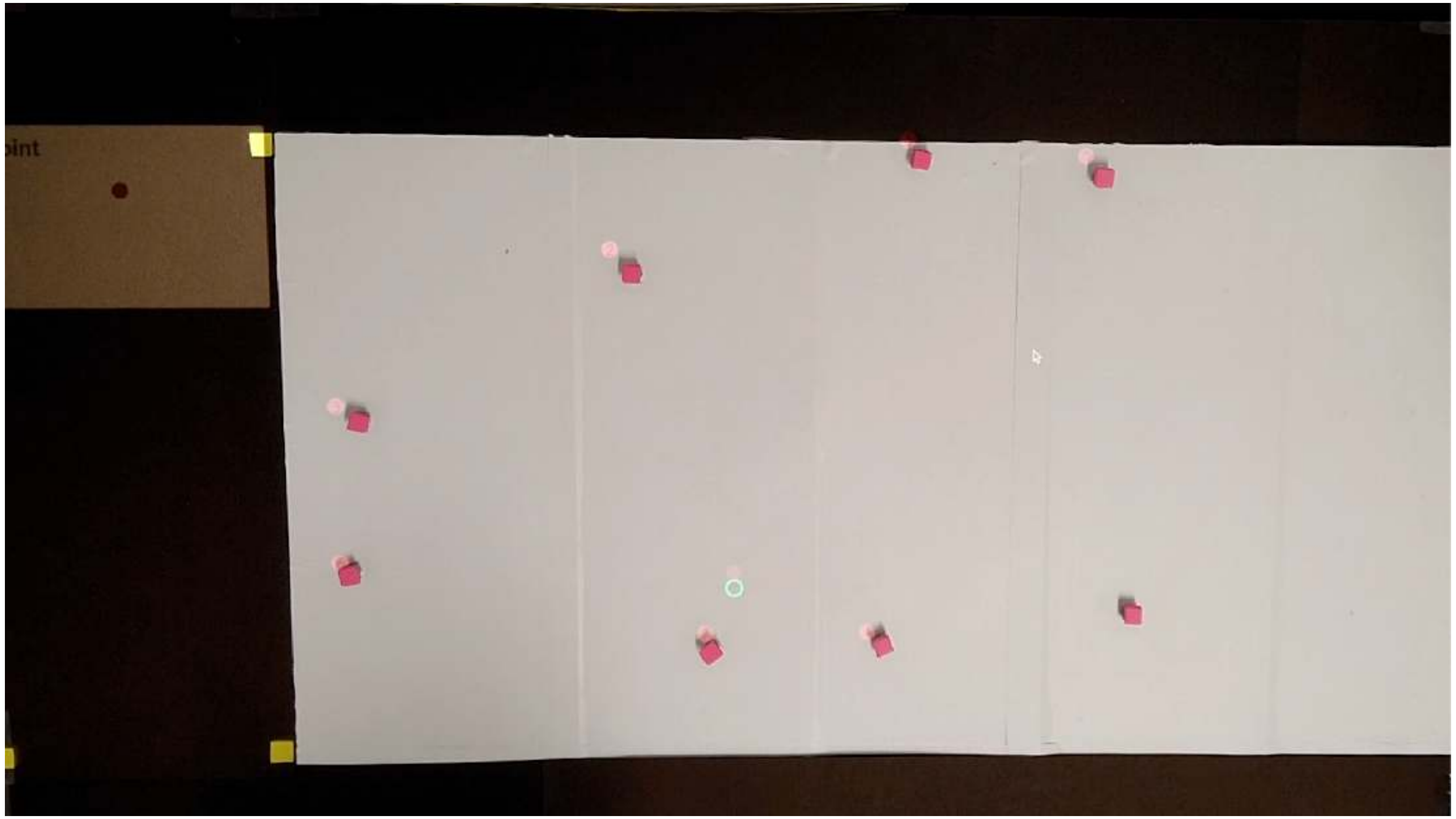




RealitySketch: Sketching Embedded and Responsive Graphics in Augmented Reality by **Suzuki**, Habib, Wei, Diverdi and Leithinger

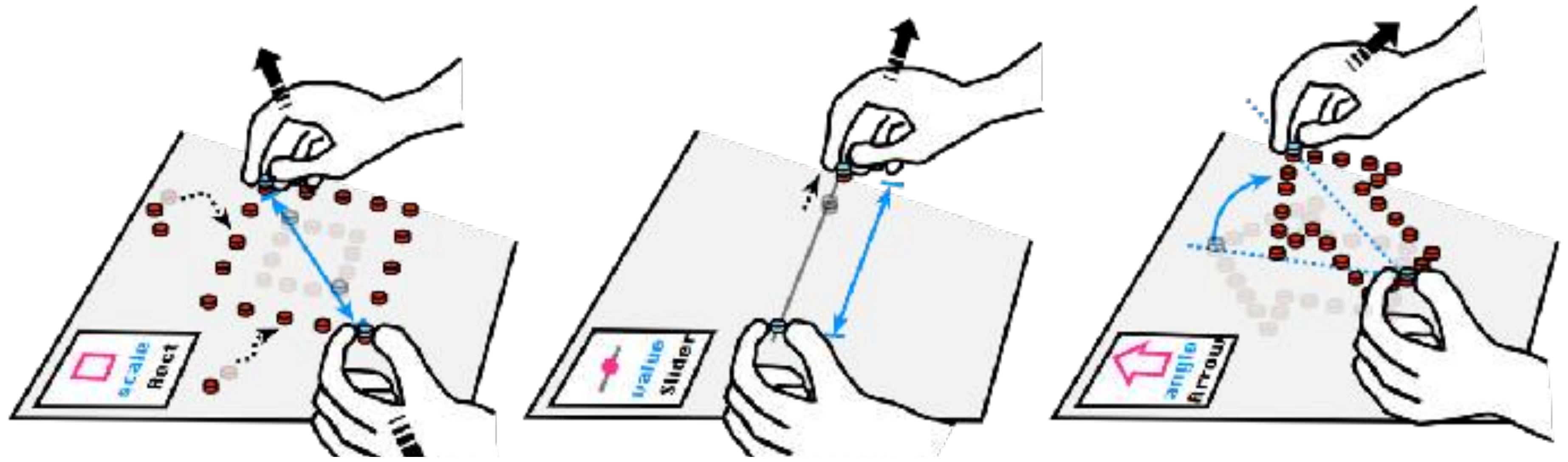
Step 1. Create a shape by sketching

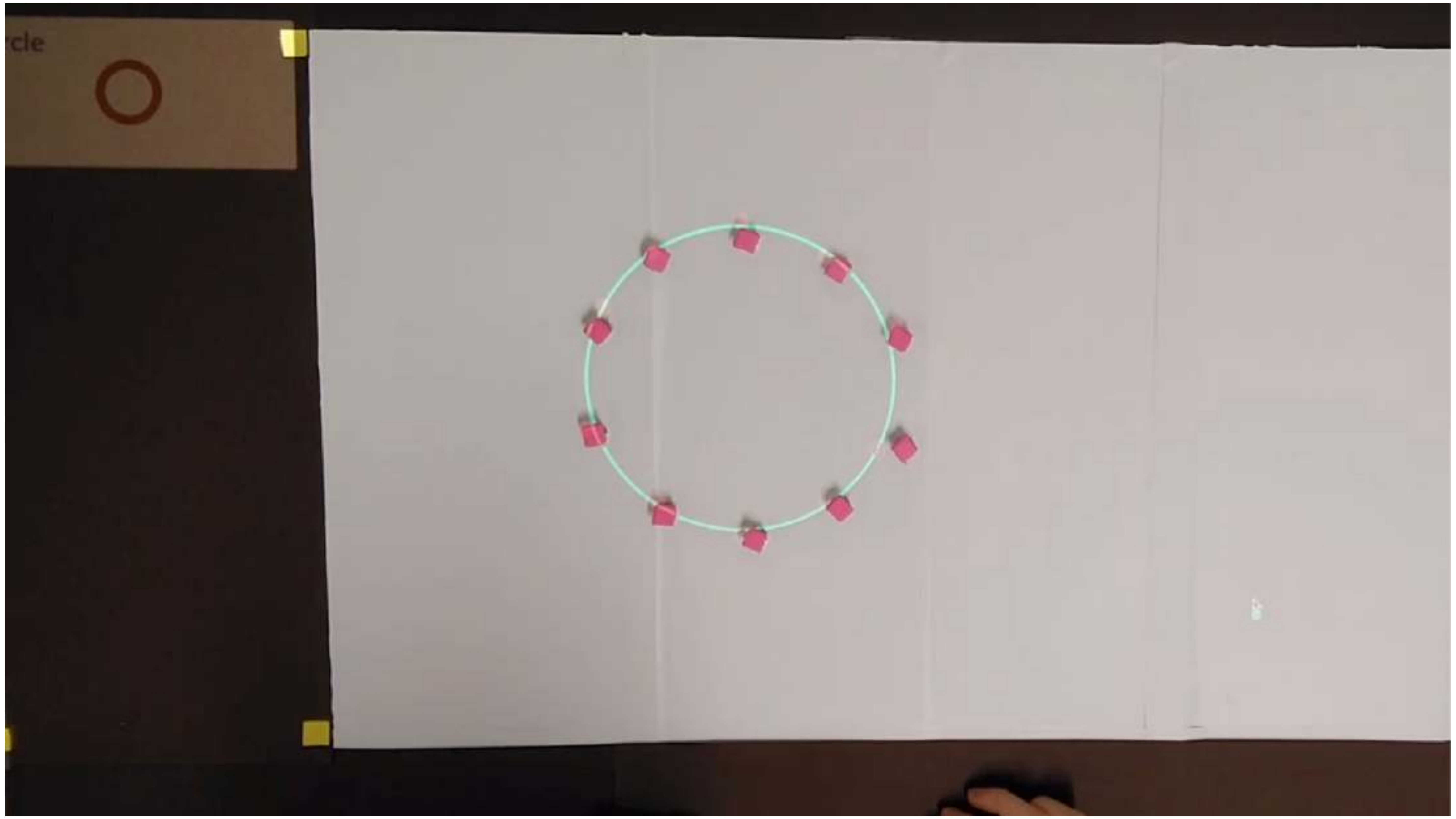




[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by Suzuki, Kato, Gross, and Yeh

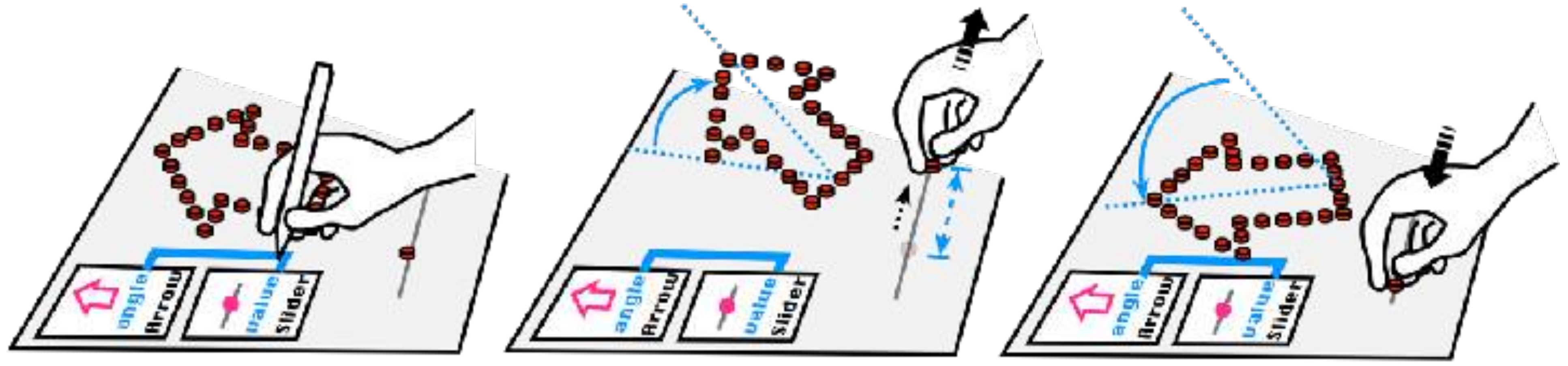
Step 2. Define a parameter to use it as a dynamic variable

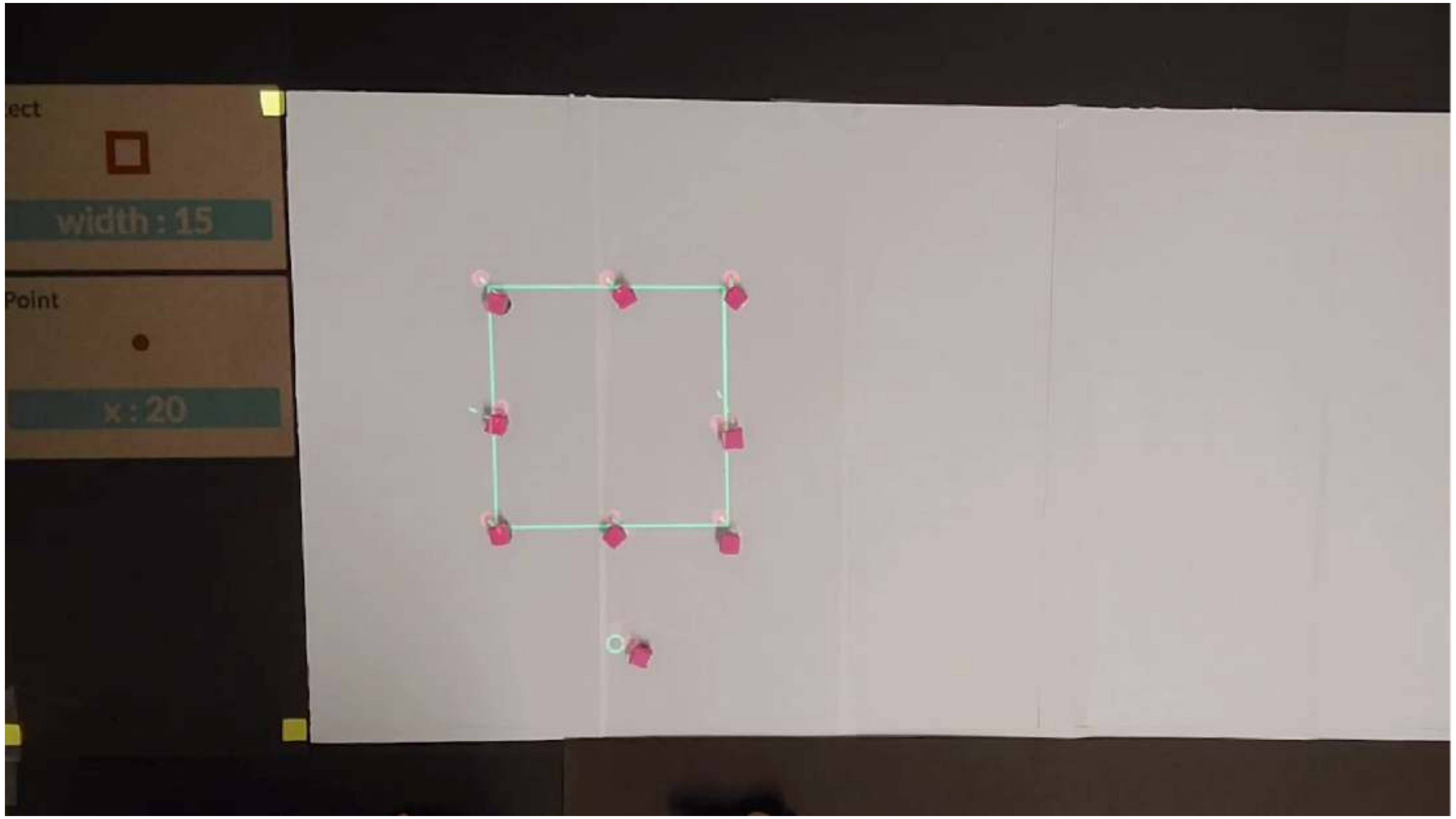




[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

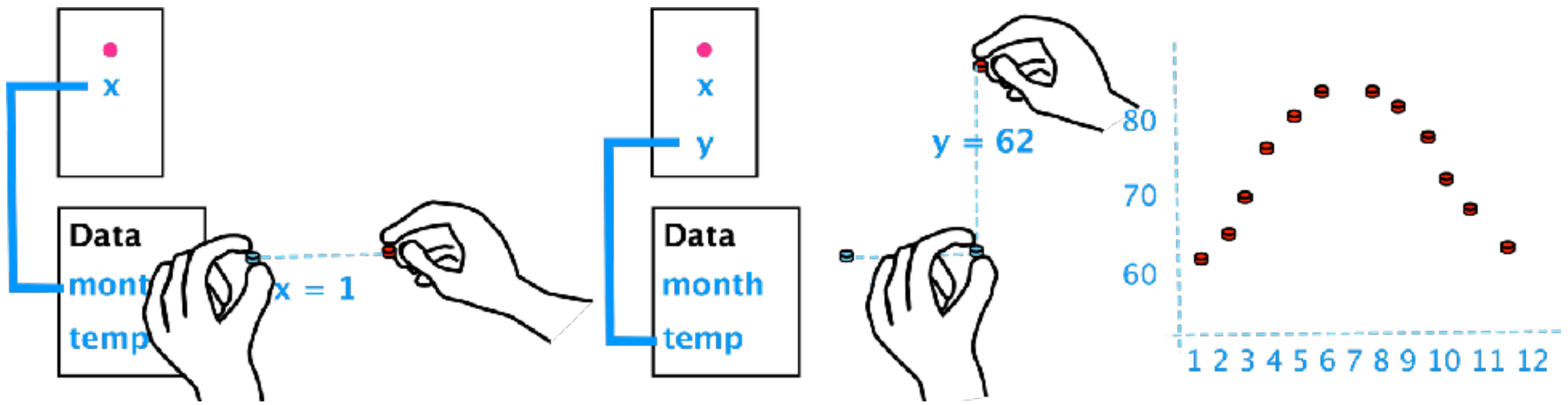
Step 3. Bind two parameters to make the shape dynamic





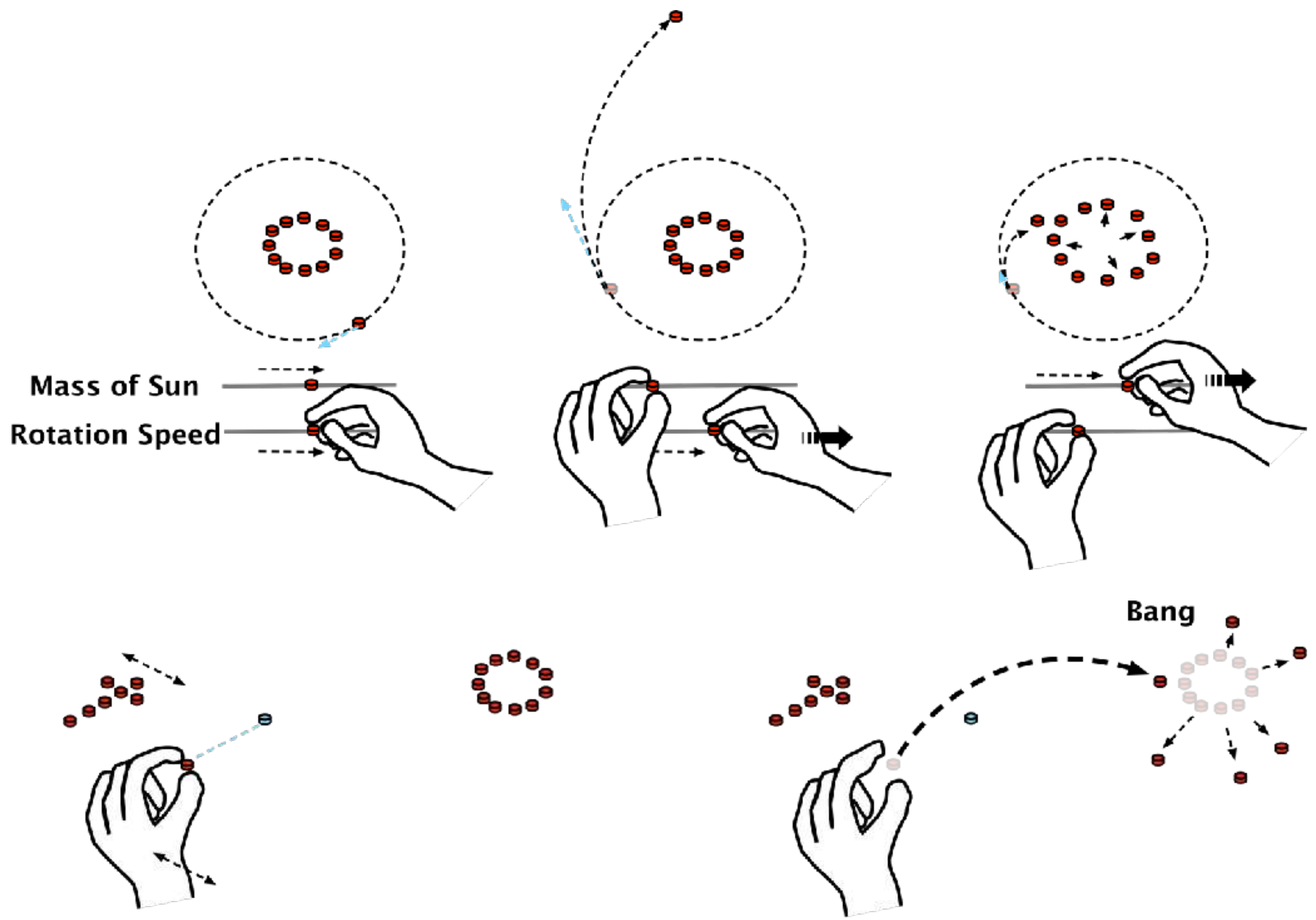
[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by Suzuki, Kato, Gross, and Yeh

Example:
Creation of dynamic data visualization



[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

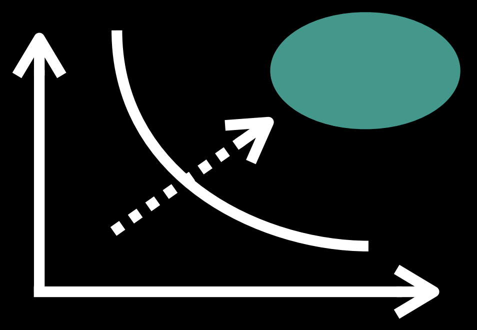
Example:
Creation of dynamic data visualization or interactive simulation, gaming, etc



[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

Background

Why This Approach?

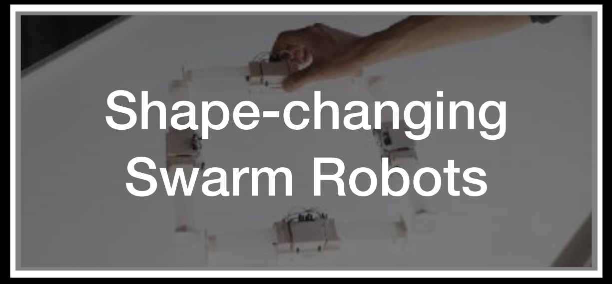


Concept

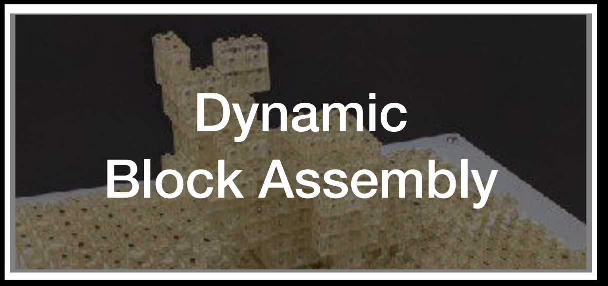
What is Dynamic and Collective Shape Construction?

Explorations

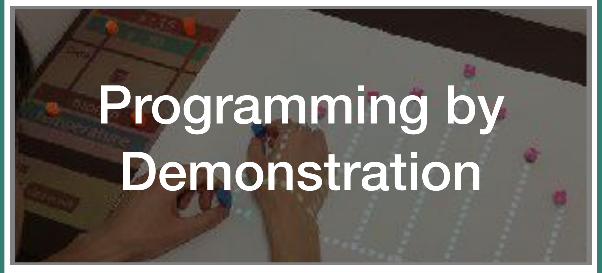
Shape Construction with **Active** Elements



Shape Construction with **Passive** Elements

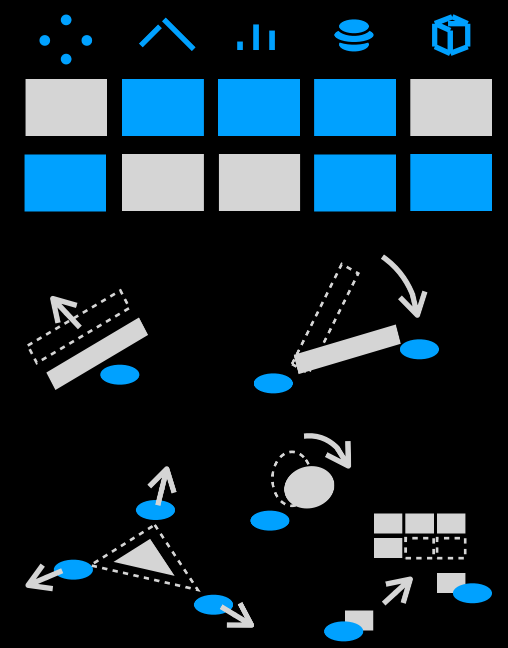


Interaction with Collective Elements



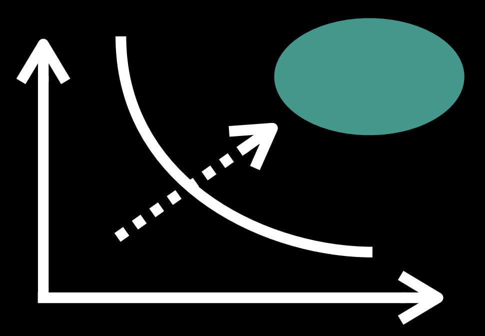
Discussion

What's Next?



Background

Why This Approach?

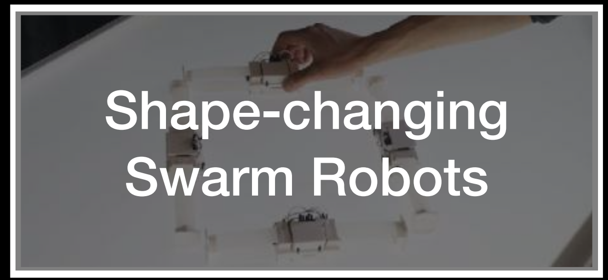


Concept

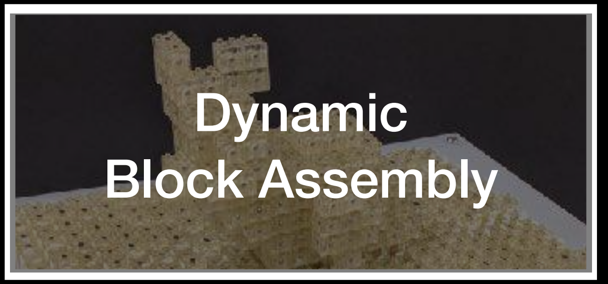
What is
Dynamic and Collective
Shape Construction?

Explorations

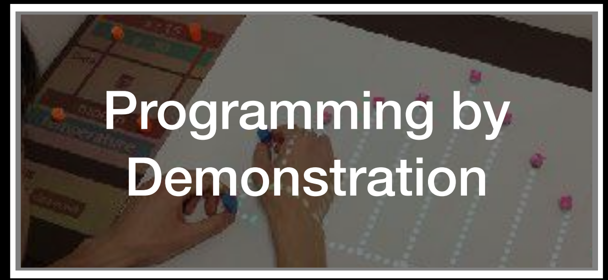
Shape Construction
with **Active** Elements



Shape Construction
with **Passive** Elements

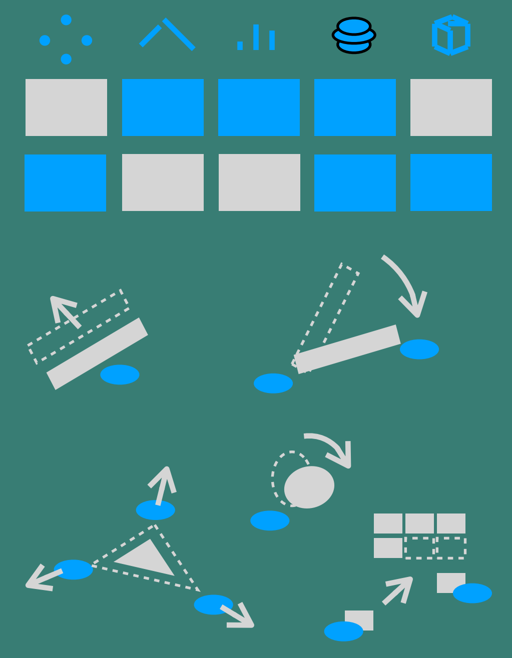


Interaction with
Collective Elements



Discussion

What's Next?



Discussion and Design Implications

1 - Active Collective Elements

How can we combine individual transformation as building blocks for various representations?

2 - Passive Collective Elements

How can we combine both active and passive elements to construct a dynamic shape?

3 - Collective Actuation

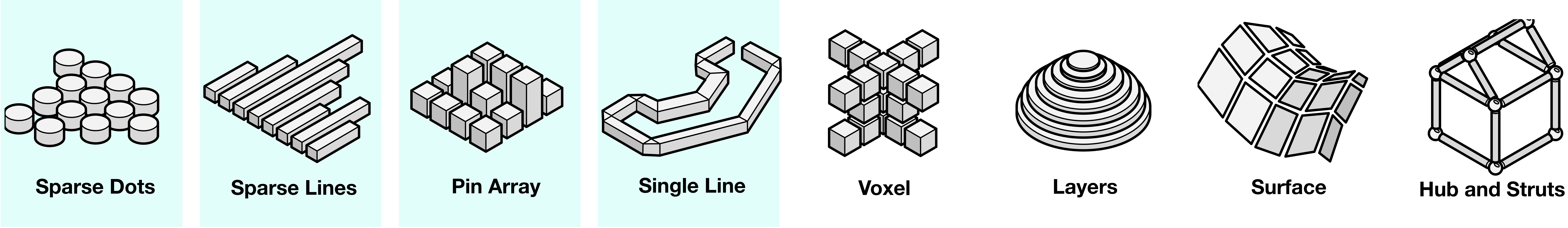
How can we leverage multiple active elements to collectively actuate passive materials?

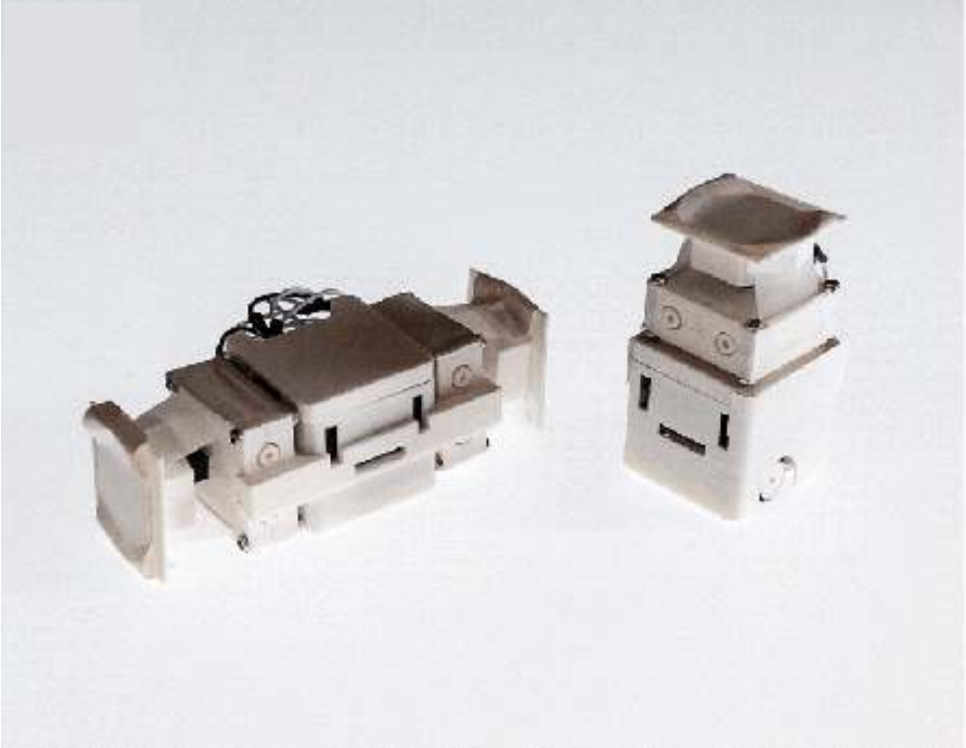
1 - Active Collective Elements

How can we combine individual transformation as building blocks for various representations?

Active Collective Elements

How can we combine individual transformation as **building blocks** for various representations?

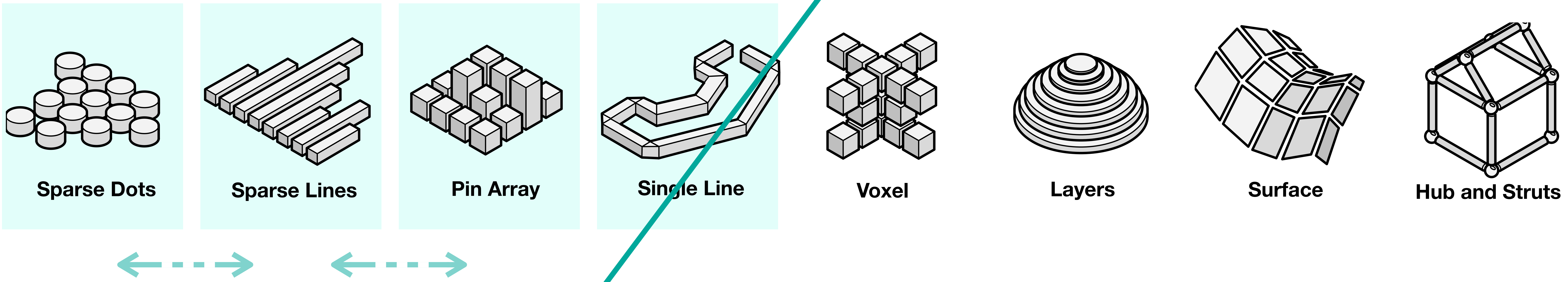


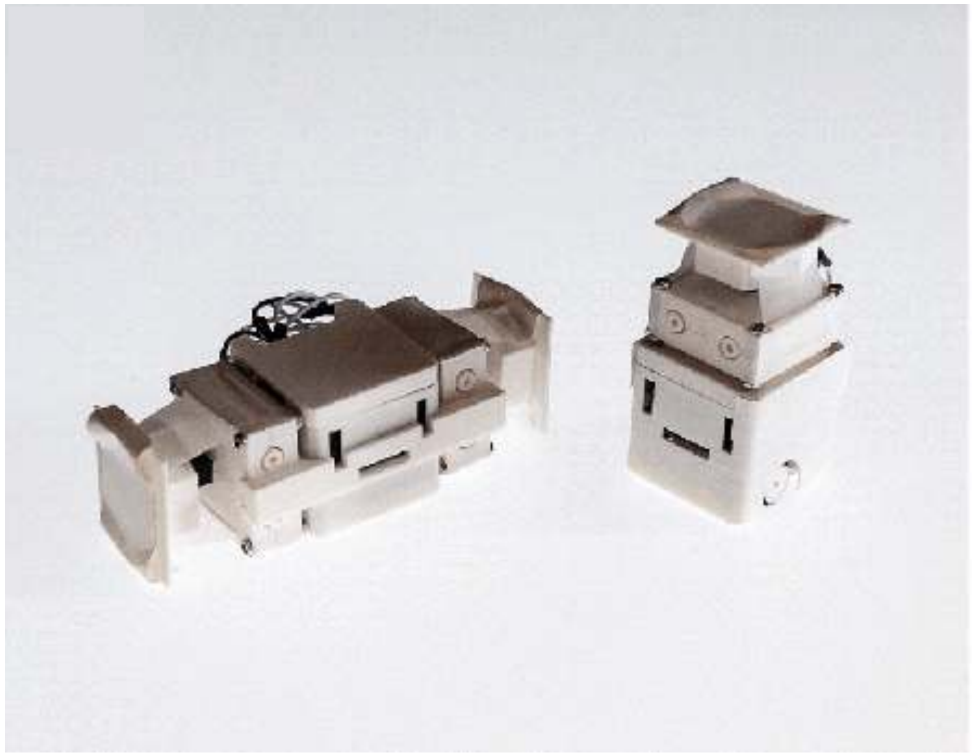


Case Study: ShapeBots

Active Collective Elements

How can we combine individual transformation as **building blocks** for various representations?





Case Study: ShapeBots

Active Collective Elements

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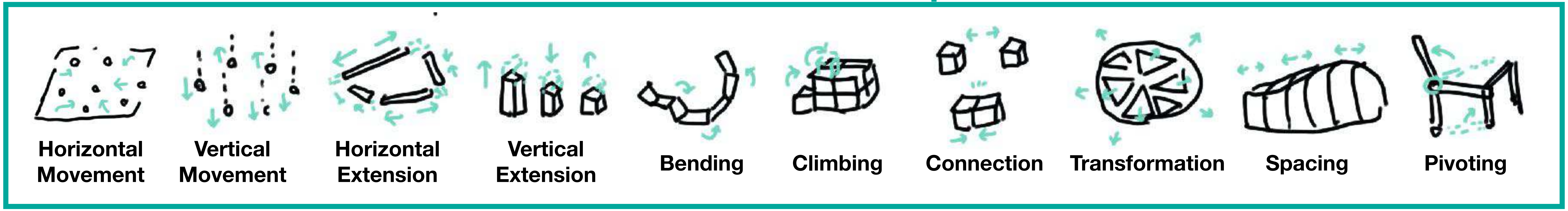
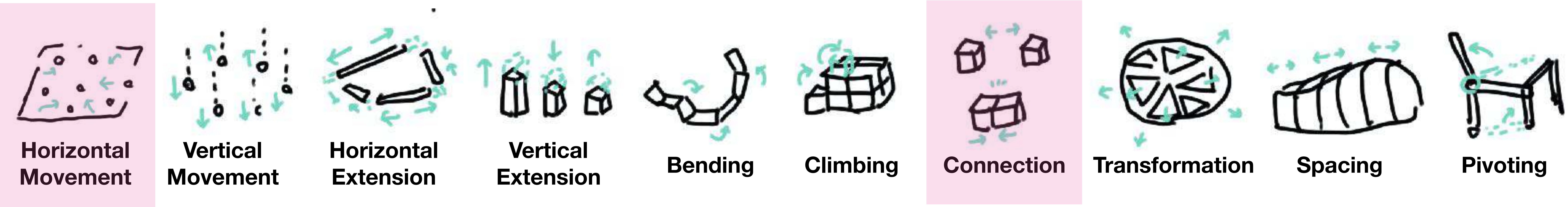
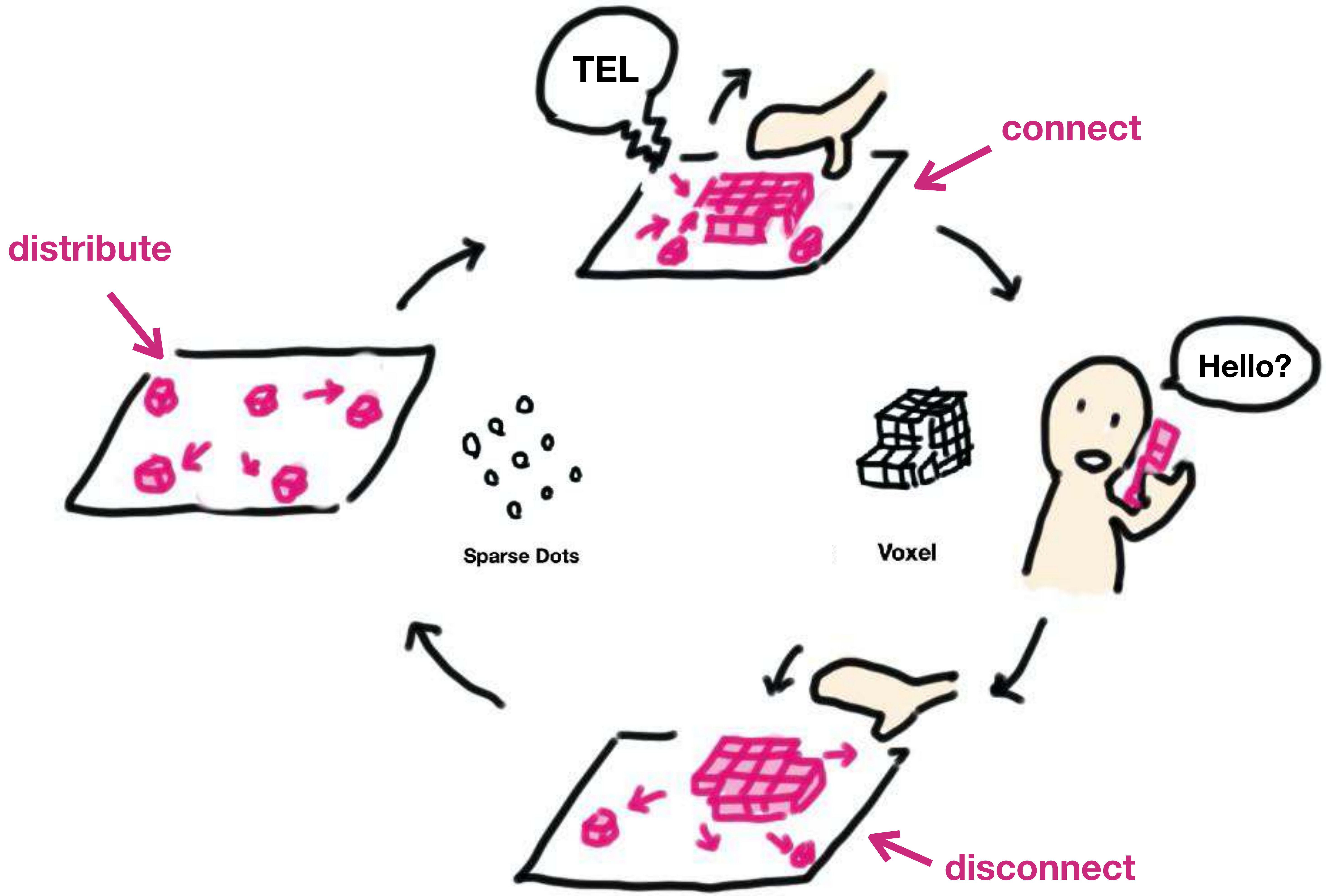
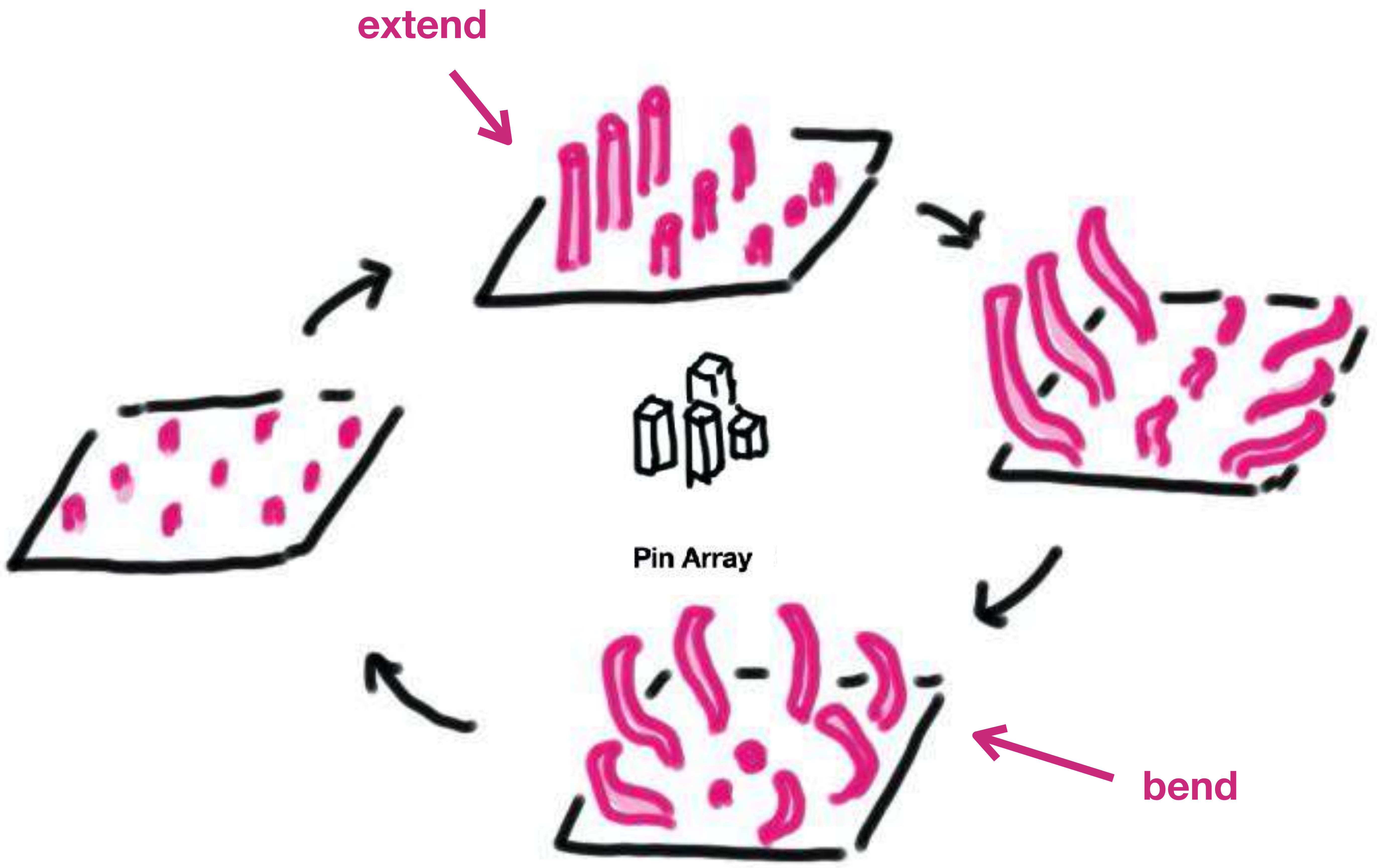


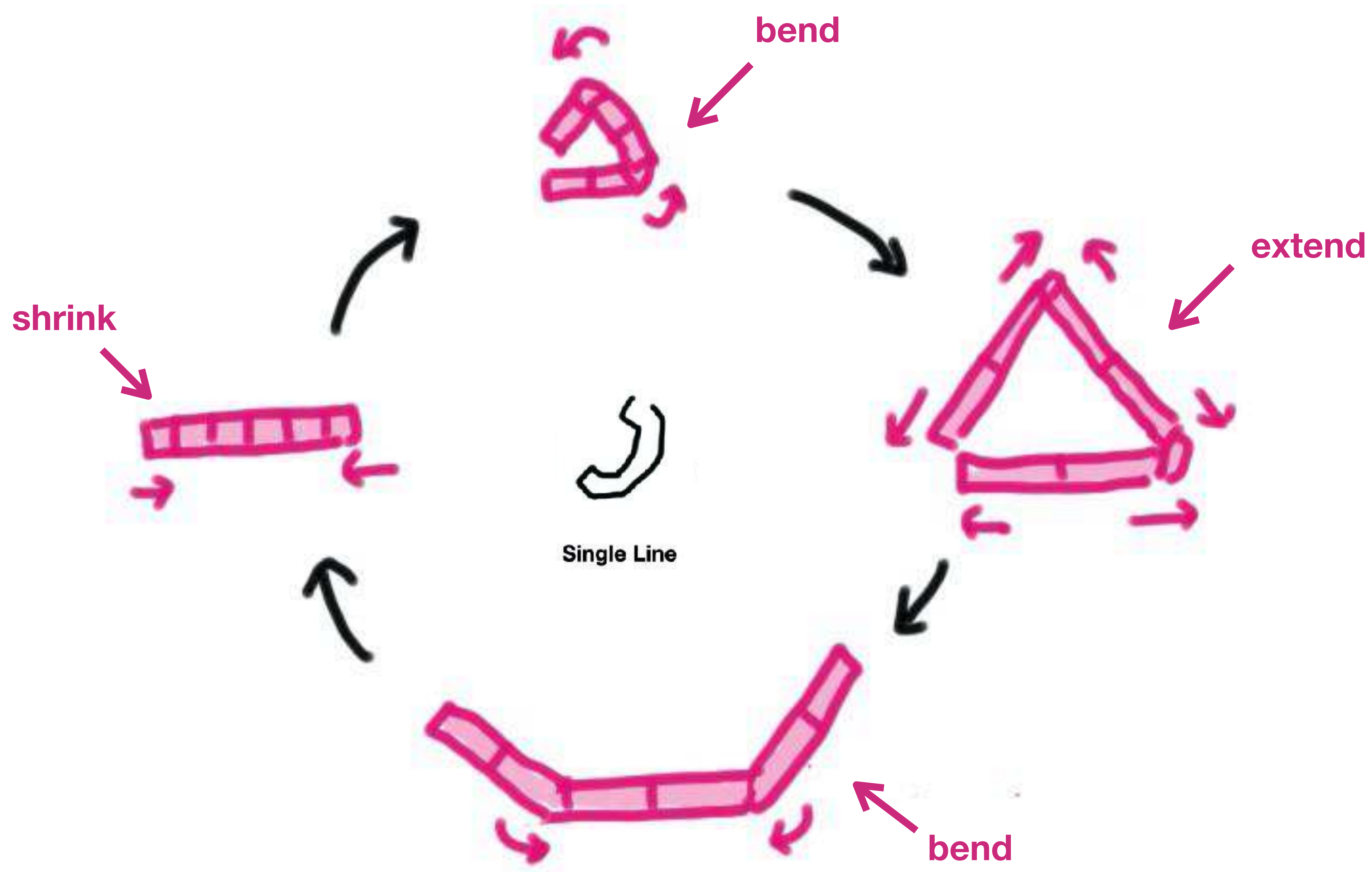




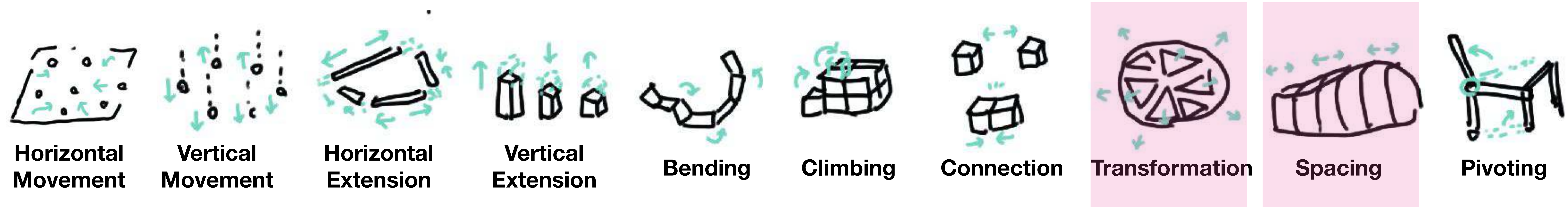
: Active Elements

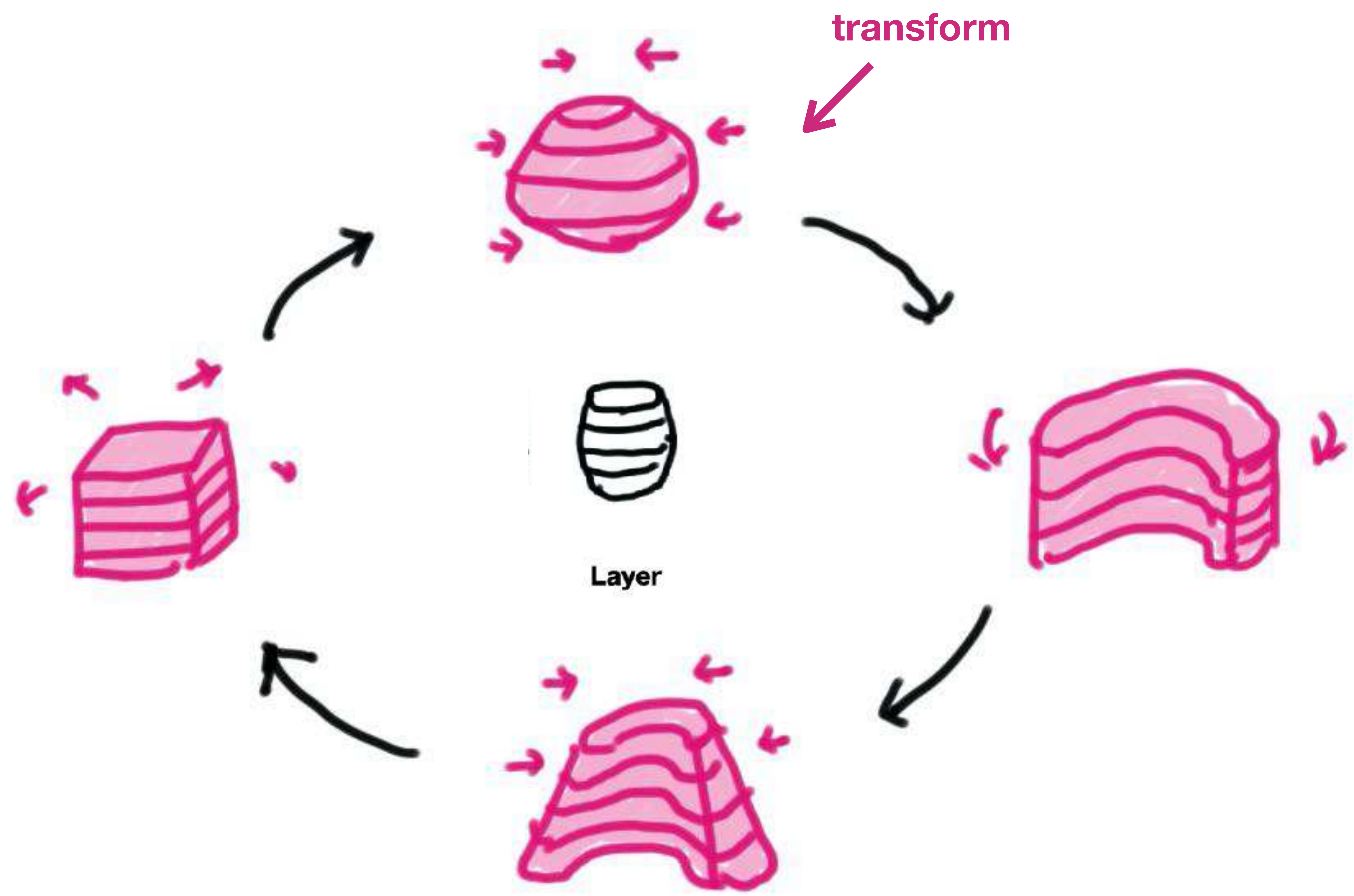


: Active Elements



: Active Elements

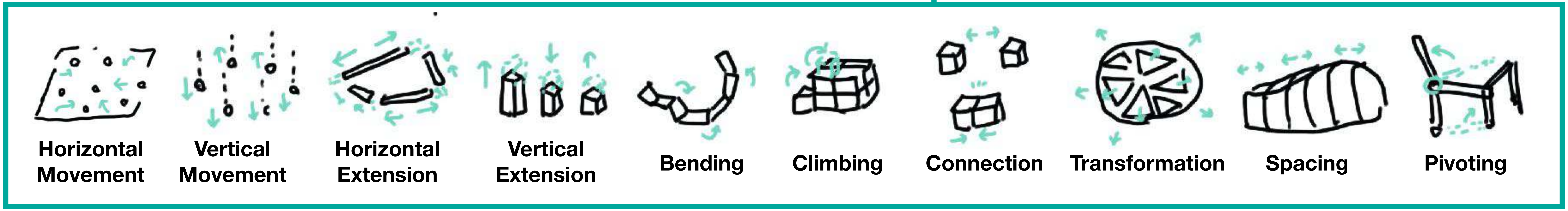




: Active Elements

Active Collective Elements

How can we combine individual transformation as **building blocks** for various representations?

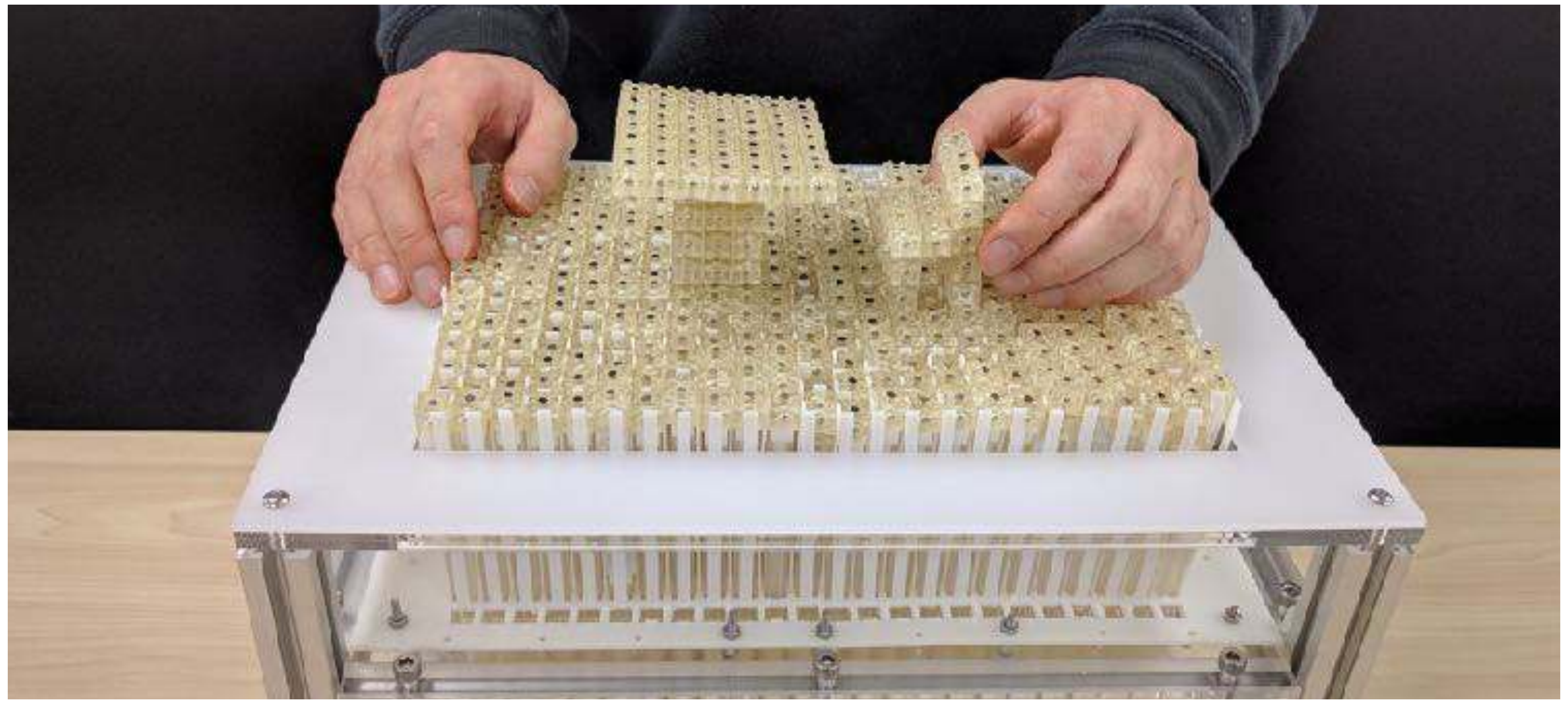


2 - Passive Collective Elements

How can we combine both **active** and **passive** elements to construct a dynamic shape?

Passive Collective Elements

How can we combine both **active** and **passive** elements to construct a dynamic shape?

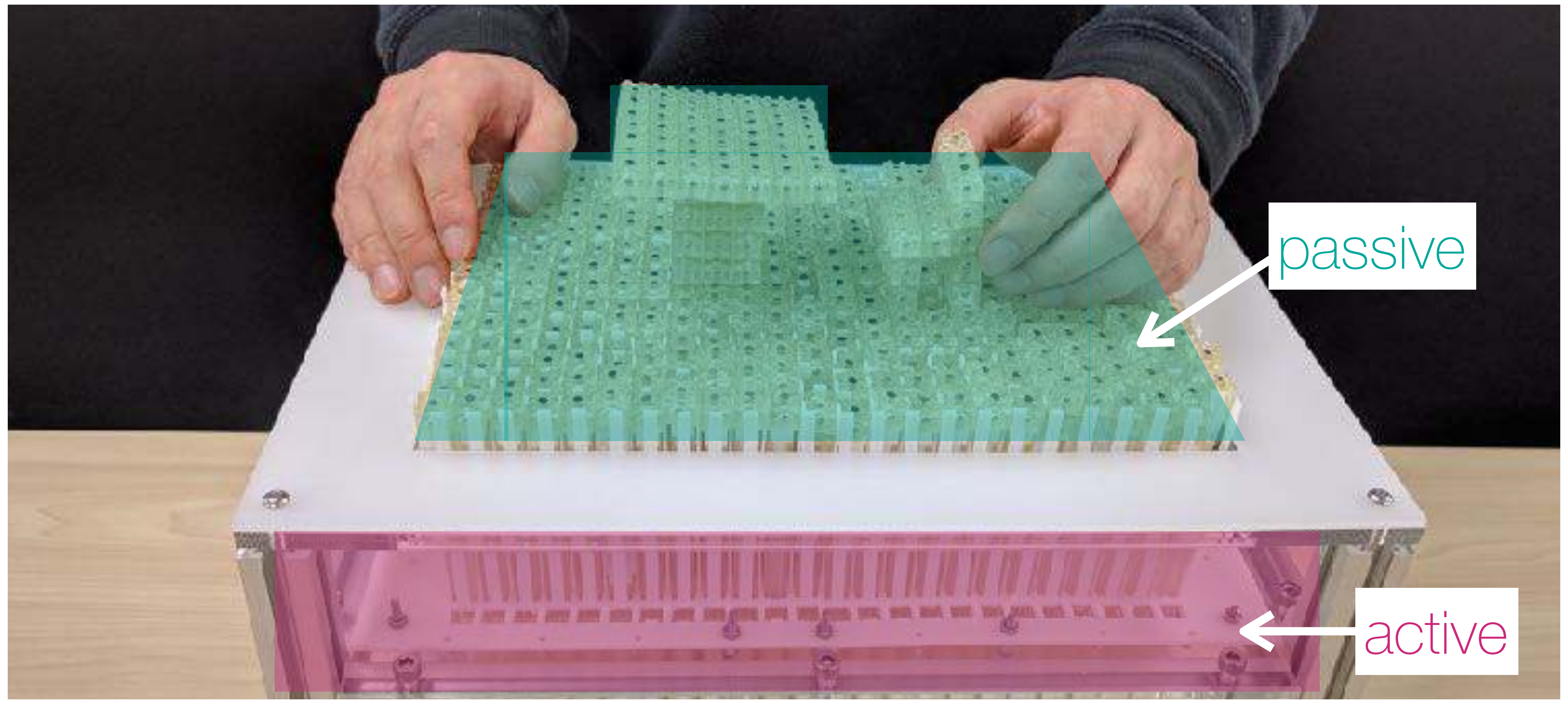


Case Study: **Dynablock**

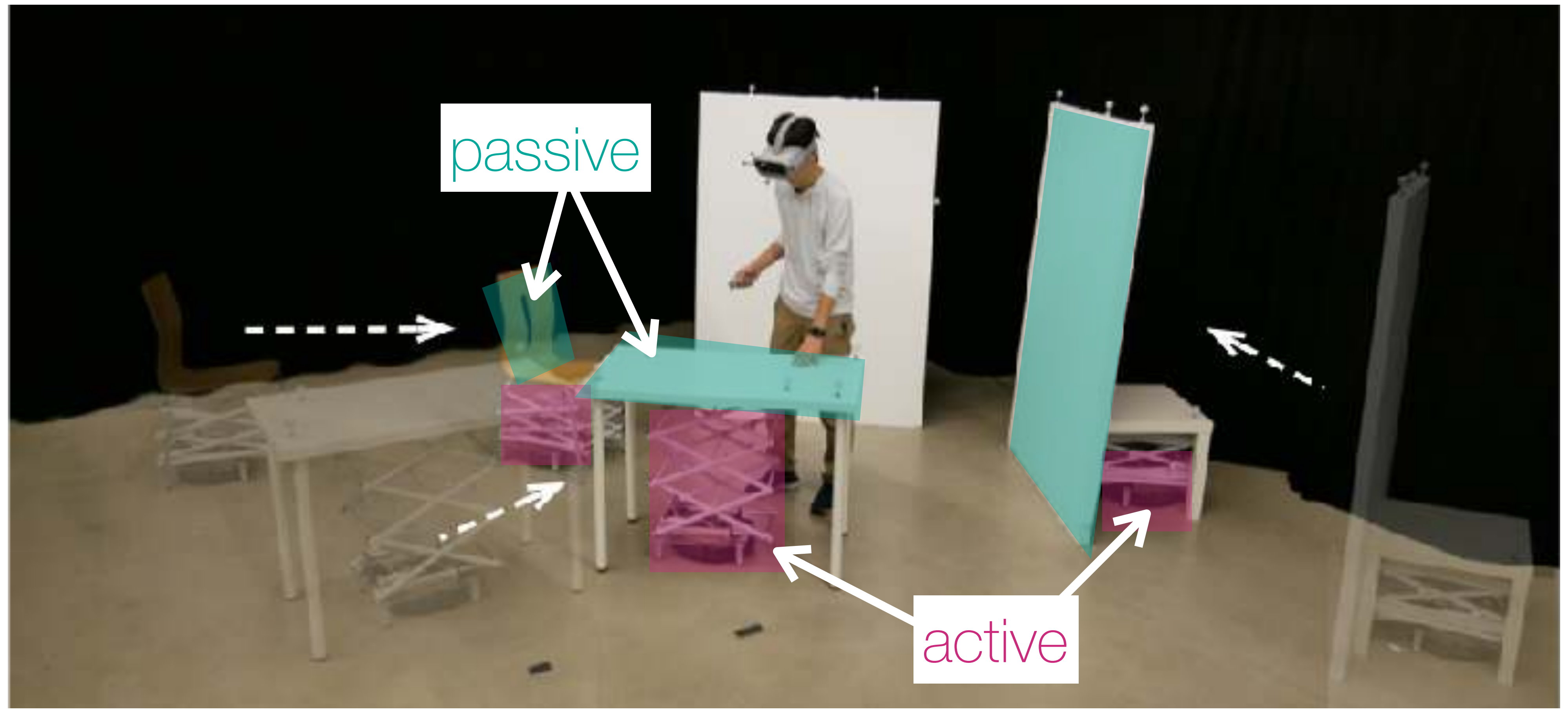
Case Study: **RoomShift**

Passive Collective Elements

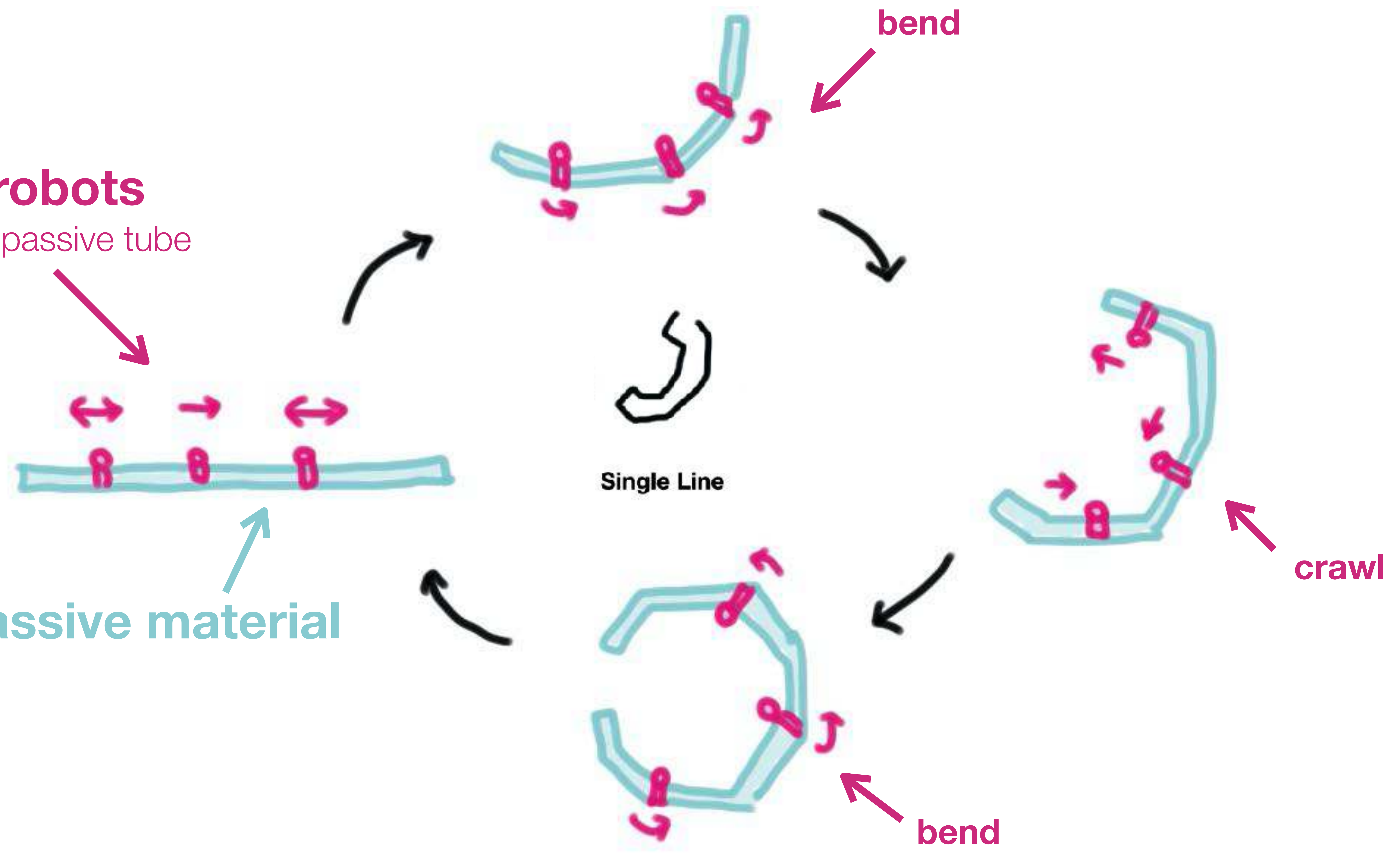
How can we combine both **active** and **passive** elements to construct a dynamic shape?



Case Study: **Dynablock**

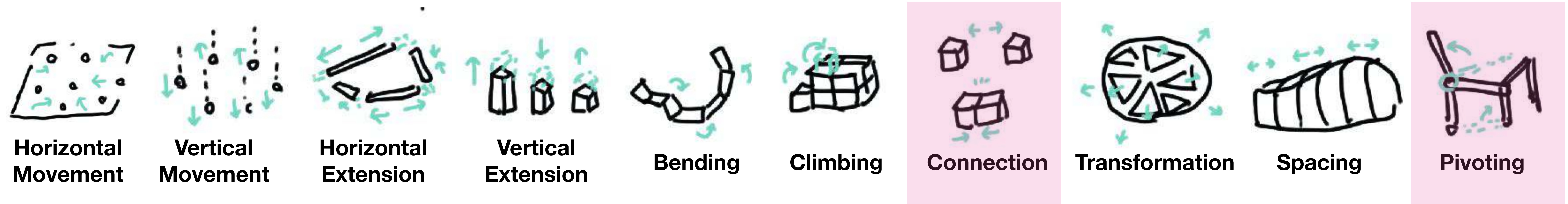


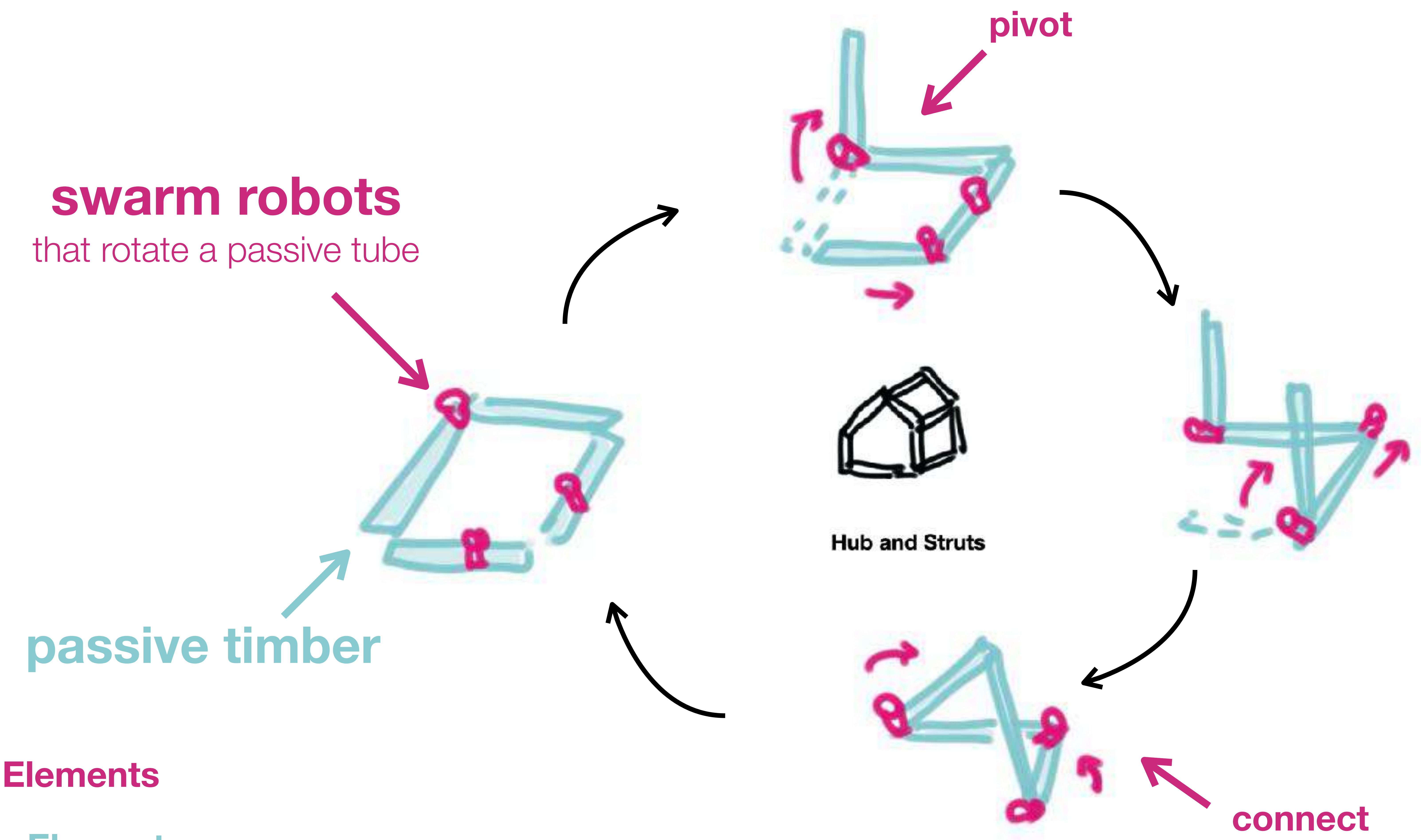
Case Study: **RoomShift**



: Active Elements

: Passive Elements





● : Active Elements

● : Passive Elements


Sparse Dots
Sparse Lines
Pin Array
Single Line
Voxel
Layers
Surface
Hub and Struts
Active Elements
This thesis
This thesis
Passive Elements
This thesis
This thesis


Sparse Dots
Sparse Lines
Pin Array
Single Line
Voxel
Layers
Surface
Hub and Struts
This thesis
This thesis
Active Elements
In this way, we can start exploring new domains and filling these gaps
Passive Elements
This thesis
This thesis

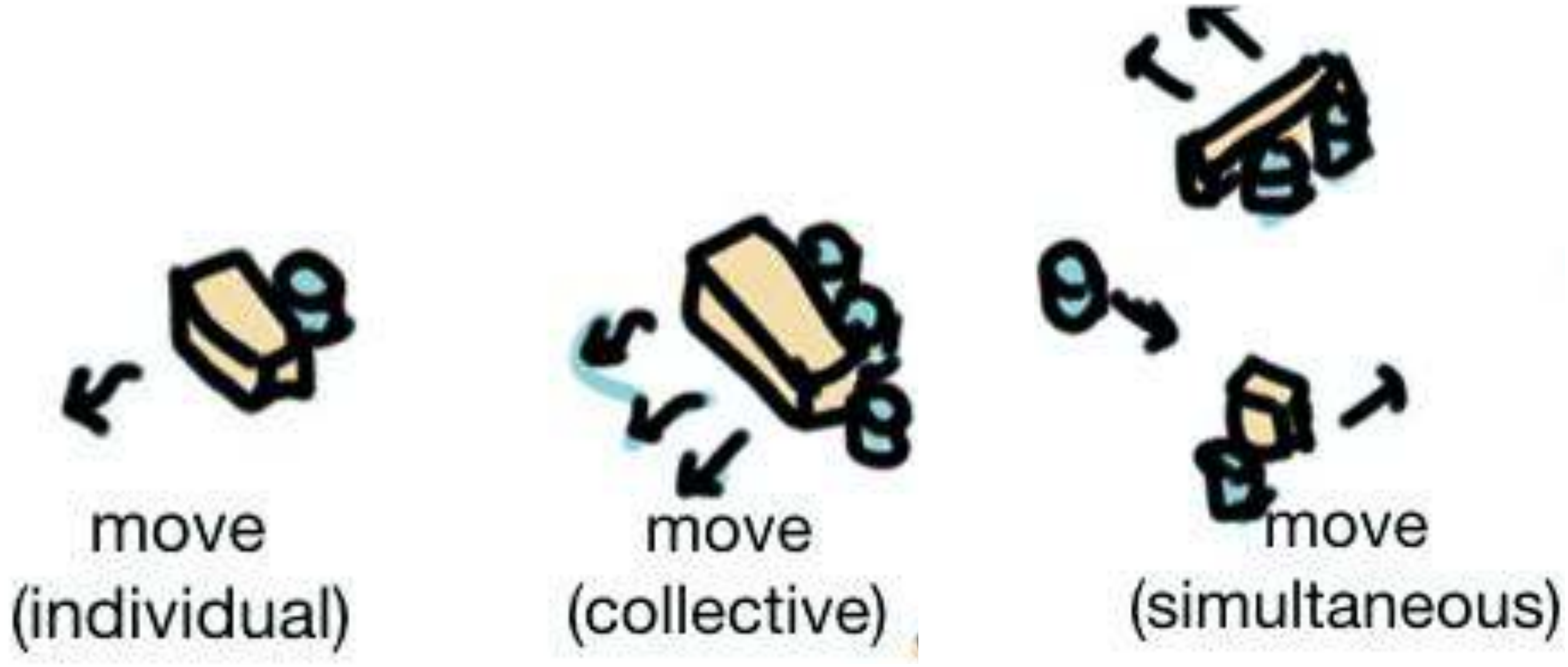
3 - Collective Actuation

How can we leverage multiple active elements to **collectively actuate** passive materials?

Collective Actuation

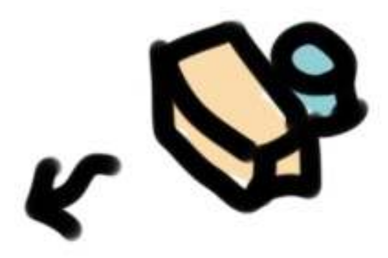
How can we leverage multiple active elements to **collectively actuate** passive materials?

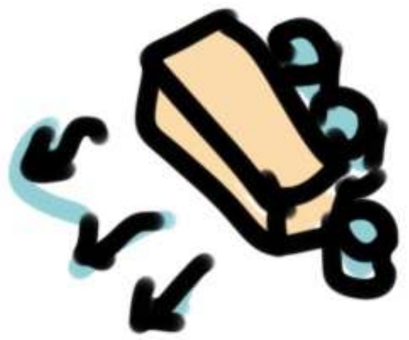
Case Study: **RoomShift**

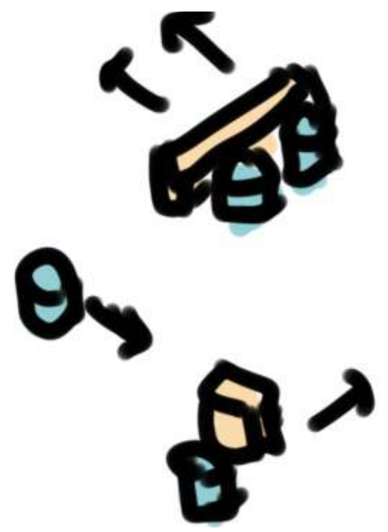


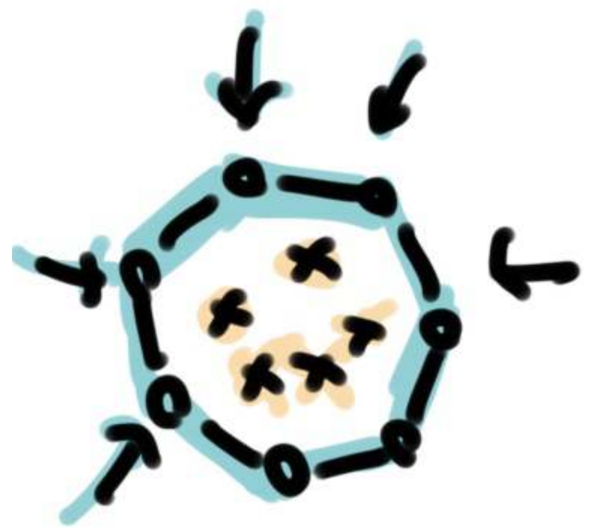
Collective Actuation

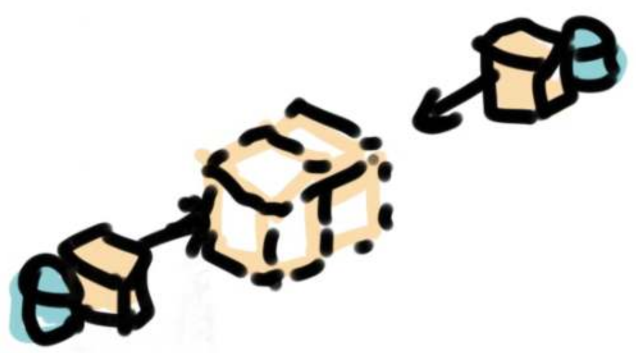
How can we leverage multiple active elements to **collectively actuate** passive materials?

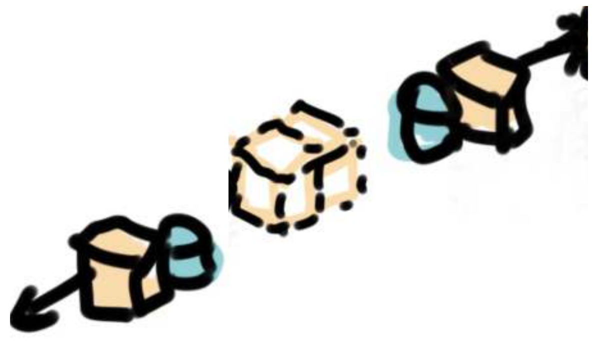

Move (individual)

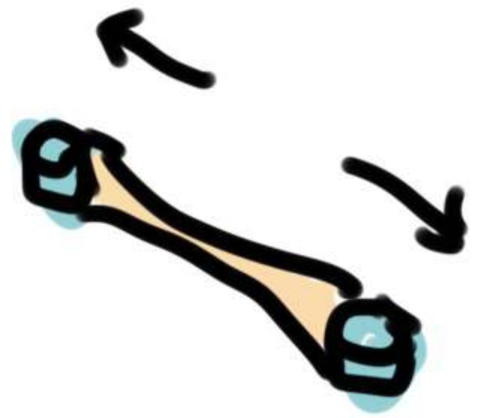

Move (collective)

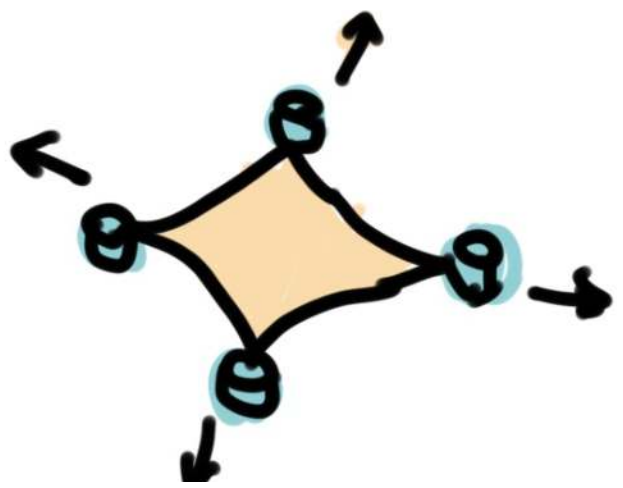

Move (simultaneous)


Enclose

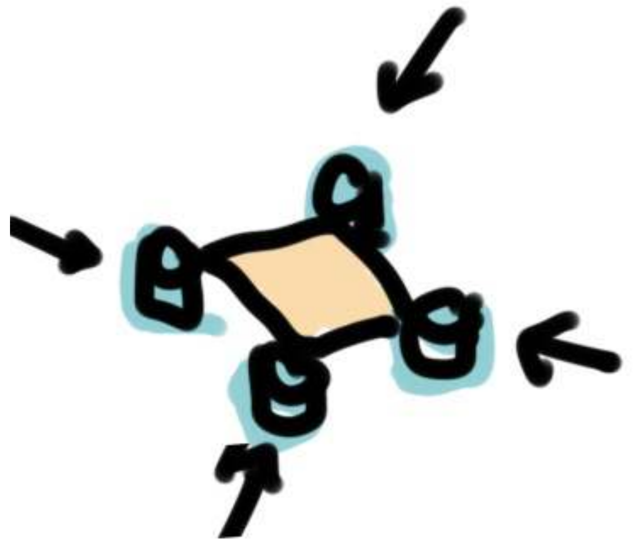

Connect


Disconnect

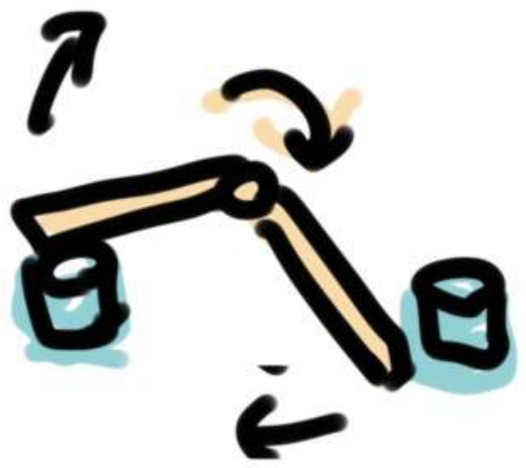

Extend

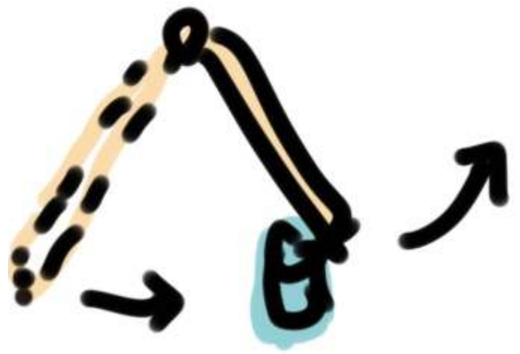

Stretch


Compress


Shrink

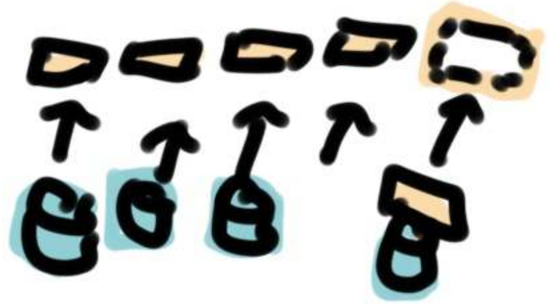

Rotate (pivot)

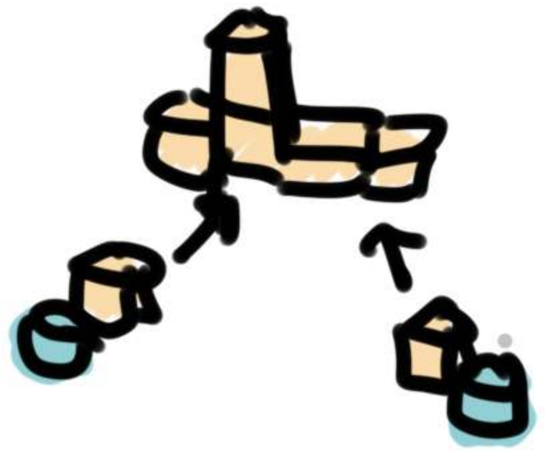

Rotate

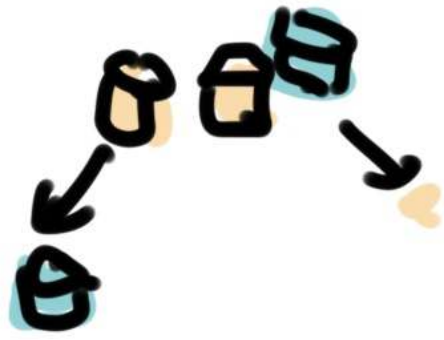

Swing


Shake


Tumble

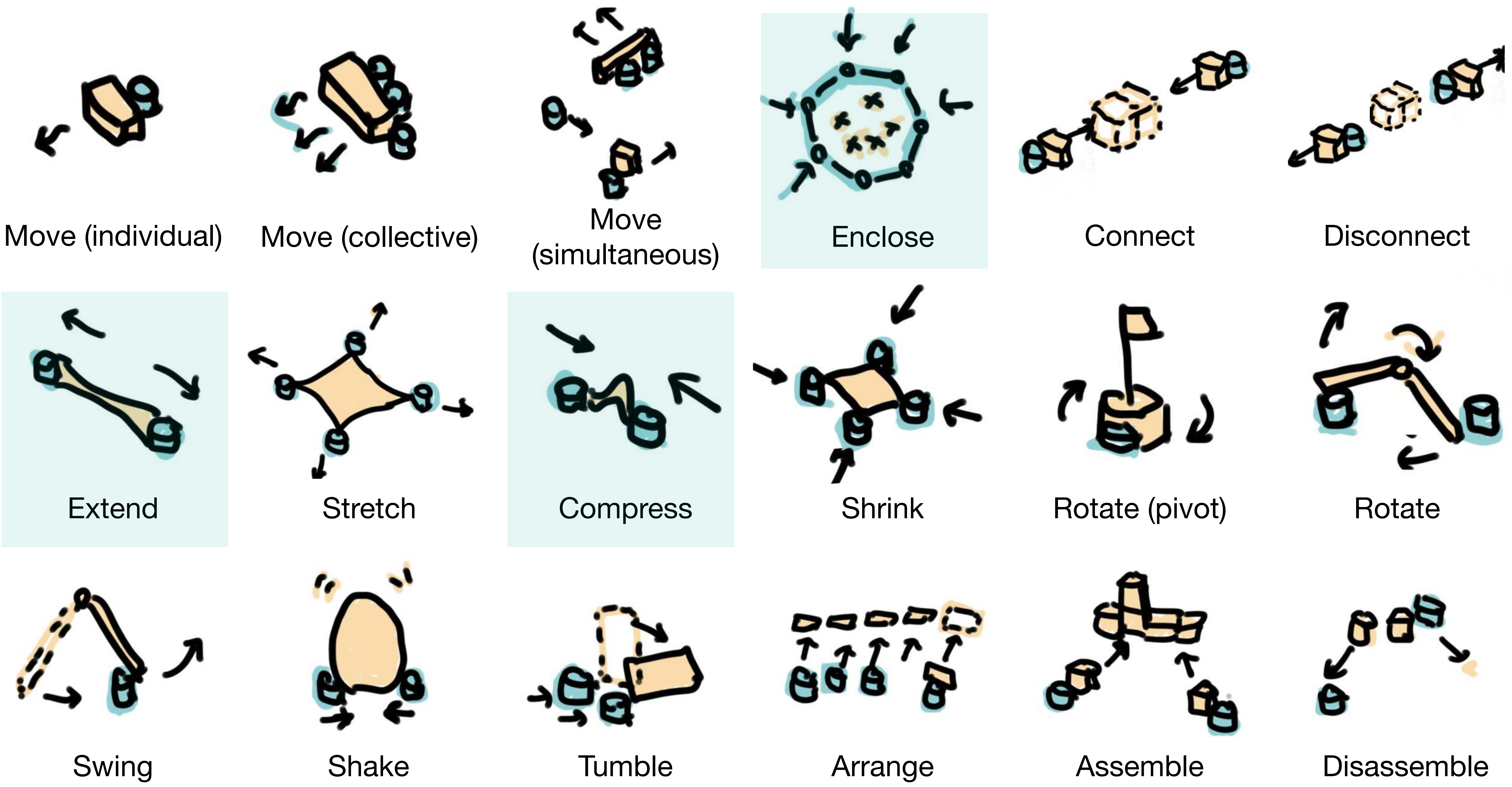

Arrange

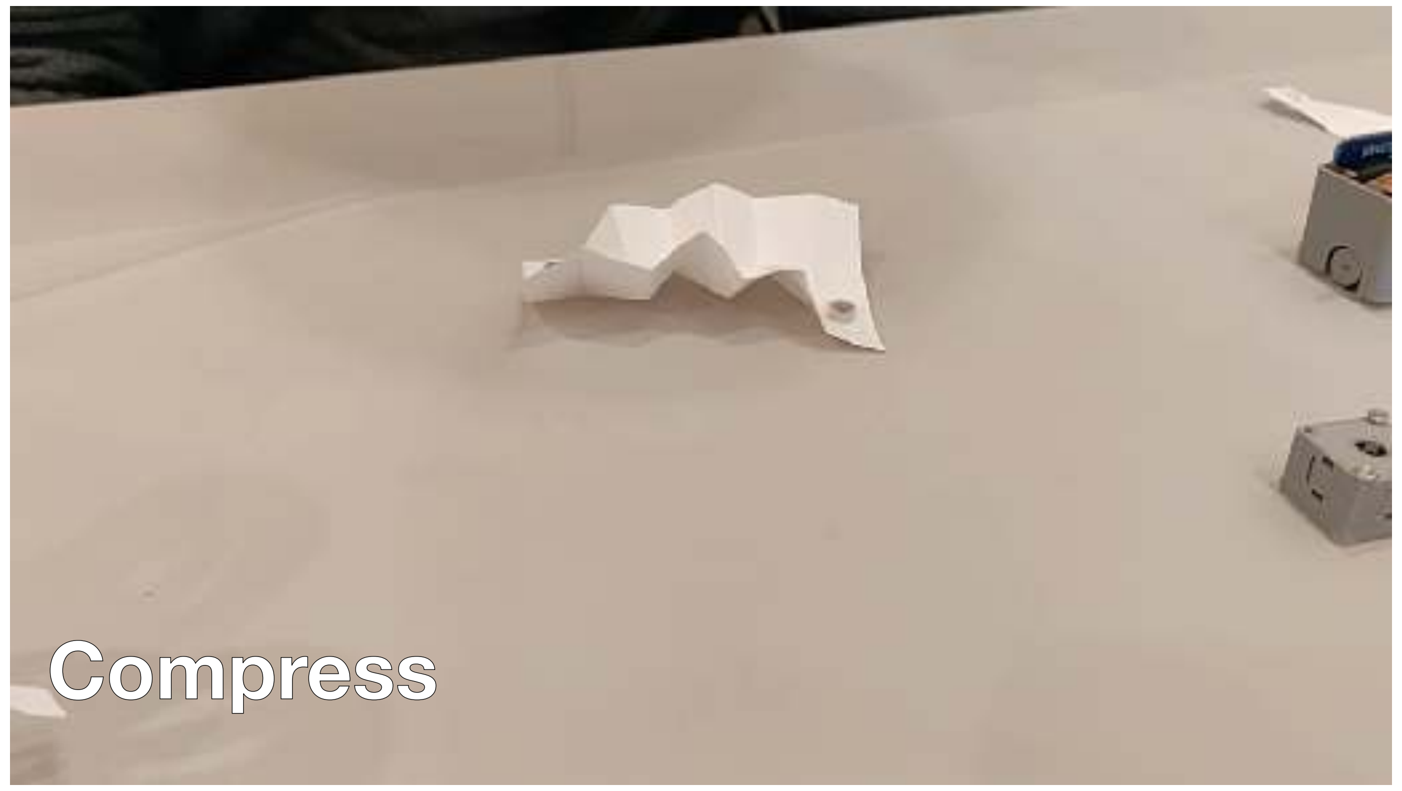

Assemble

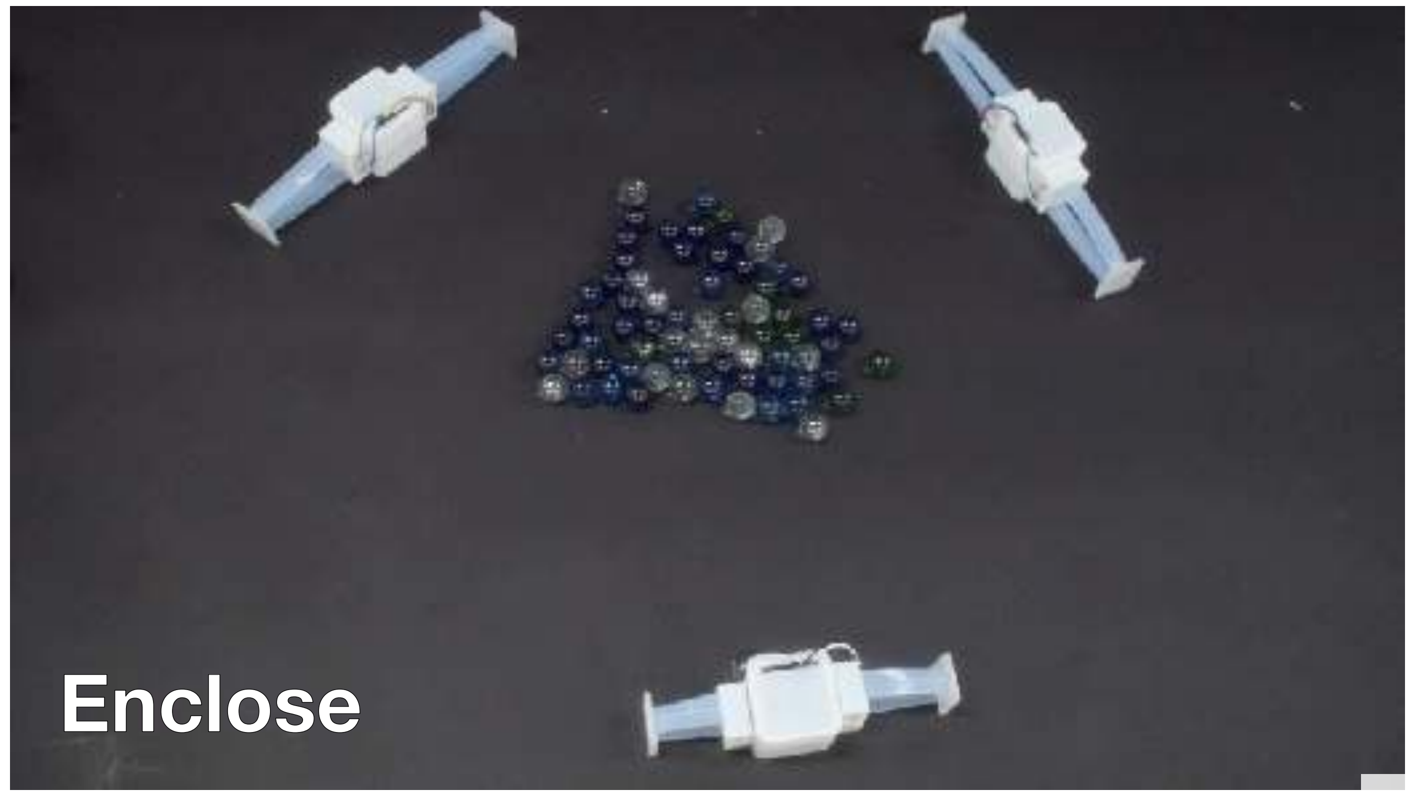

Disassemble

Collective Actuation

How can multiple active elements **collectively actuate** passive materials?



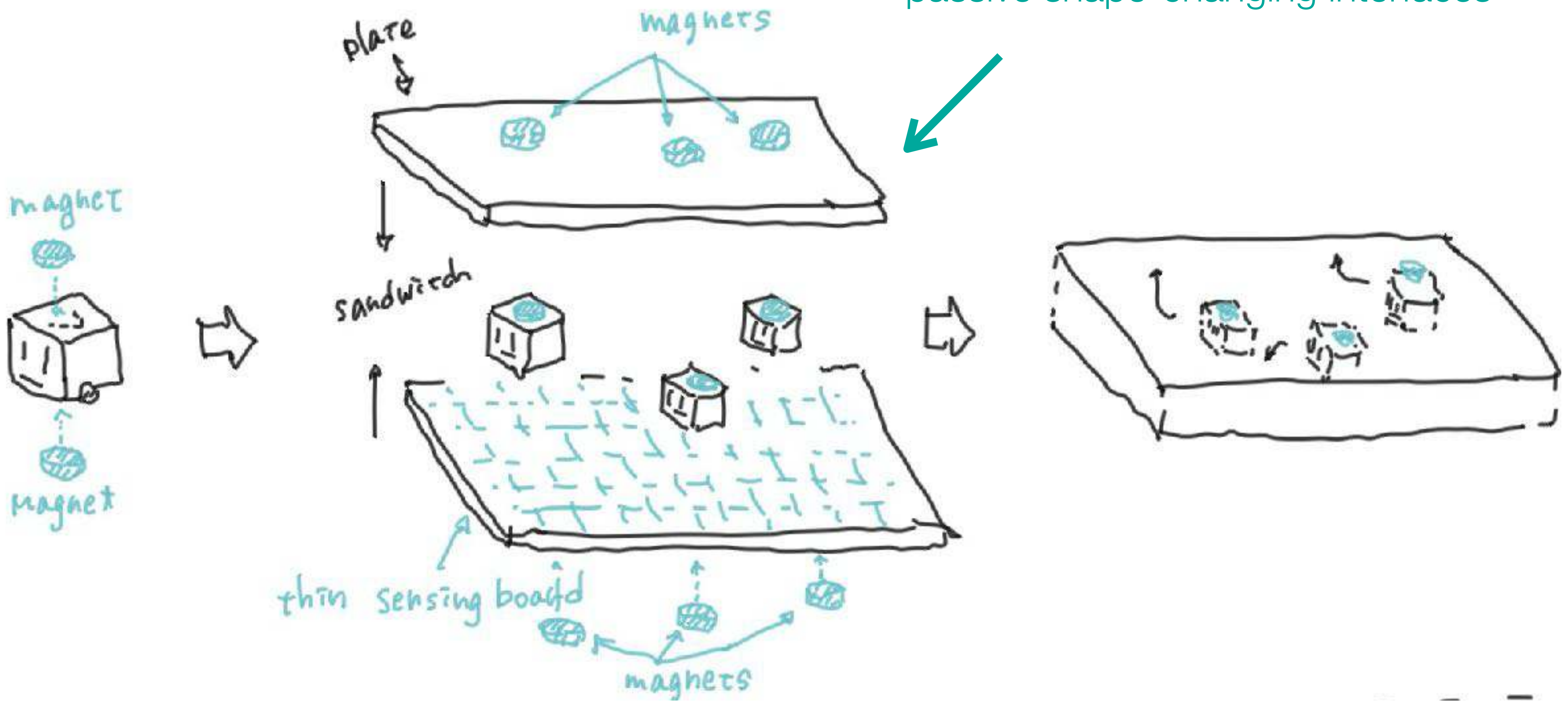


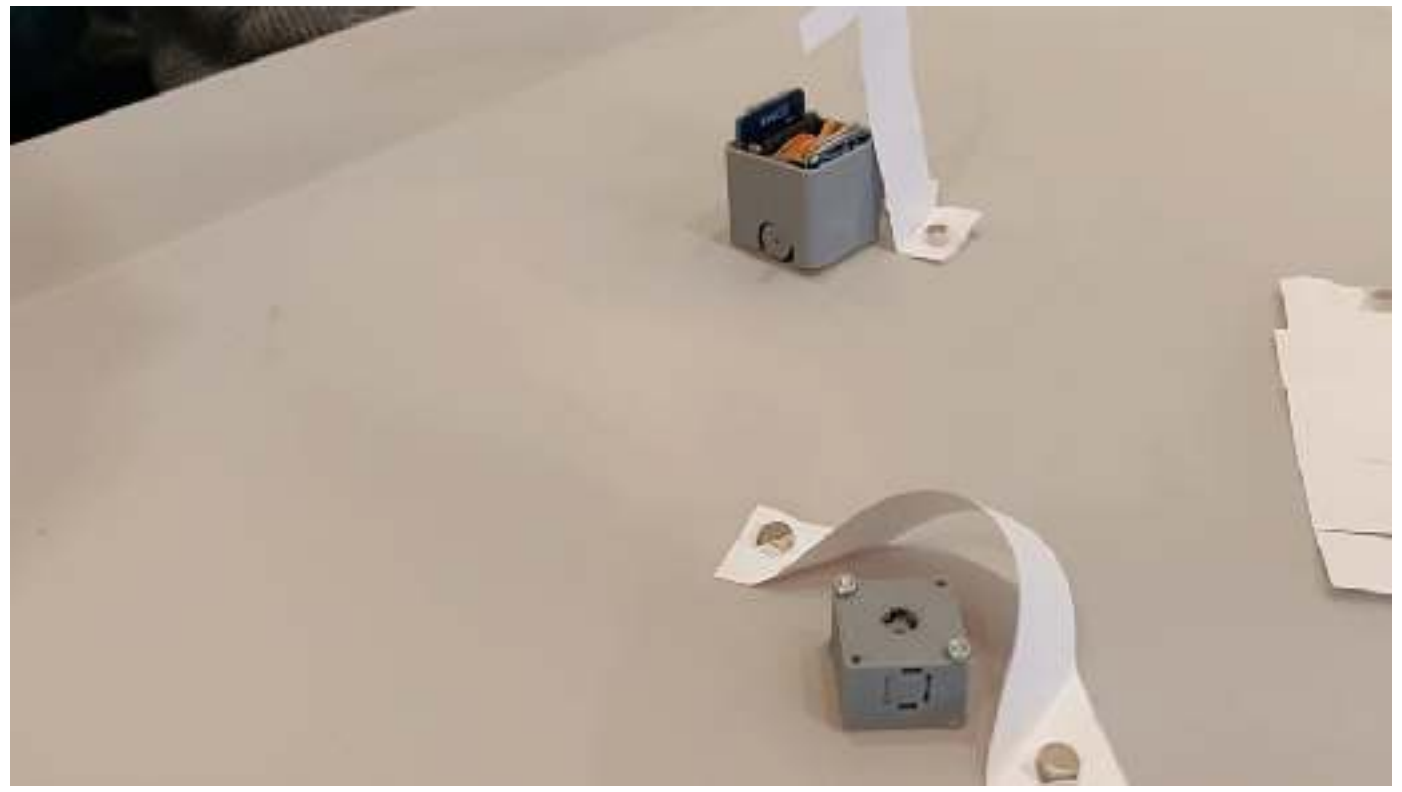


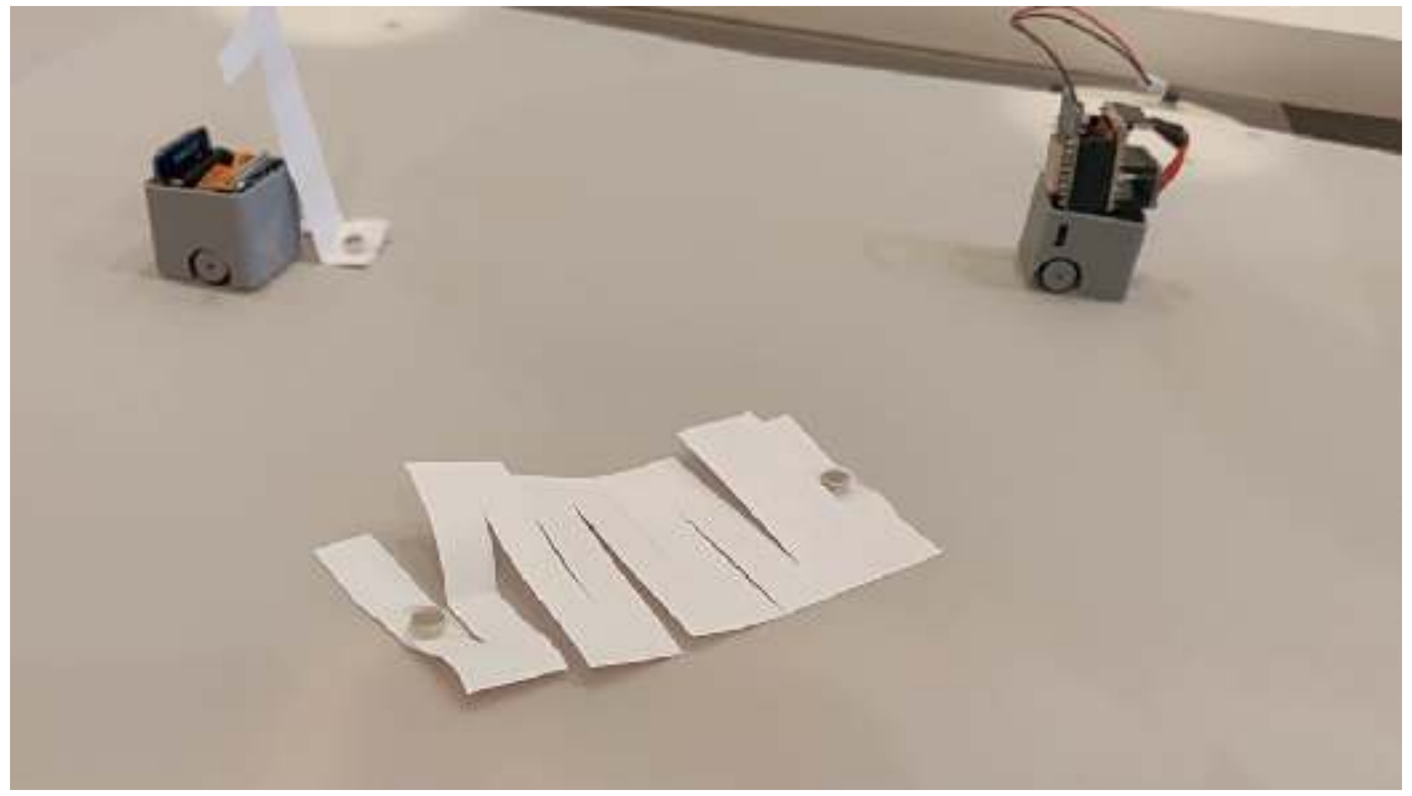
Collective Actuation

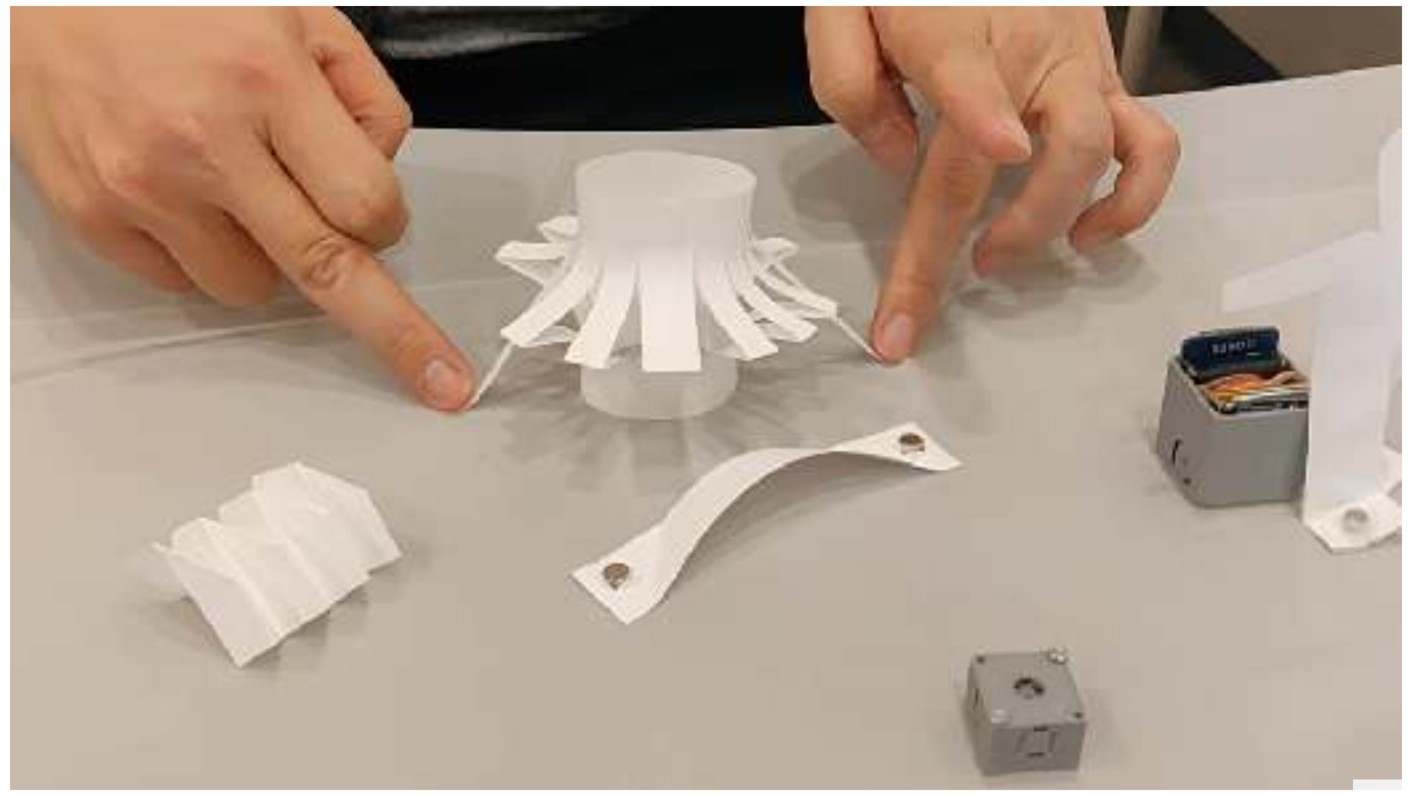
How can multiple active elements **collectively actuate** passive materials?

swarm robots + magnets
as a prototyping environment for
passive shape-changing interfaces









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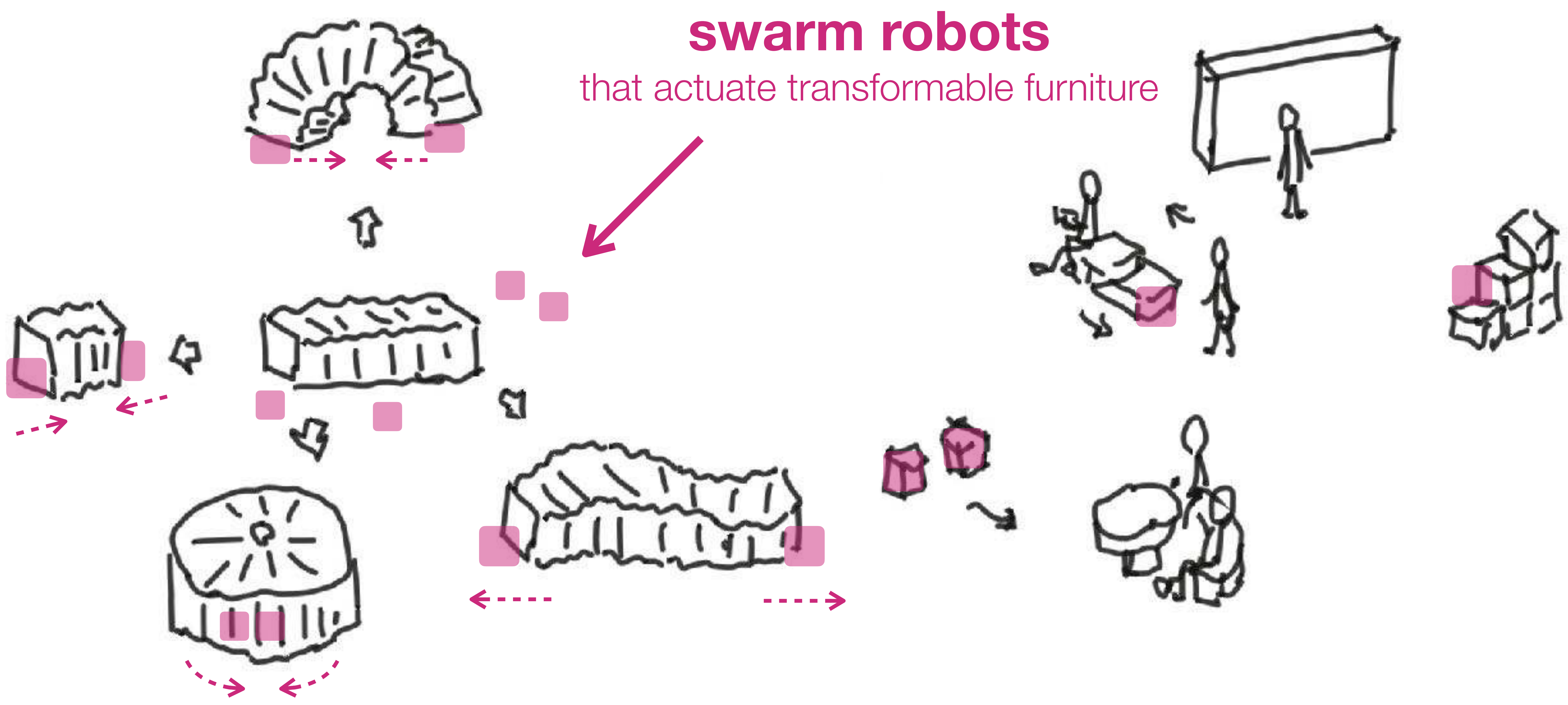
How can multiple active elements **collectively actuate** passive materials?



Collective Actuation

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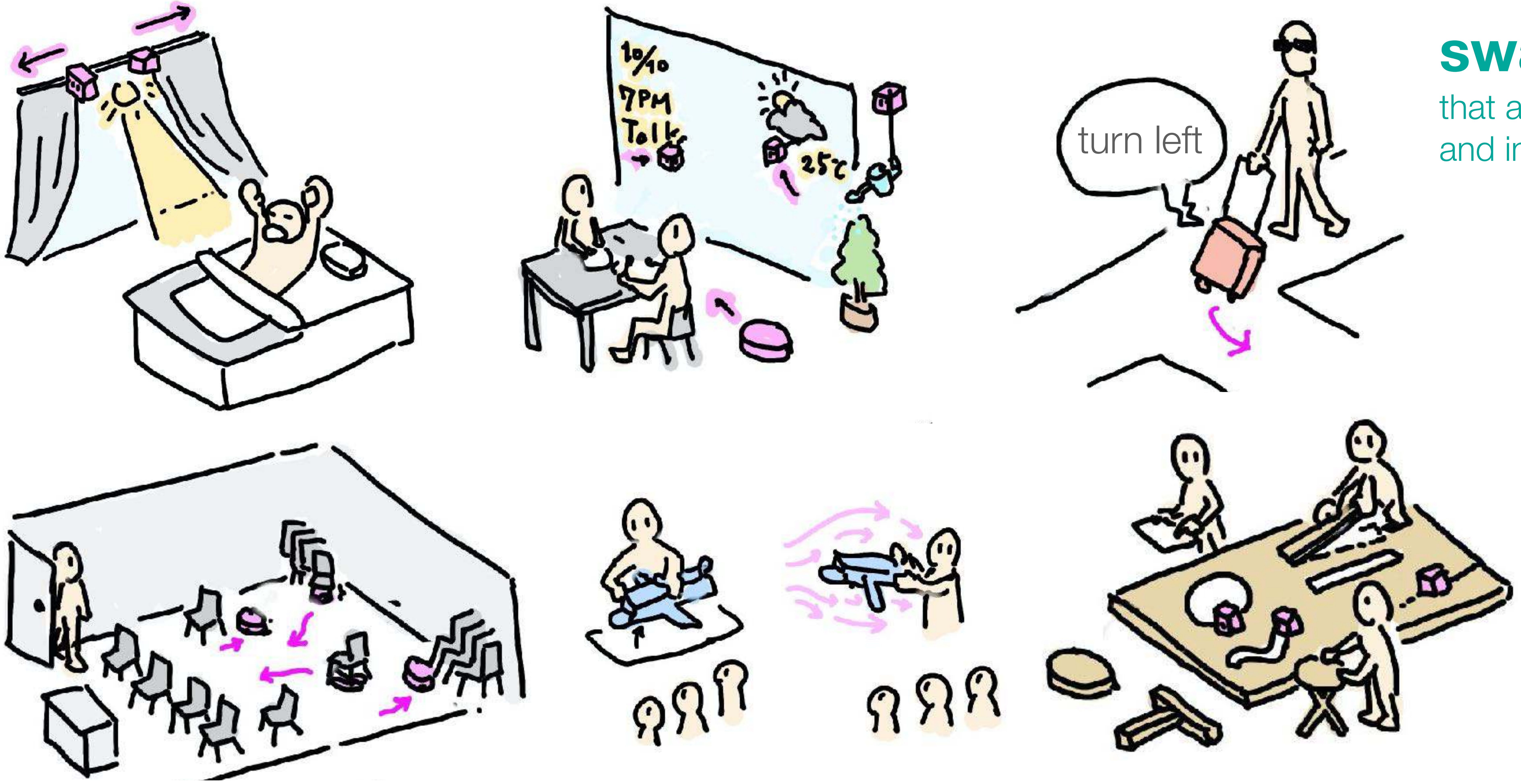
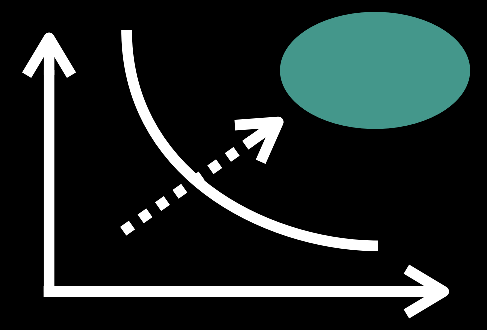


swarm robots

that are seamlessly blended
and integrated into everyday life

Background

Why This Approach?

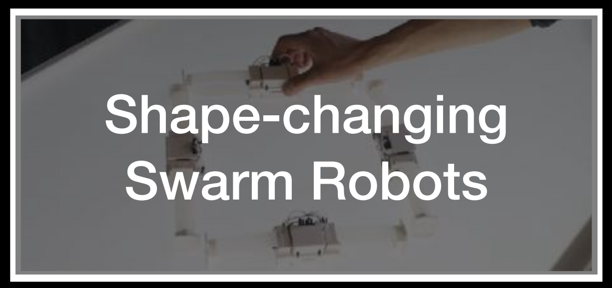


Concept

What is
Dynamic and Collective
Shape Construction

Explorations

Shape Construction
with **Active** Elements

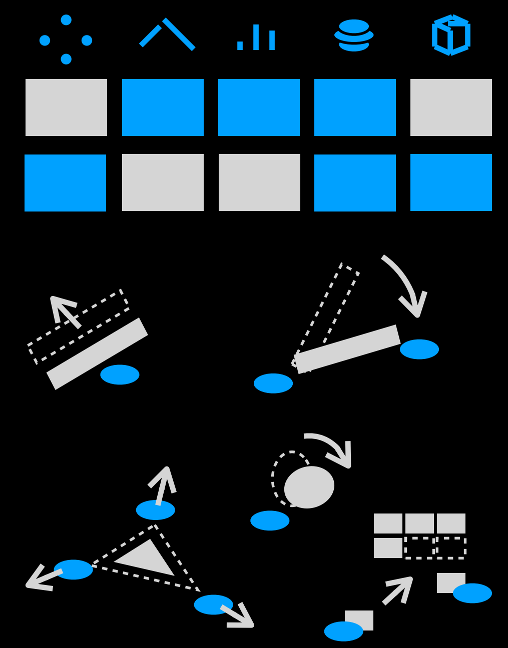


Shape Construction
with **Passive** Elements

Interaction with
Collective Elements

Discussion

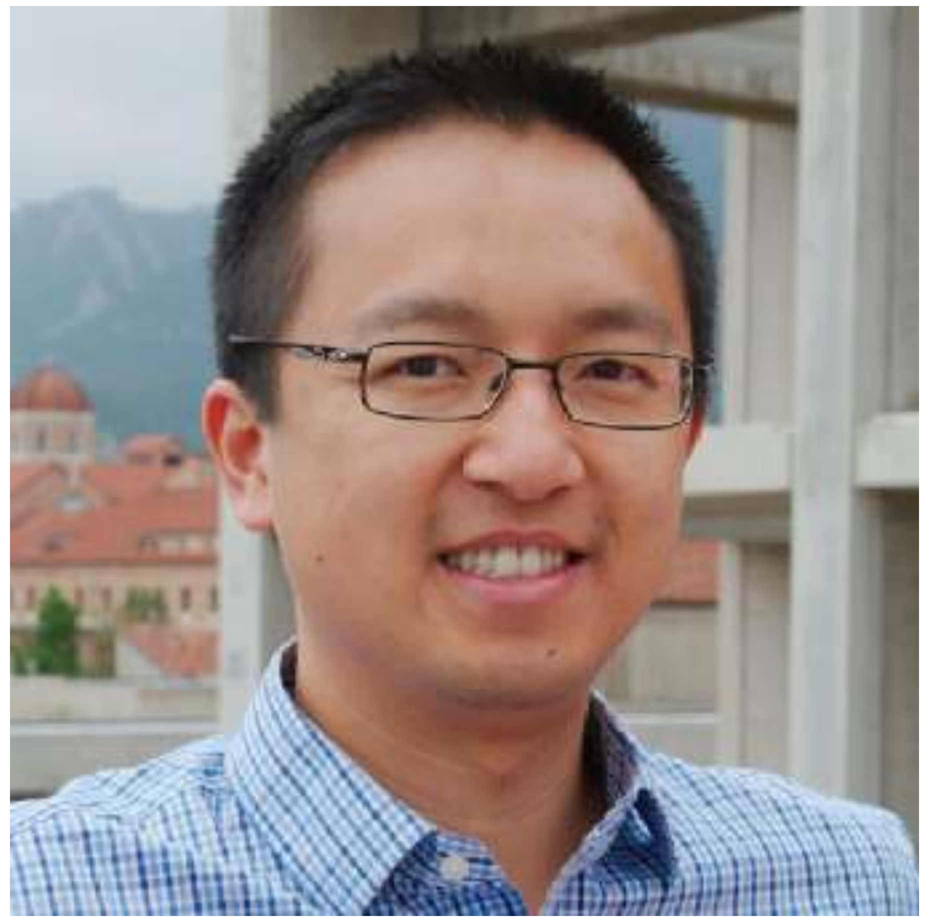
What's Next?



Thank My Advisors and Thesis Committee

Daniel Leithinger
CU Boulder

Mark D. Gross
CU Boulder



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CU Boulder

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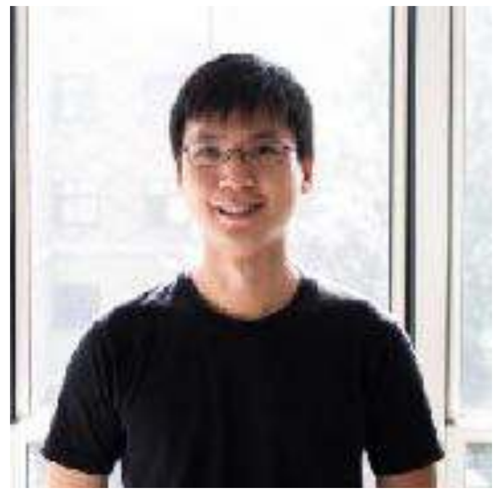
MIT Media Lab

Takeo Igarashi
UTokyo

Thank All of My Collaborators

Ellen Do
CU Boulder

Dan Szafir
CU Boulder



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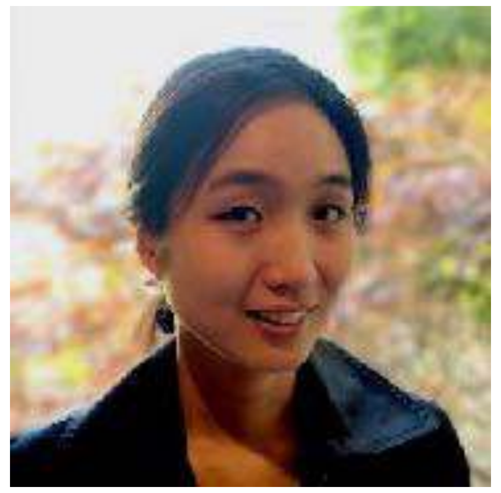
CU Boulder



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Adobe Research

Michael Bernstein
Stanford

Dynamic Shape Construction and Transformation with Collective Elements

Ryo Suzuki
University of Colorado Boulder / @ryosuzk / http://ryosuzuki.org/

Additional Slides

Q&A: Contributions

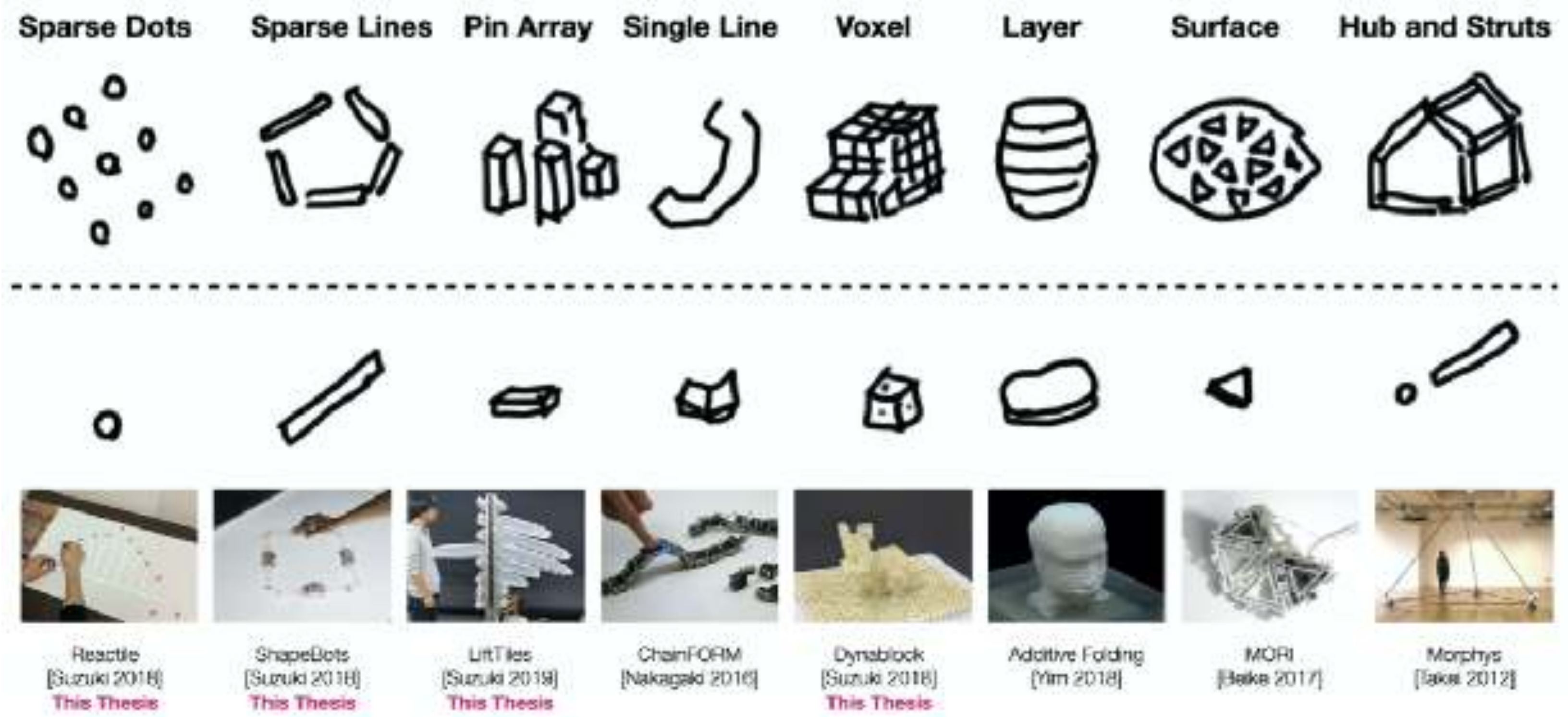
1.2 Thesis Contributions

This thesis makes contributions to the field of Human-Computer Interaction in the following areas:

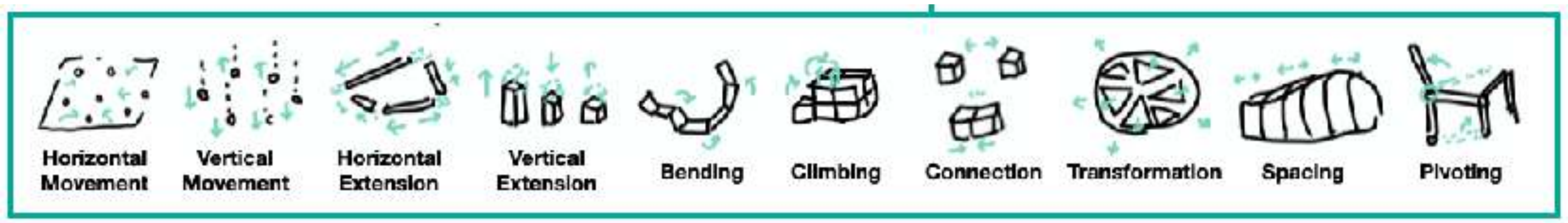
1. A design space exploration of dynamic shape construction with collective elements
2. Taxonomy and investigation of active shape construction and transformation with collective elements
3. Techniques for creating a dynamic shape with shape-transformable swarm robots
4. Techniques for constructing 3D shapes with an assembly of passive connectable blocks
5. Techniques for actuating existing objects to reconfigure spatial layouts
6. Techniques for programming the dynamic shape construction on a 2D surface with direct physical manipulation

High-level

1. Exploration of representations



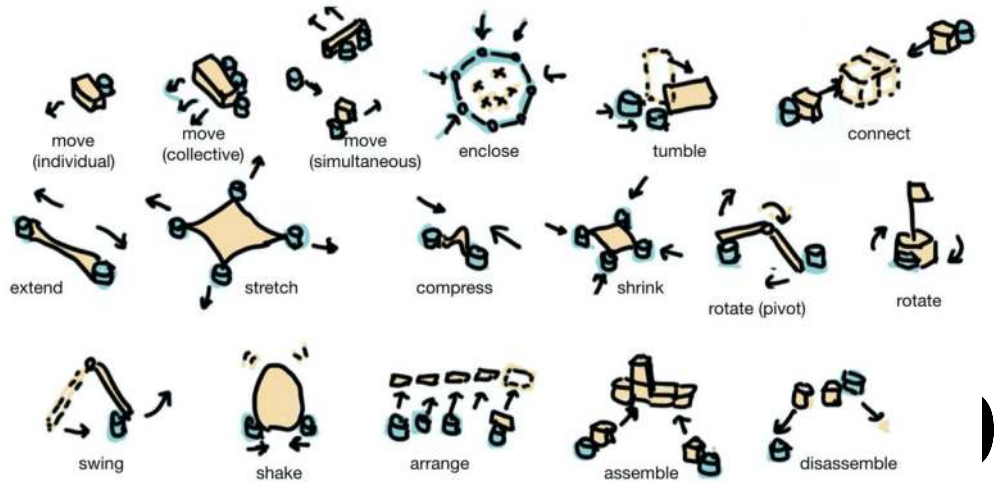
2. Exploration strategy 1: combining building blocks



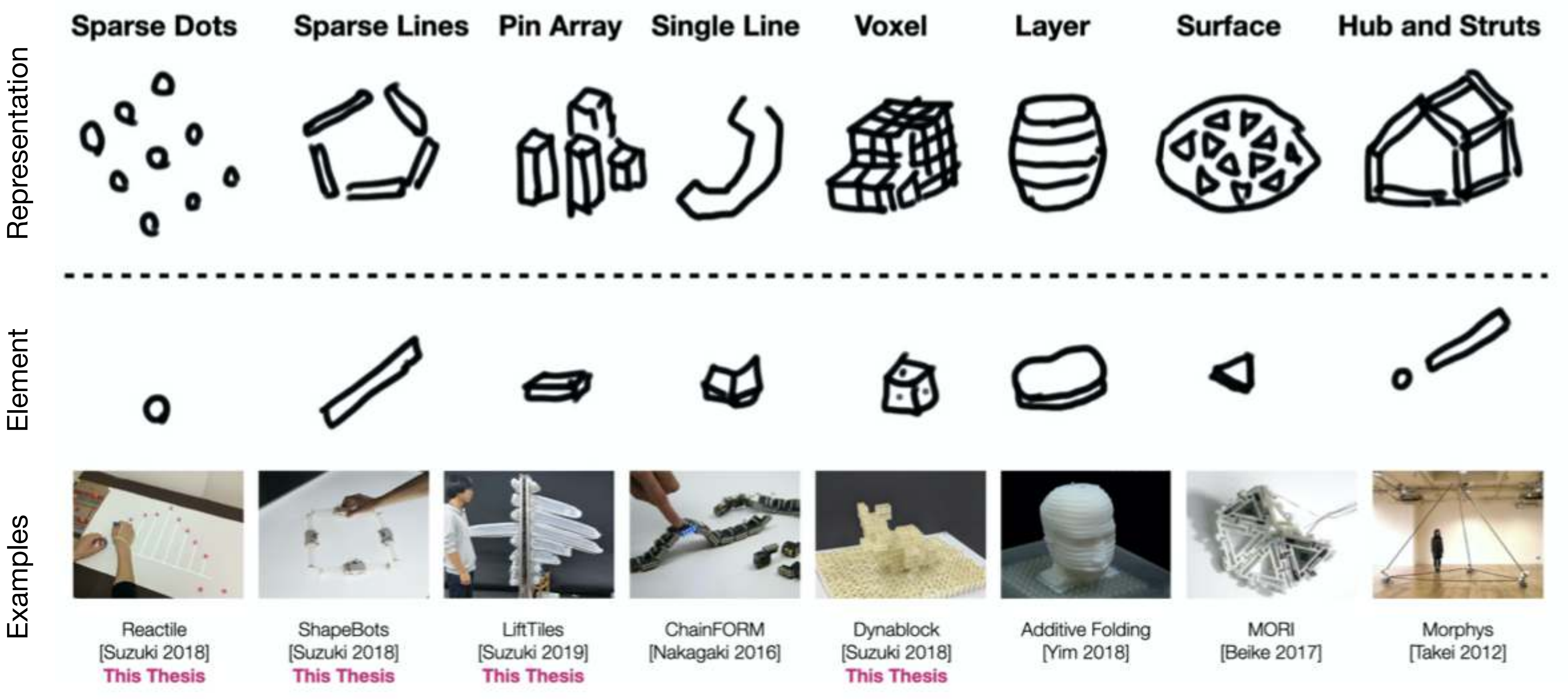
3. Exploration strategy 2: combining active & passive

Case Study: **Dynablock**

Case Study: **RoomShift**



Q&A: Representations



Q&A: Representations


voxel

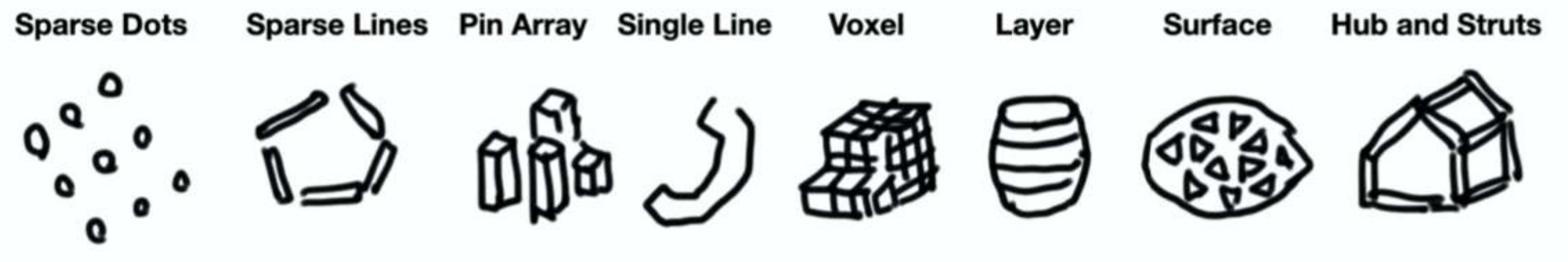

surface

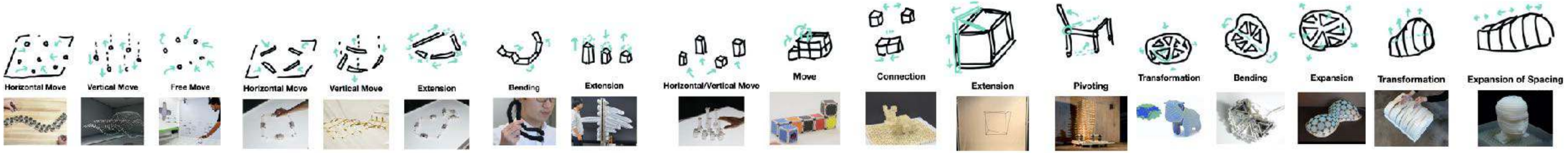

line


wirefram

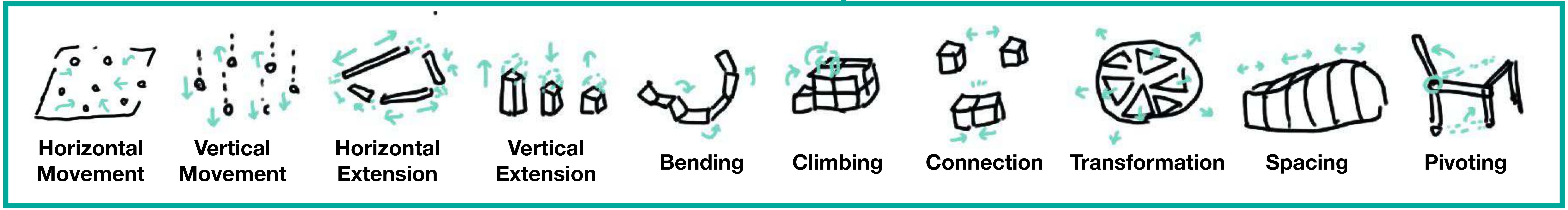

sliced layers

Q&A: Representations

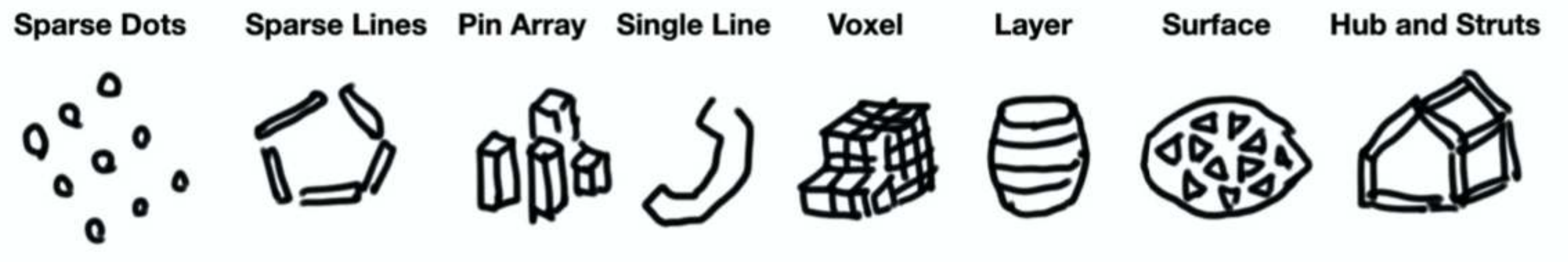




How can we combine individual transformation as **building blocks** for various representations?

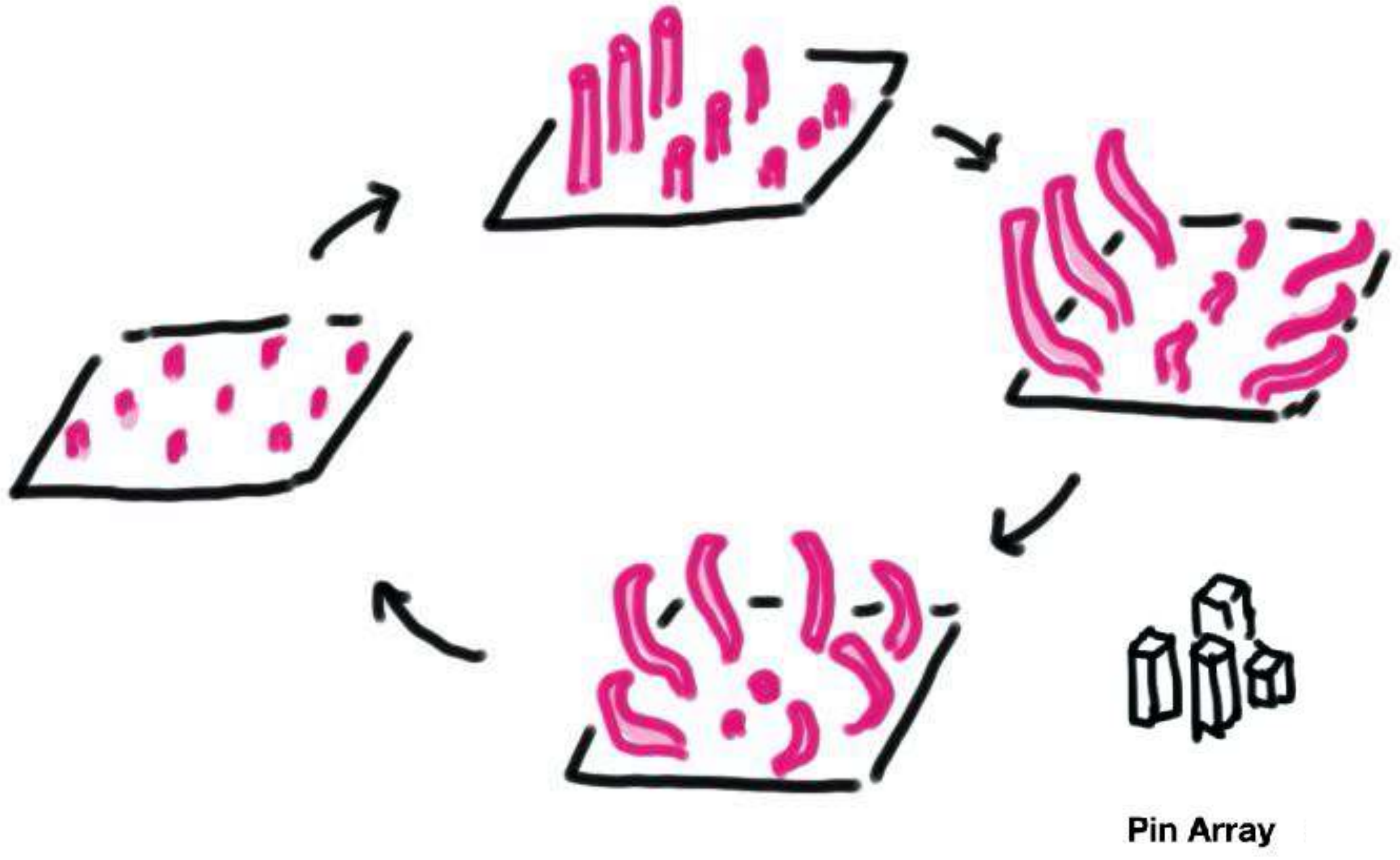


Q&A: Representations

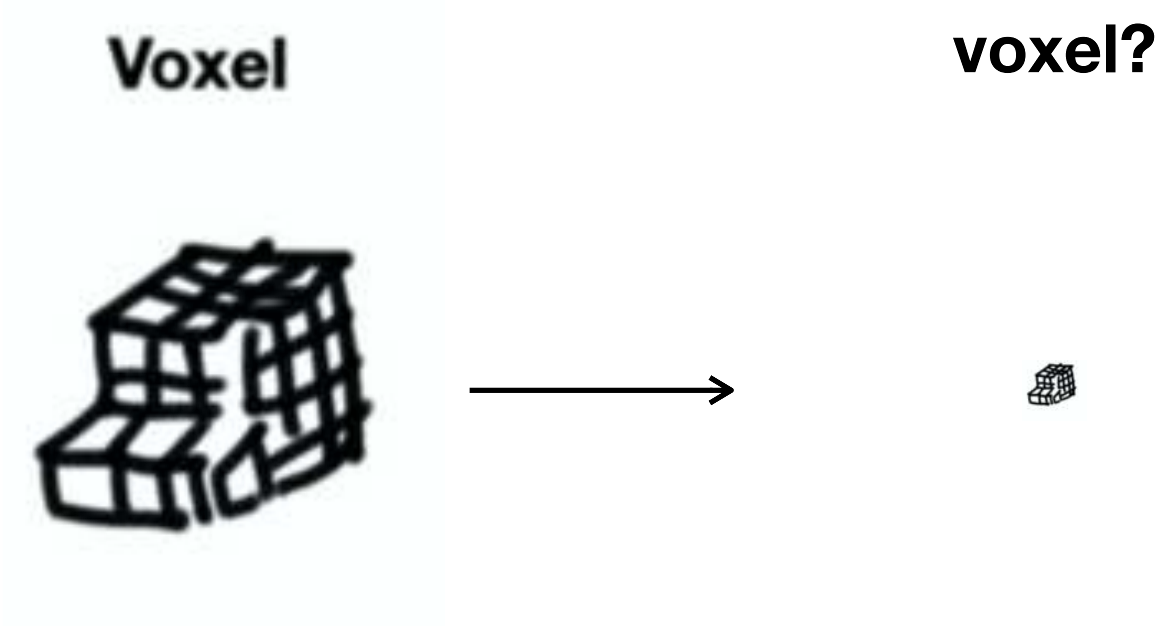


....

continue



Is this pin-array?

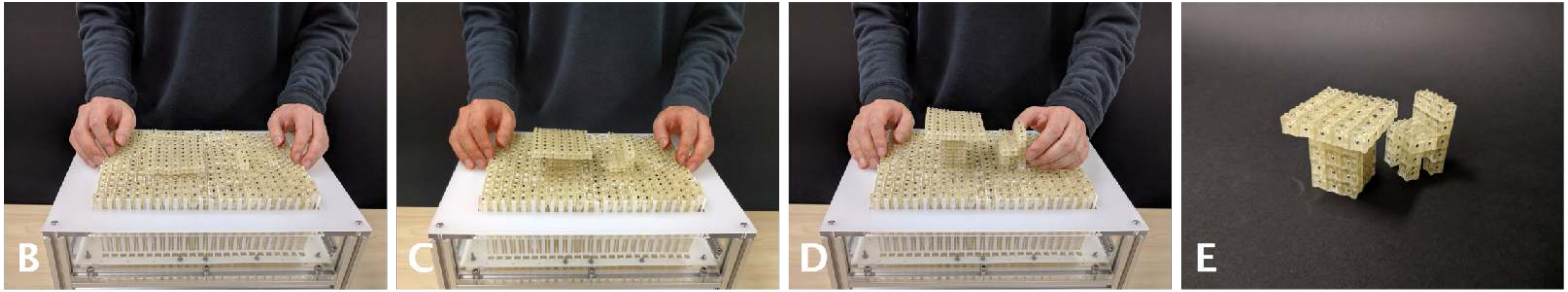


Resolution: 5mm 0.05mm

Is this still voxel?

Q&A: Limitations and Future Work

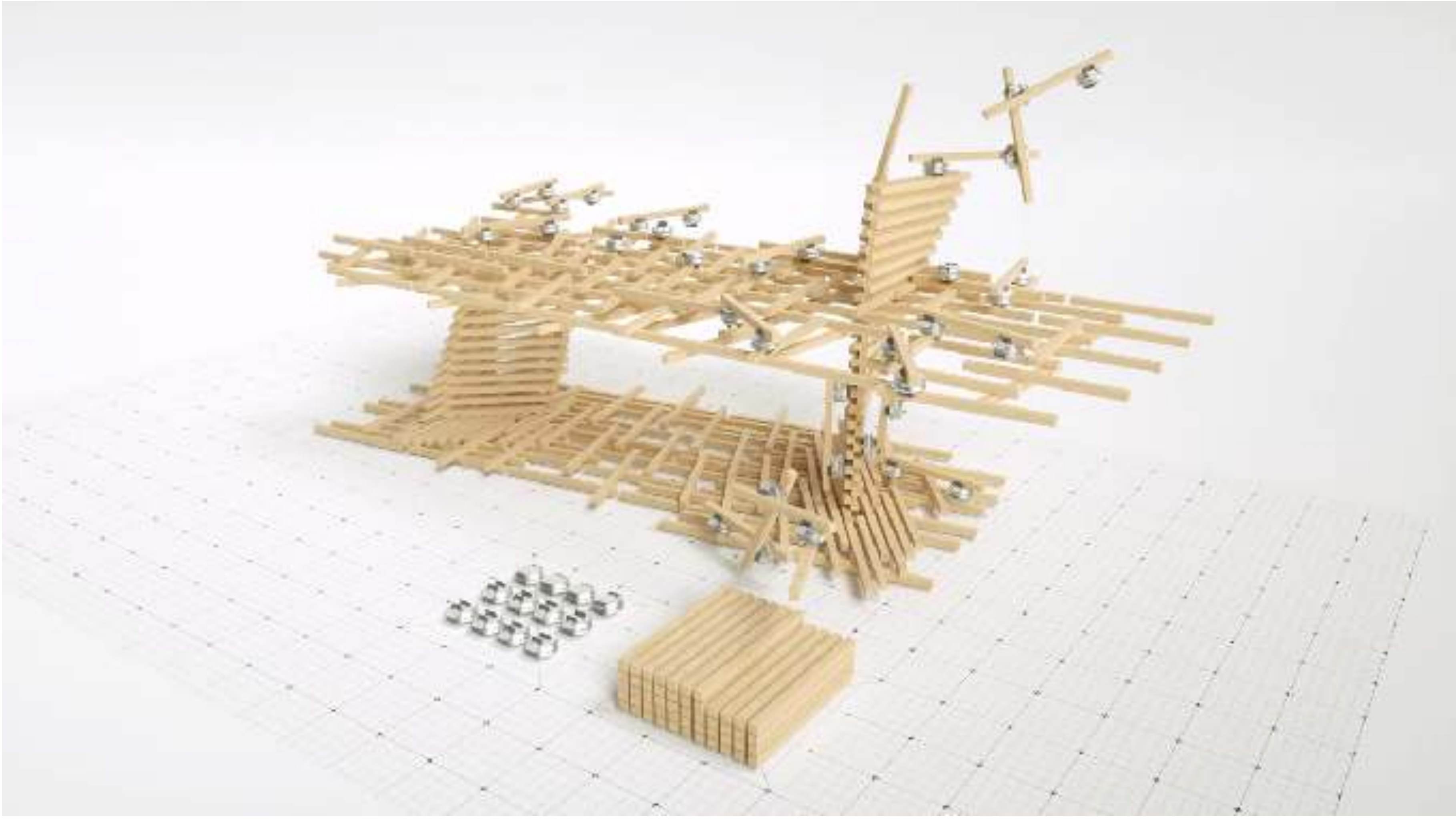
Information Display vs Fabrication

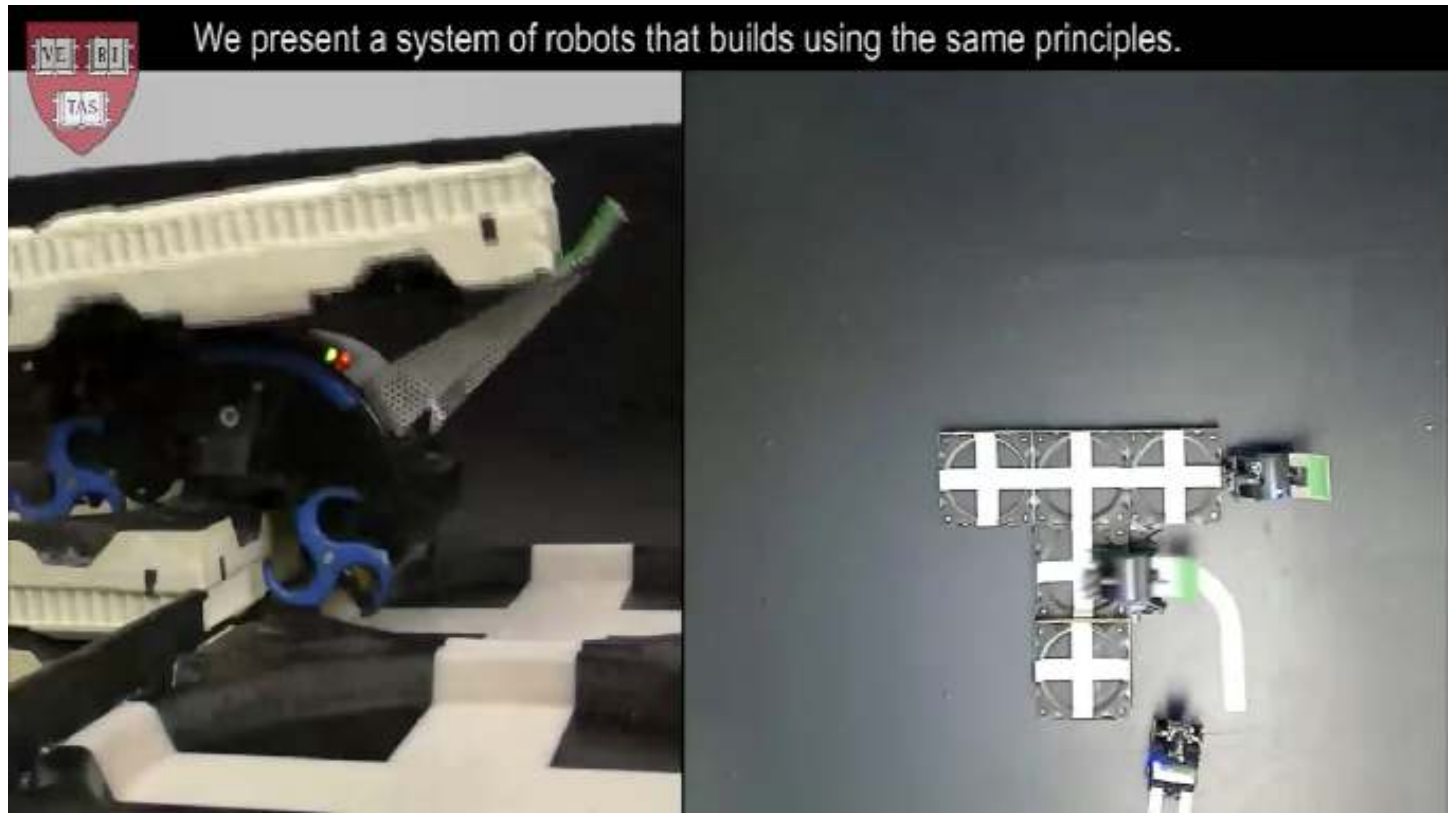


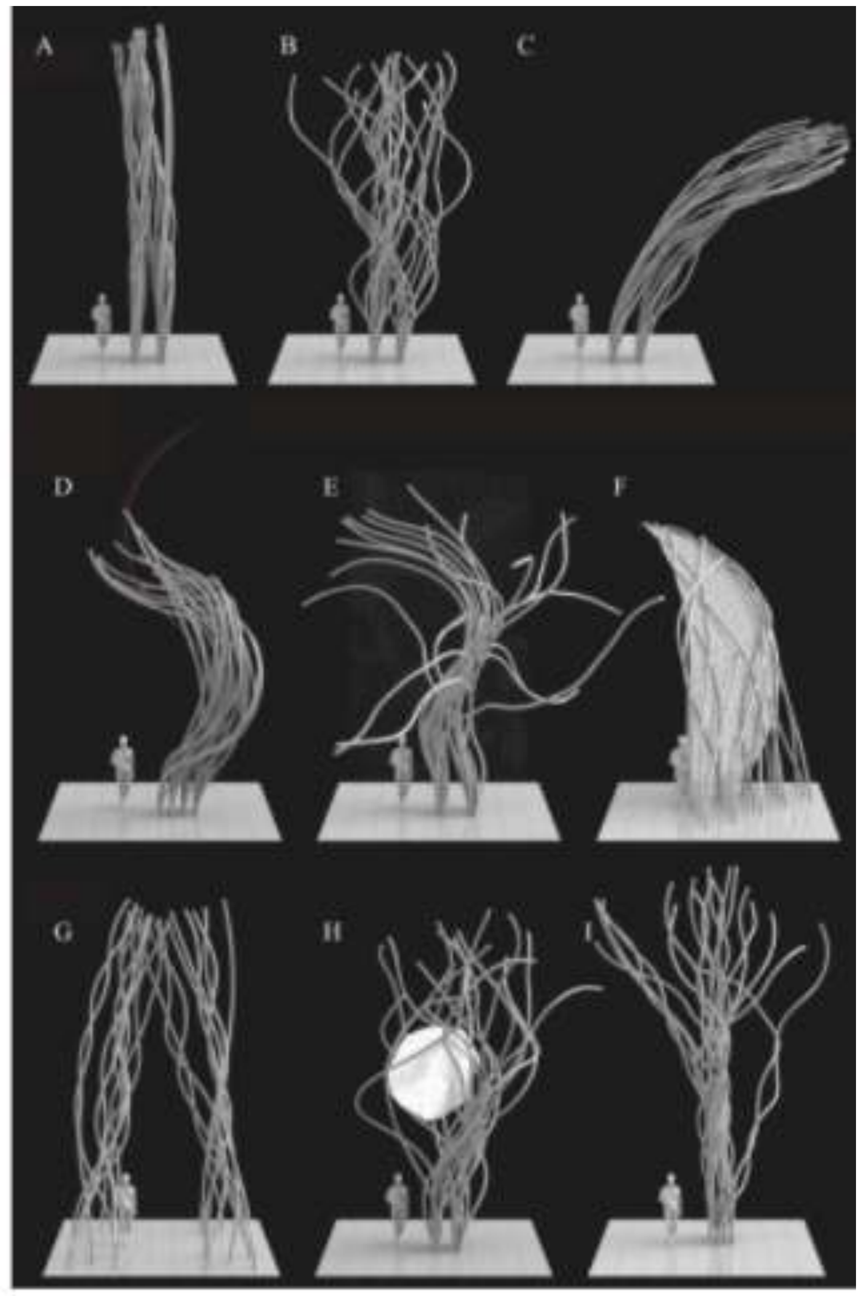
Dynamic **Static**

Q&A: Limitations and Future Work

Information Display vs Fabrication







swarm construction

Q&A: Limitations and Future Work

Technical Limitations

computation / communication	*central control vs local control (all projects)*
sensing / tracking	*only support position tracking (e.g., ShapeBots)*
power supply	*only last less than hours (e.g., ShapeBots)*
connection / disconnection	*not very stable (e.g., Dynablock)*

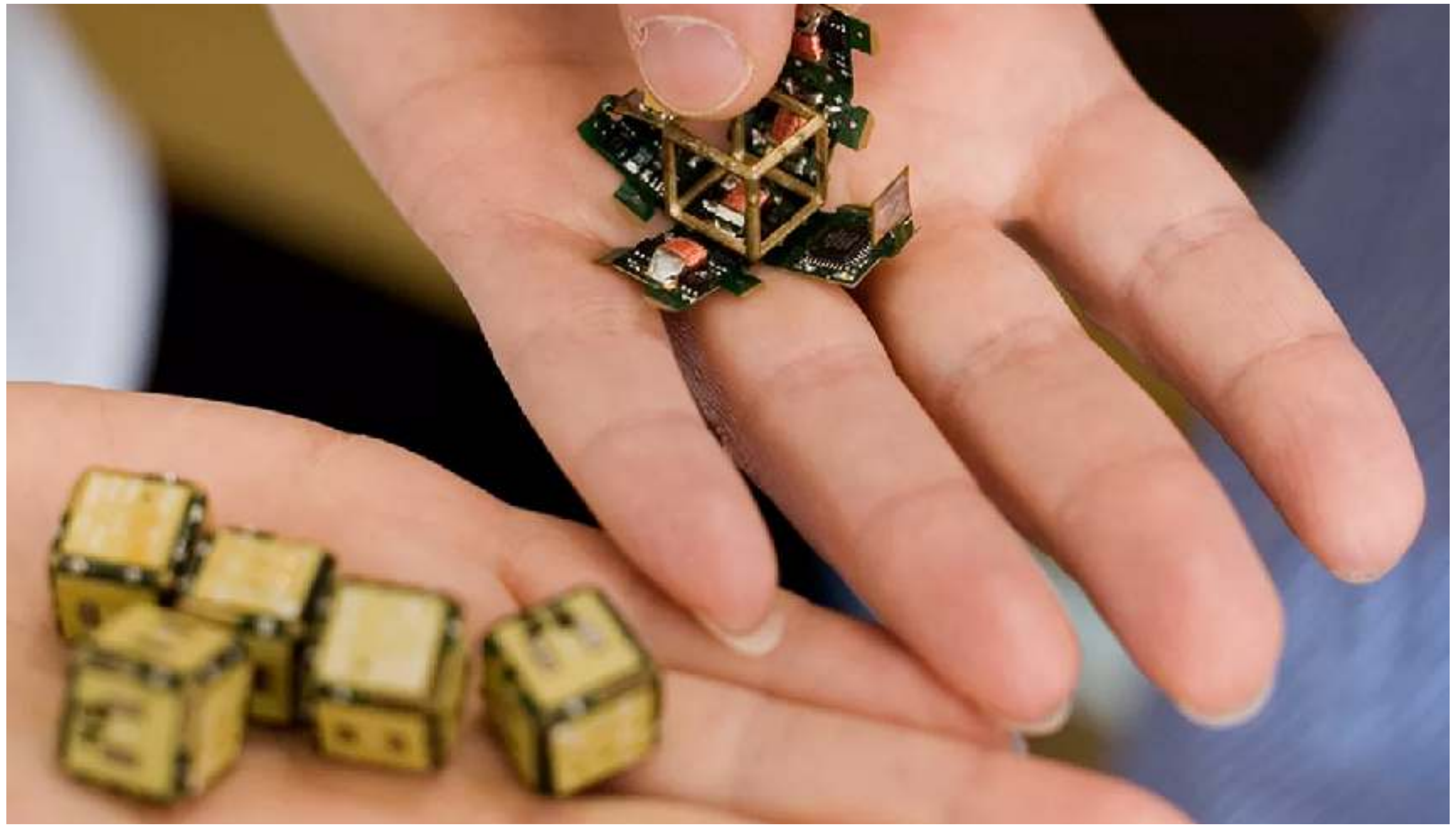
Q&A: Limitations and Future Work

Technical Limitations

wireless power transformation

[IMWUT'18] Luciola : A Millimeter-Scale Light-Emitting Particle Moving in Mid-Air Based On Acoustic Levitation and Wireless Powering, Uno et al.

electro-permanent magnets

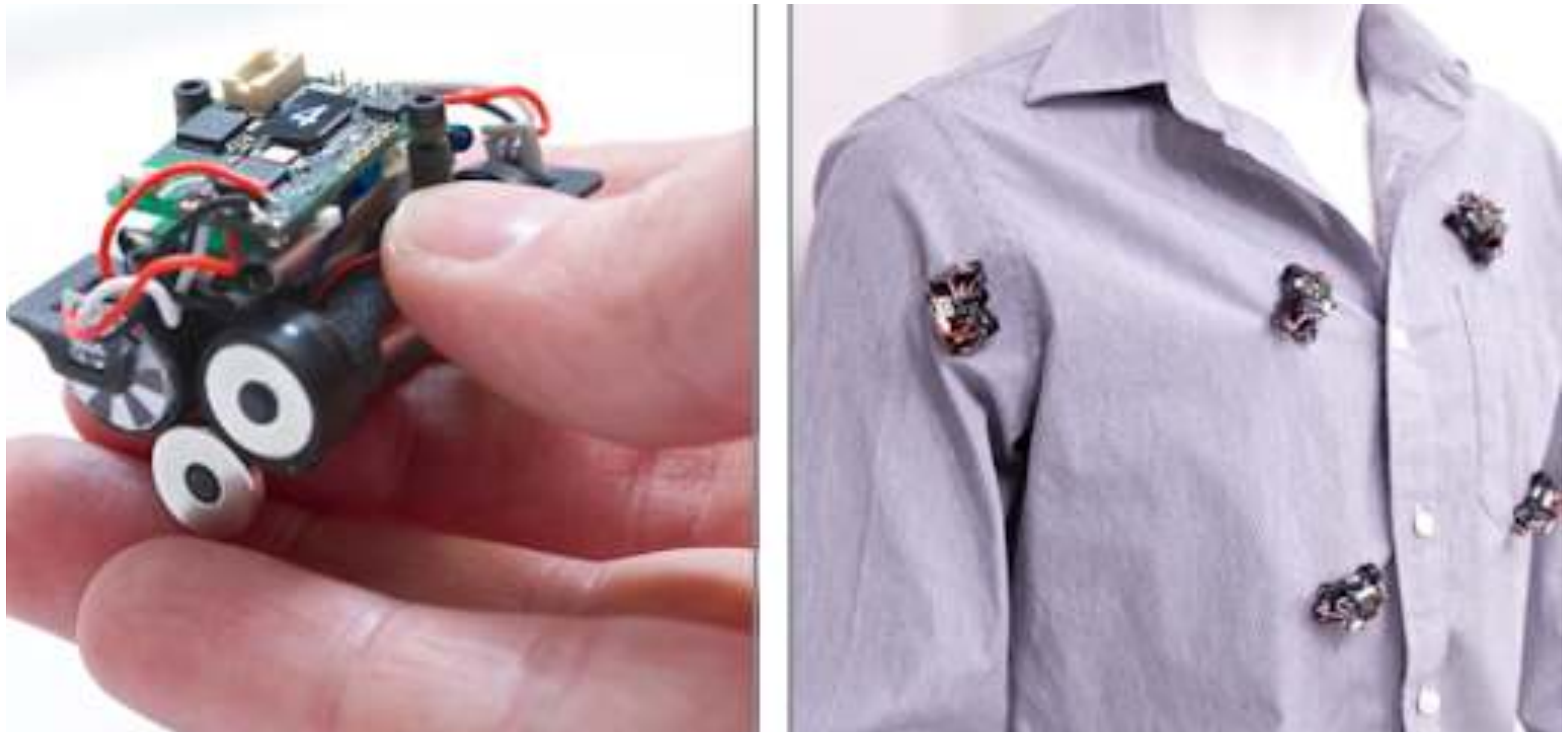


[ICRA'10] Robot pebbles: One centimeter modules for programmable matter through self-disassembly, Gilpin

Q&A: Limitations and Future Work

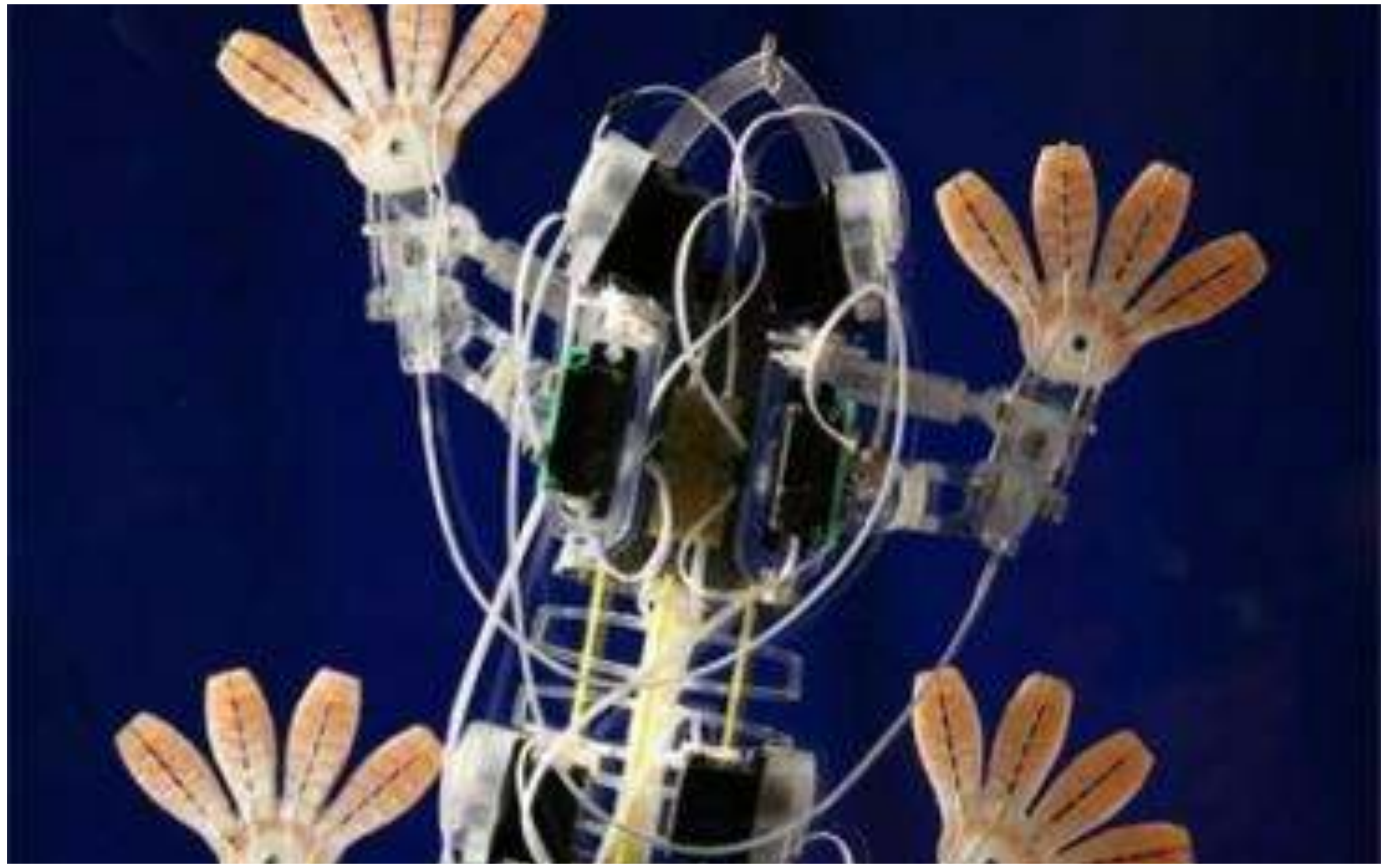
Technical Limitations

on-body (magnet)



[UIST'16] Rovables: Miniature On-Body Robots as Mobile Wearables, Dementyev et al.

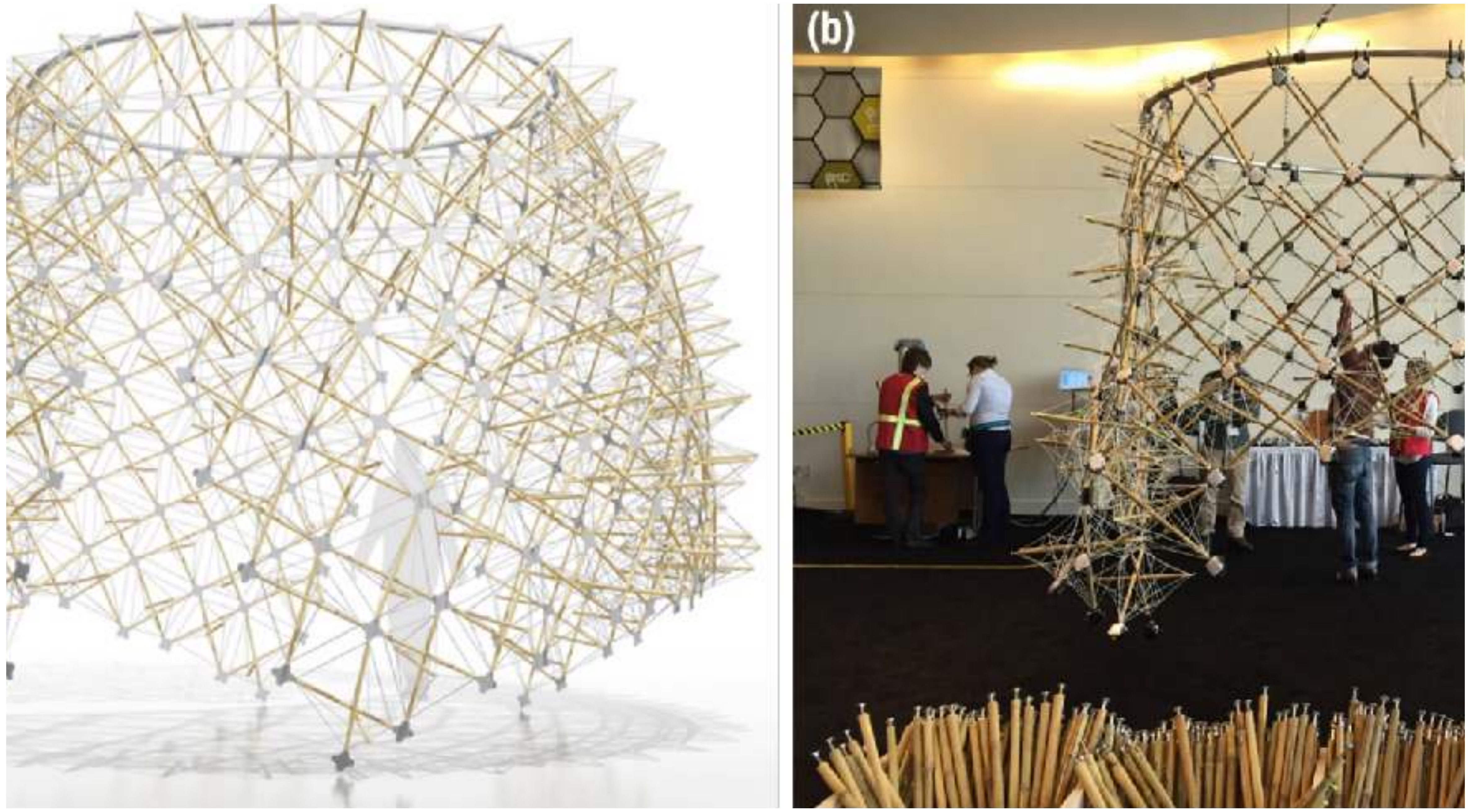
wall-climbing
(gecko-inspired dry adhesion)



[ICRA'07] Whole body adhesion: hierarchical, directional and distributed control of adhesive forces for a climbing robot, Kim et al.

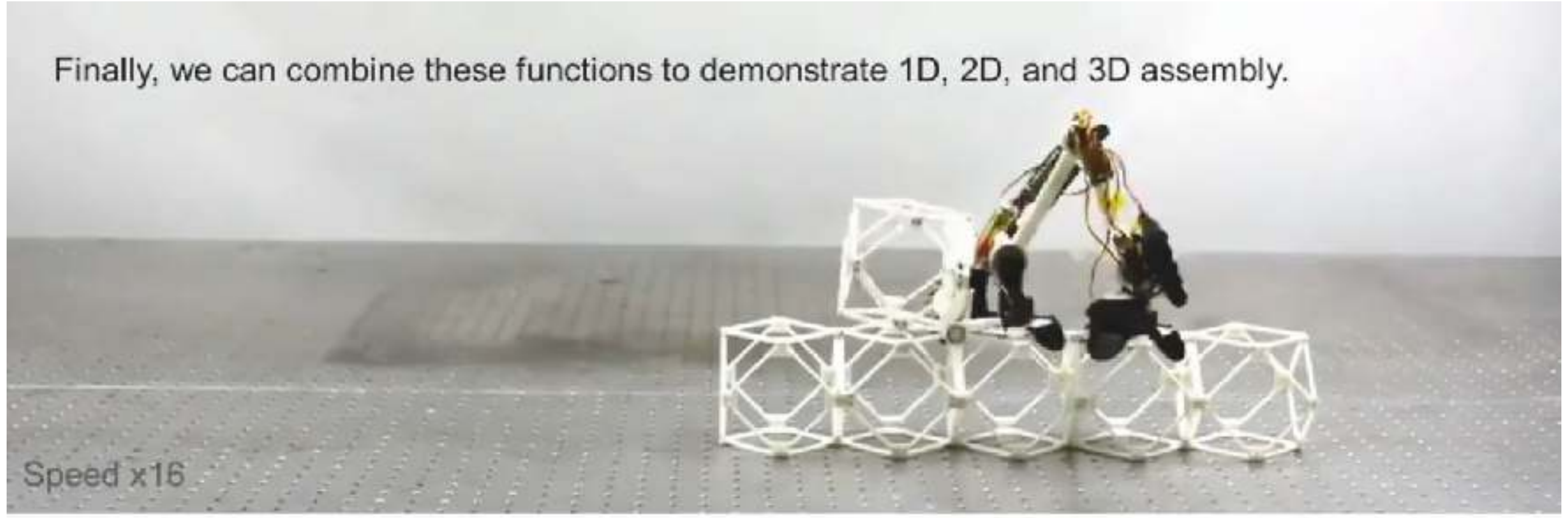
Q&A: Human in the Loop vs Autonomous

human-robot collaboration



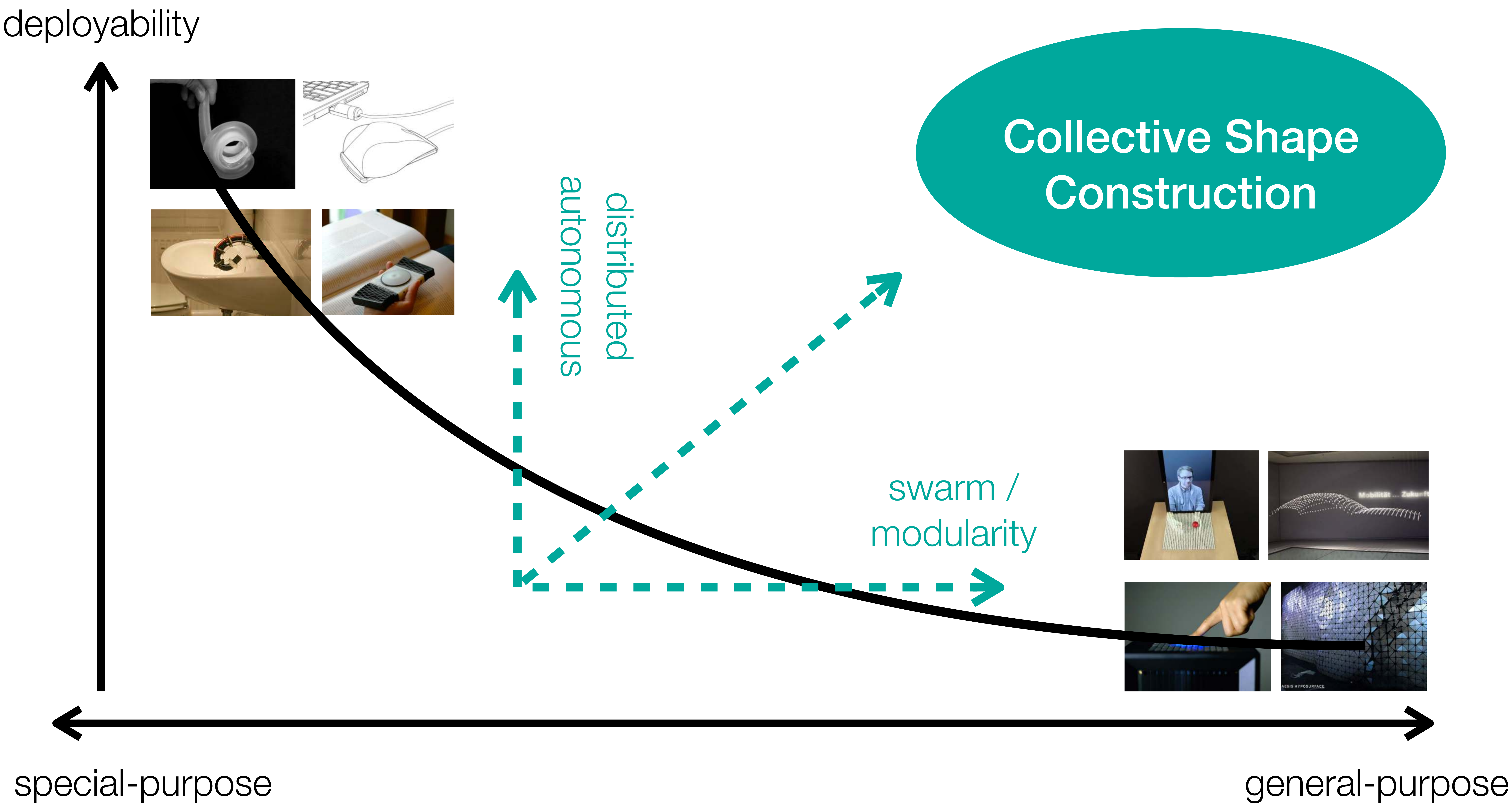
[UIST'16] Autodesk Hive - Crowdsourced Fabrication, Lafreniere et al.

robotic construction

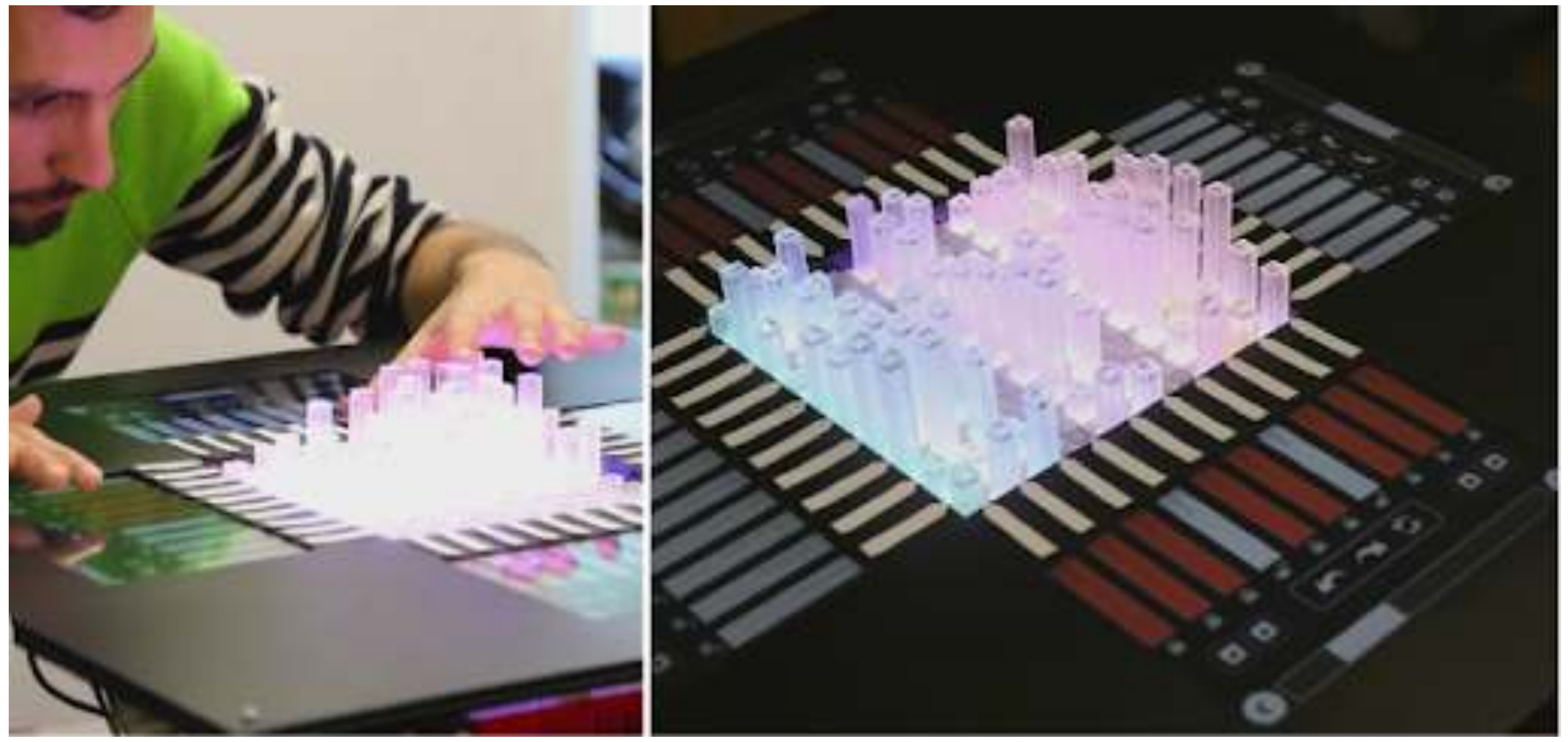


[AIAA'17] BILL-E: Robotic platform for locomotion and manipulation of lightweight space structures, Jenett

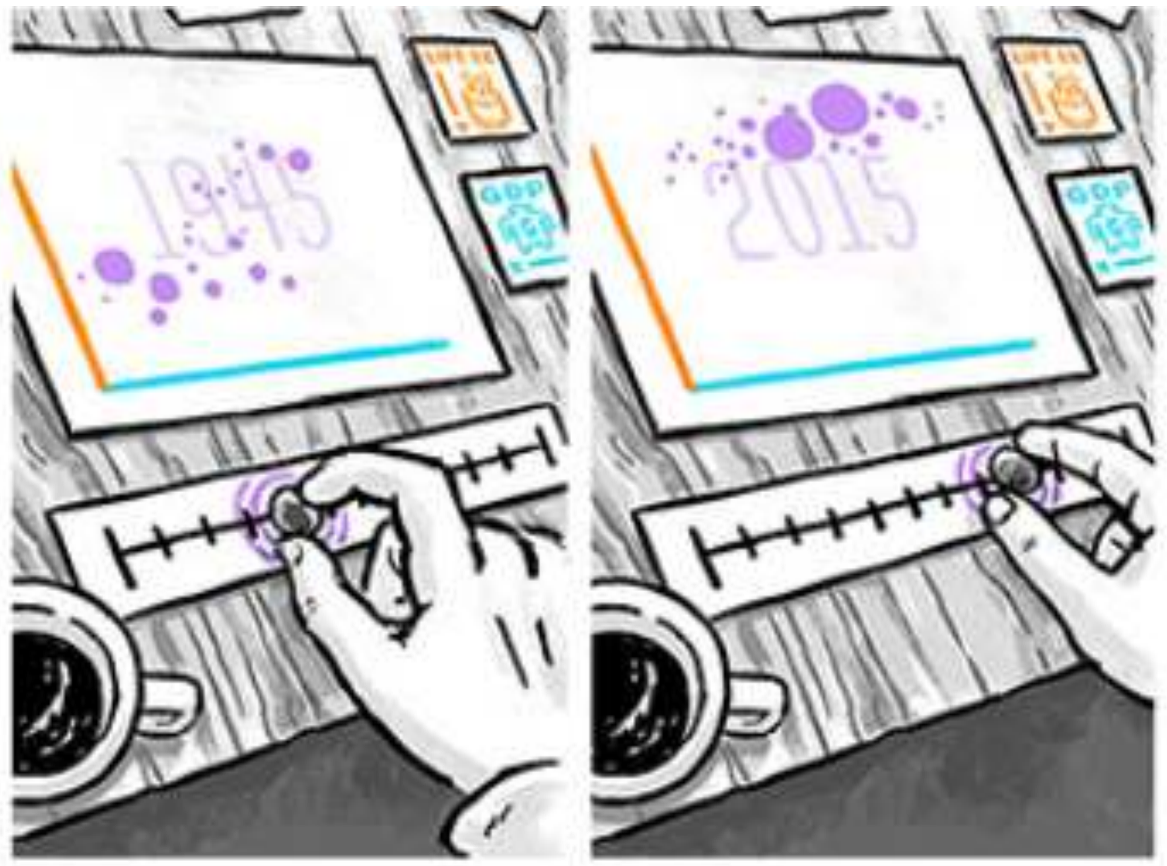
Q&A: Deployable / General-purpose



Q&A: Applications for Data Physicalization

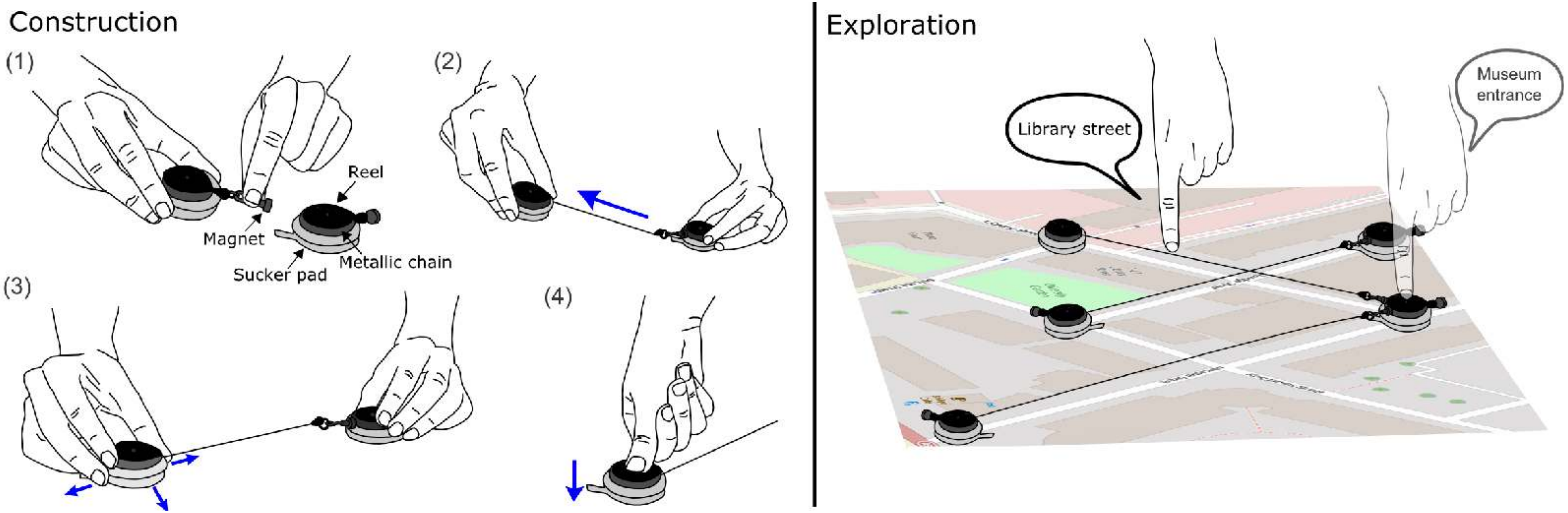


data physicalization



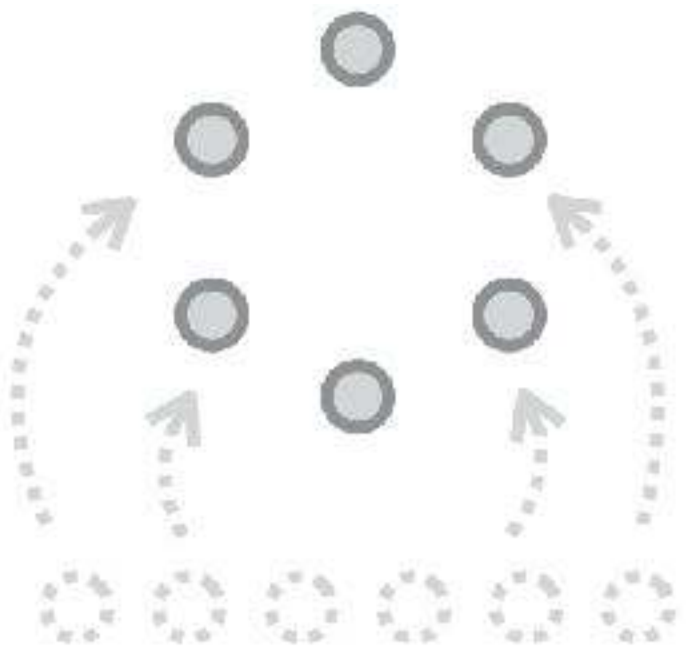
Q&A: Applications for Accessibility

using robots as both inputs and outputs to help users construct



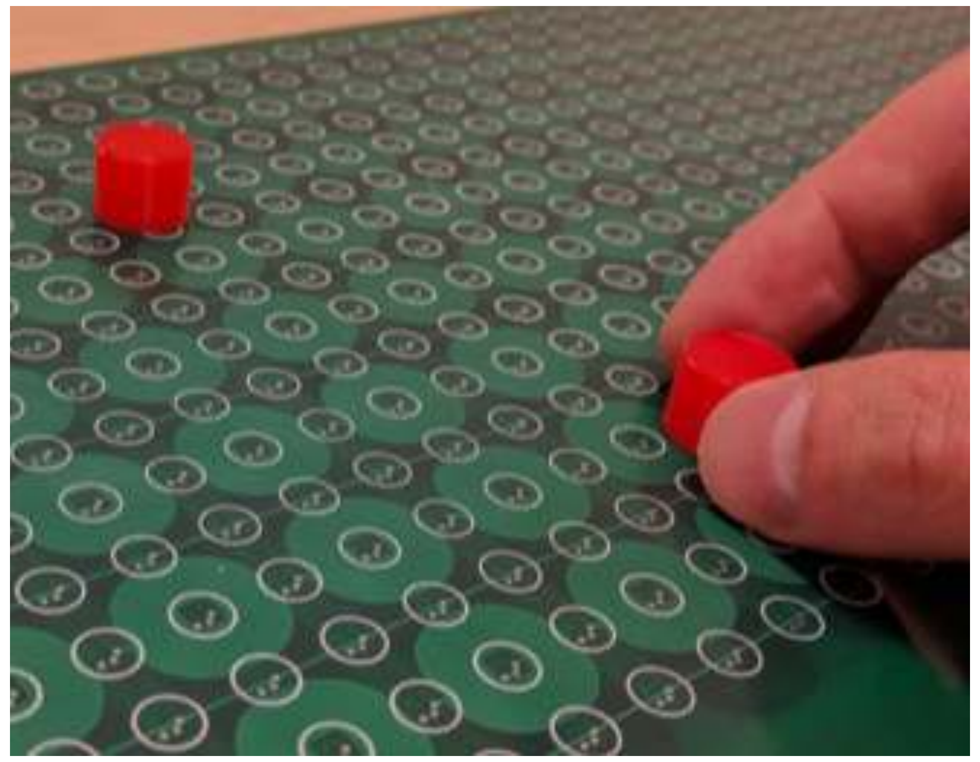
[CHI'16] Tangible Reels: Construction and Exploration of Tangible Maps by Visually Impaired Users, Ducasse et al.

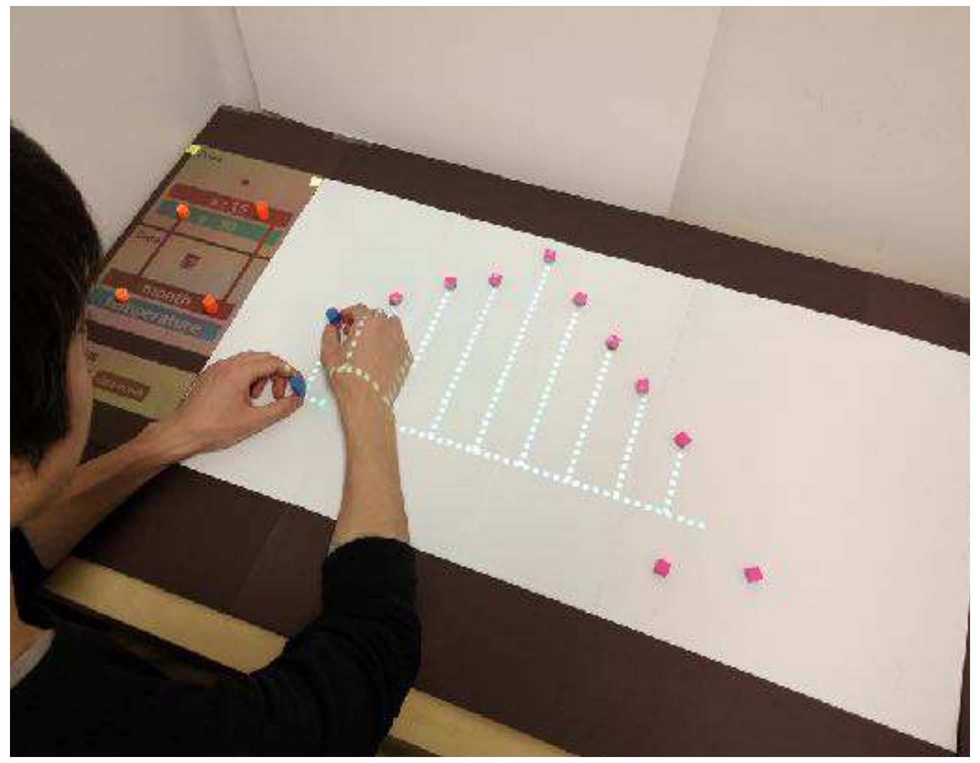
Q&A: Applications for Accessibility



Parallel Actuation

Parallel actuation of a swarm of magnetic markers for **sparse dots** representation



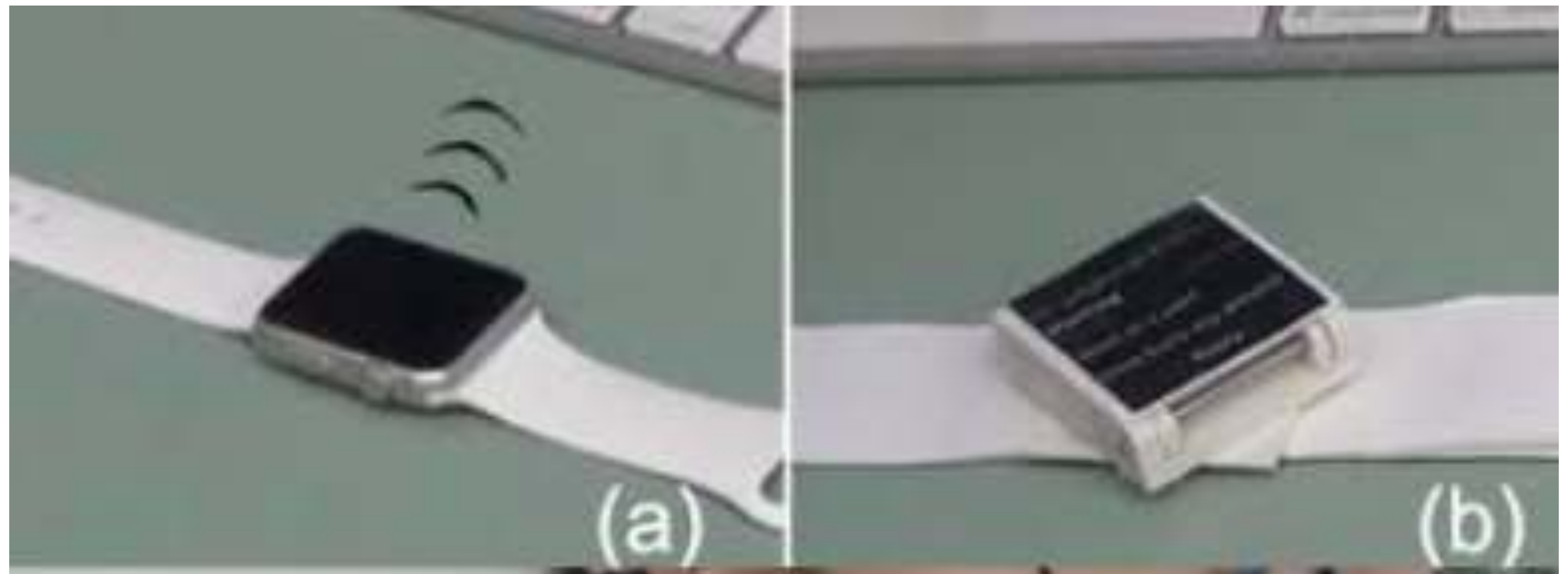


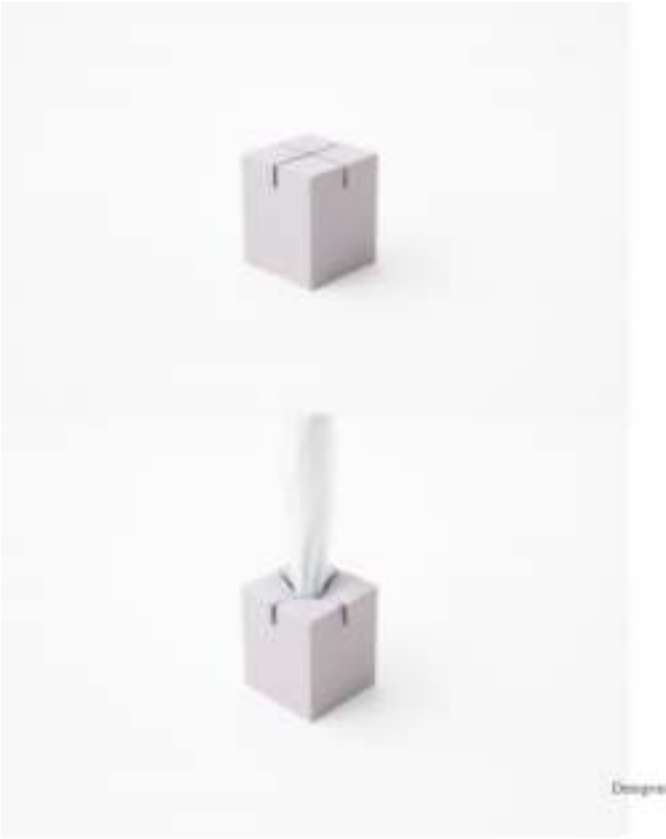
Application: Tactile Assistant for Blind People

[ASSETS 2017] *FluxMarker: Enhancing Tactile Graphics with Dynamic Tactile Markers* by Suzuki, Stangl, Gross, and Yeh

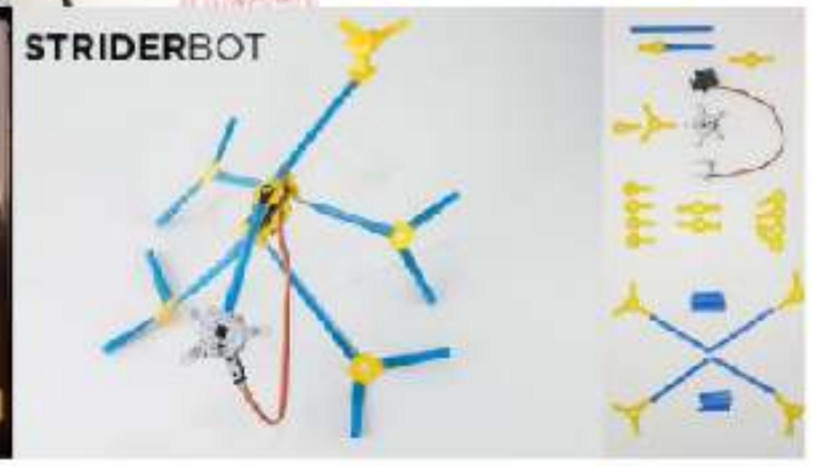
[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by Suzuki, Kato, Gross, and Yeh

Q&A: Dynamic Physical Affordances





Q&A: Dynamic Physical Affordances



Q&A: Global vs Local Computation

computation / communication	*central control vs local control (all projects)*
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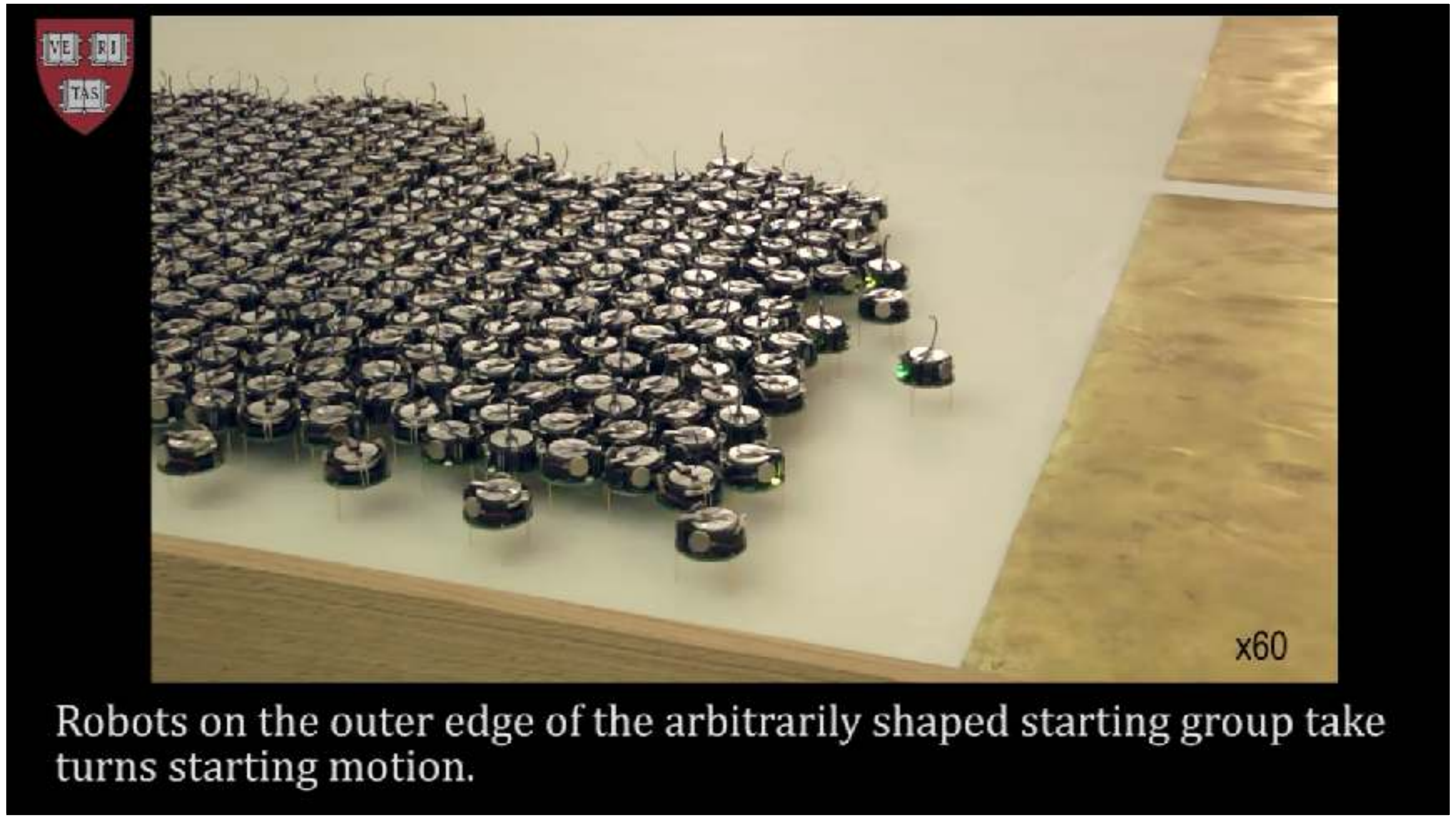
Q&A: Global vs Local Computation

distributed control



[Science'14] Programmable Self-Assembly in a Thousand-Robot Swarm, Rubenstein et al.

global-to-local compiler

[Science'14] Designing Collective Behavior in a Termite-inspired Robot Construction Team, Werfel et al.

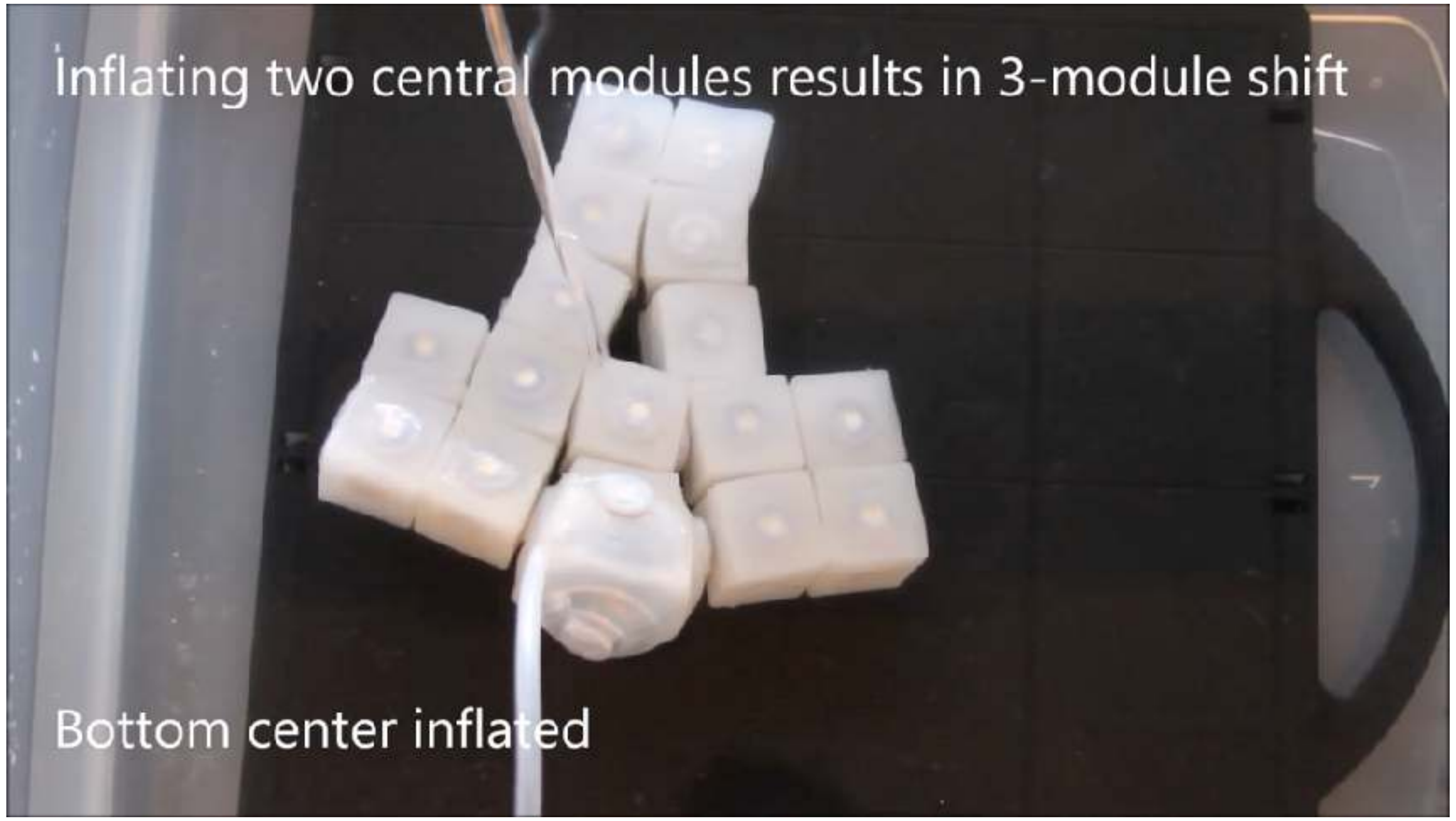
Q&A: Alternative Programming

Object-oriented programming: each element can memorize property so that the user can combine

Q&A: Soft vs Rigid

swarm soft robots

modular soft robots

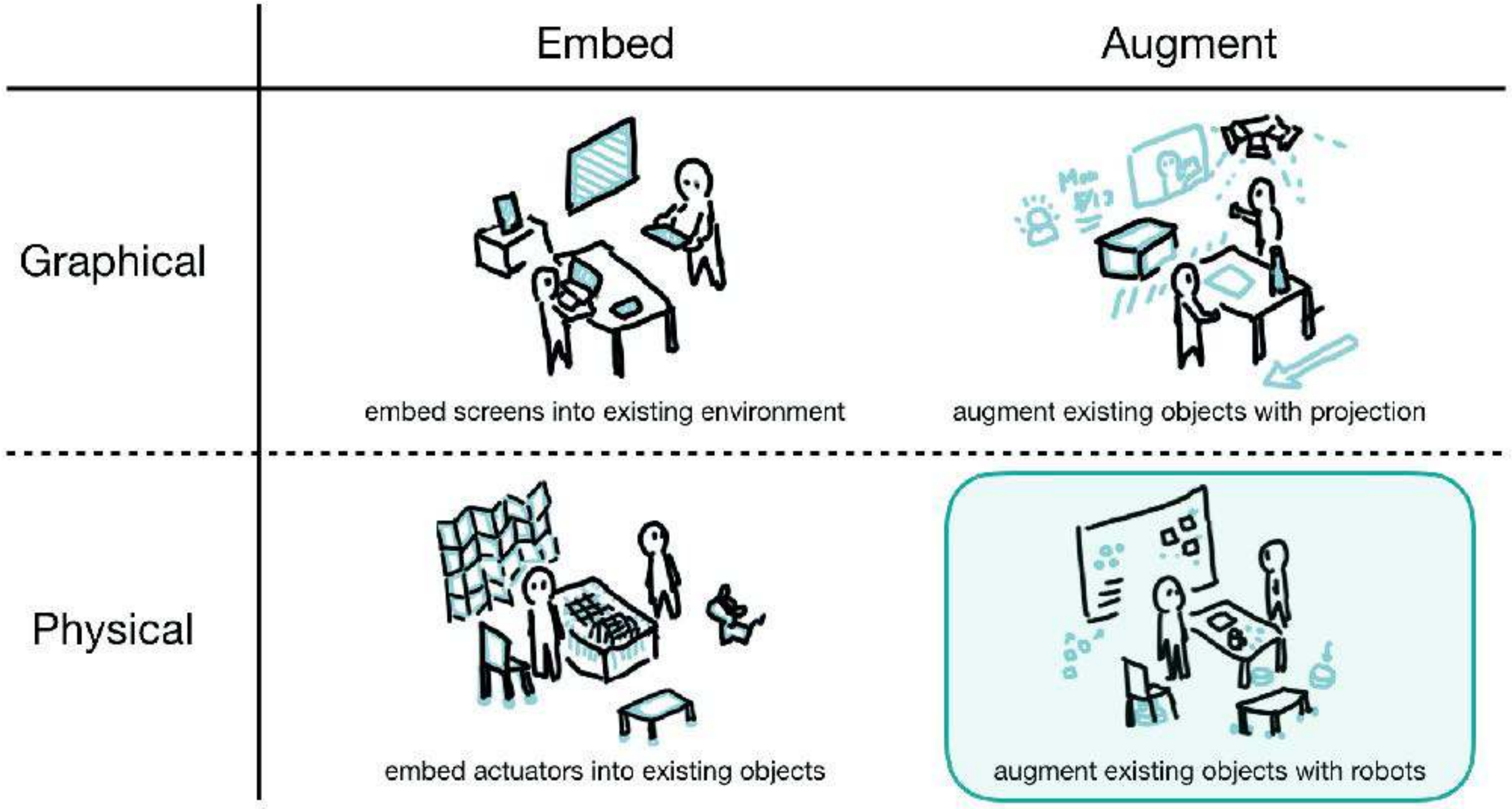


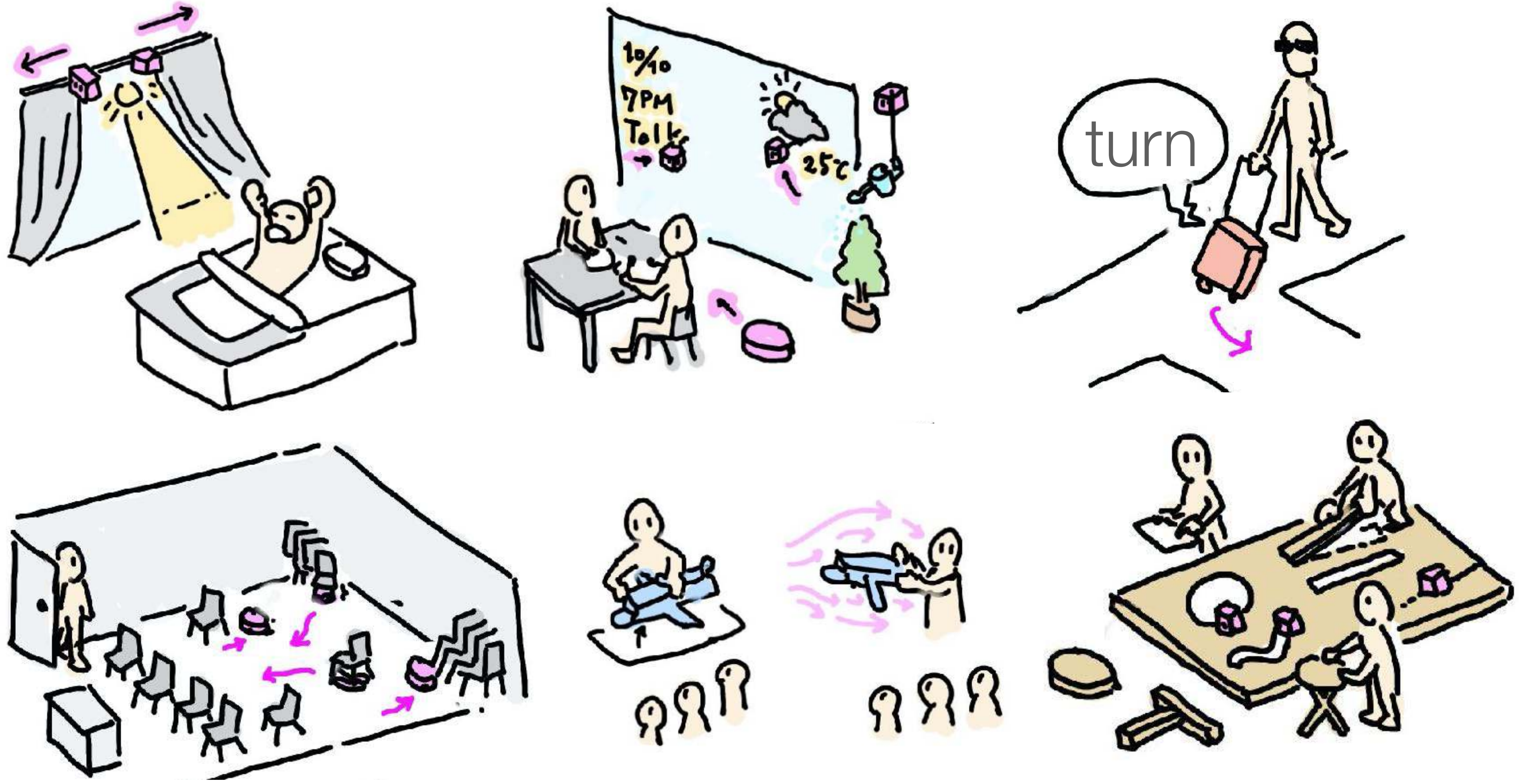
[PLoS ONE'17] Soft Modular Robotic Cubes: Toward Replicating Morphogenetic Movements of the Embryo, Vergara et al.

[DIS'19] MorphIO: MorphIO: Entirely Soft Sensing and Actuation Modules for Programming Shape Changes through Tangible Interaction, Nakayama et al.

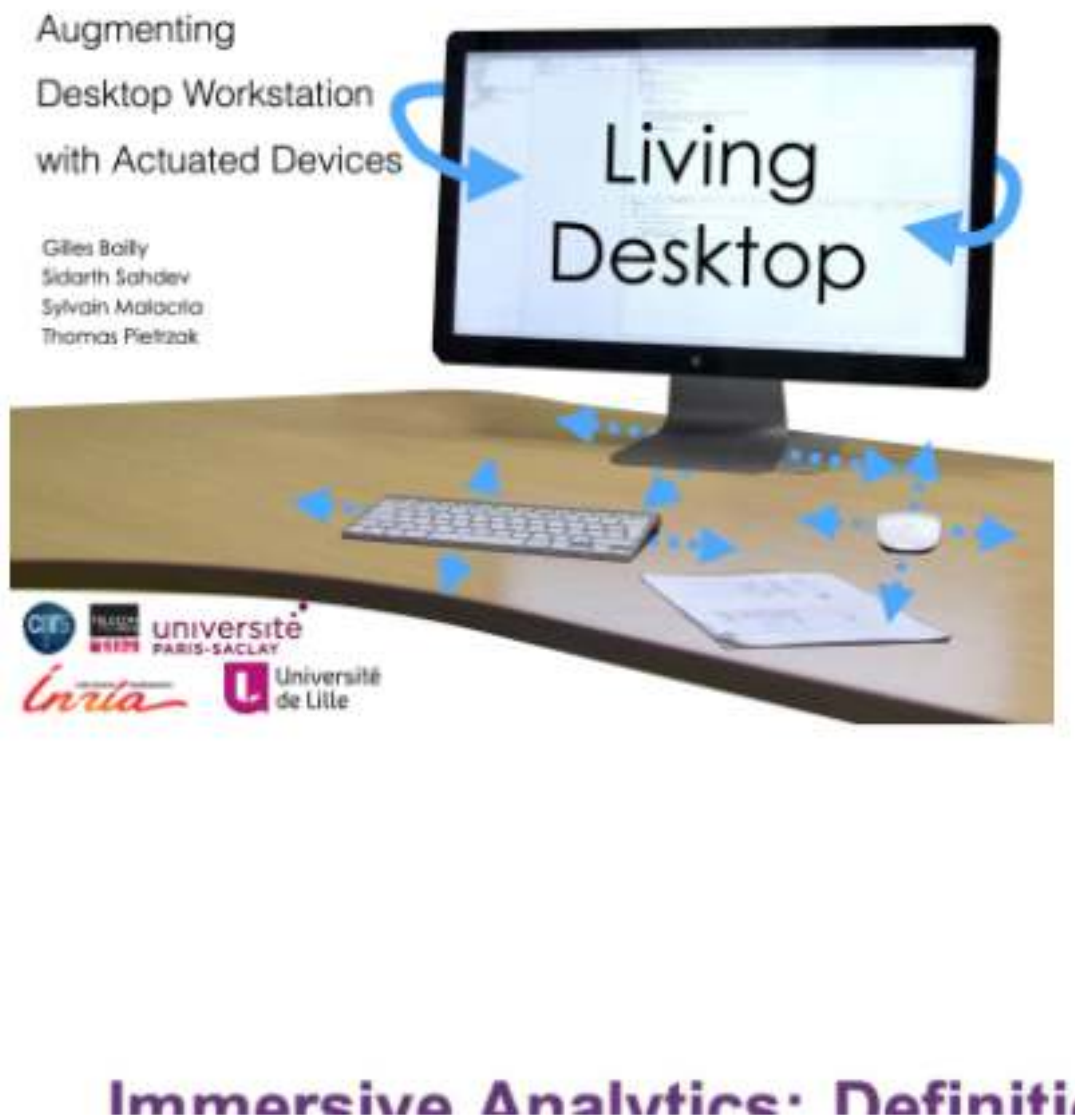
Q&A: Embedded vs Augmented

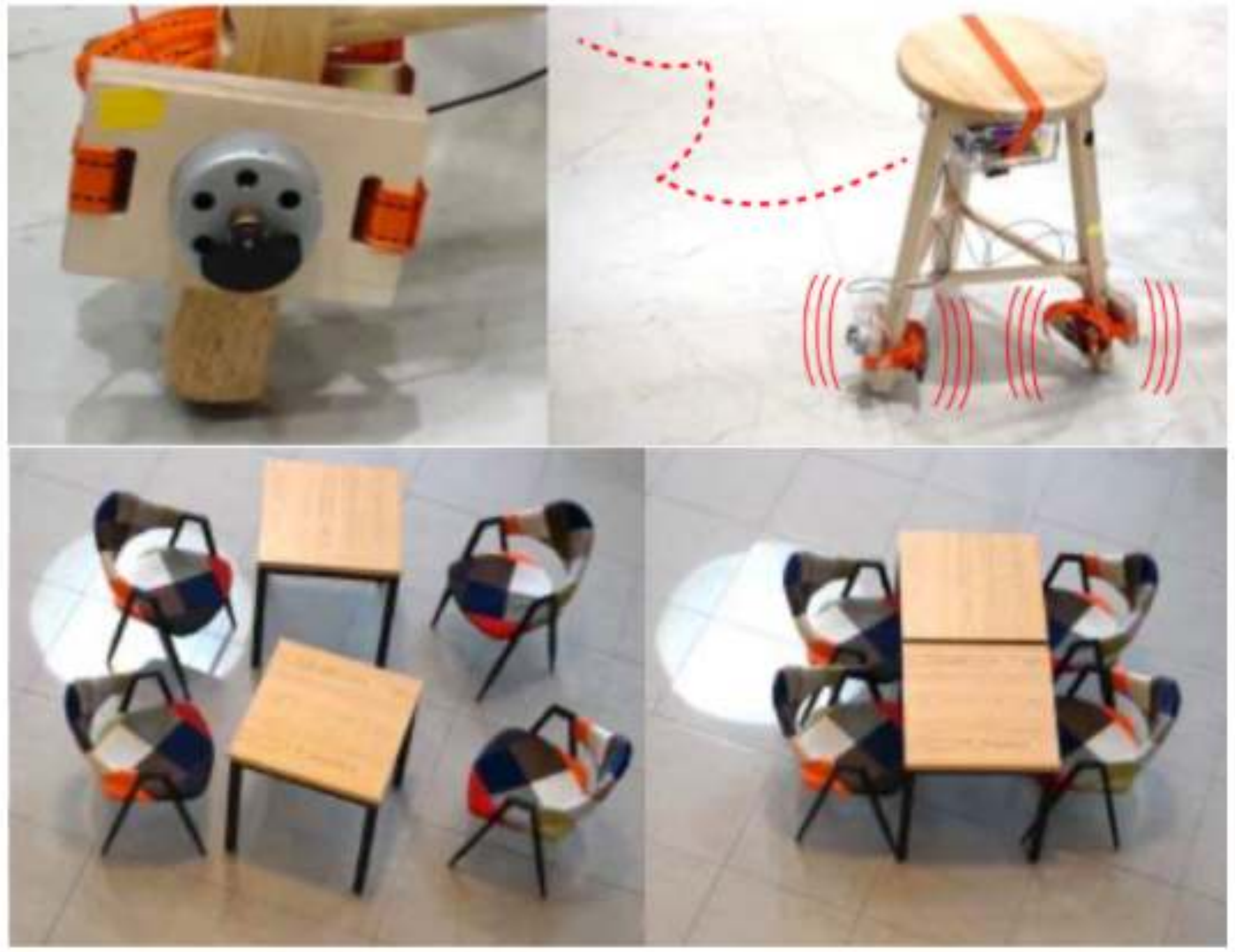
swarm robots
that are seamlessly blended
and integrated into everyday life



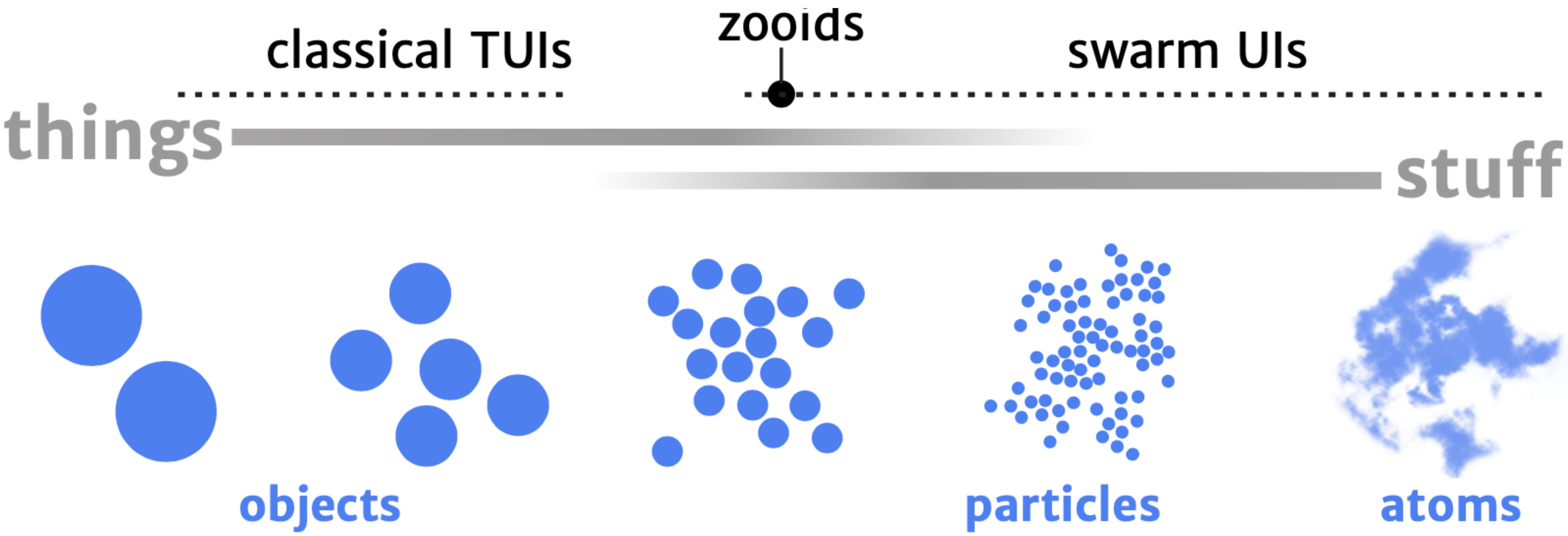


Q&A: Embedded vs Augmented





Q&A: Things vs Stuff



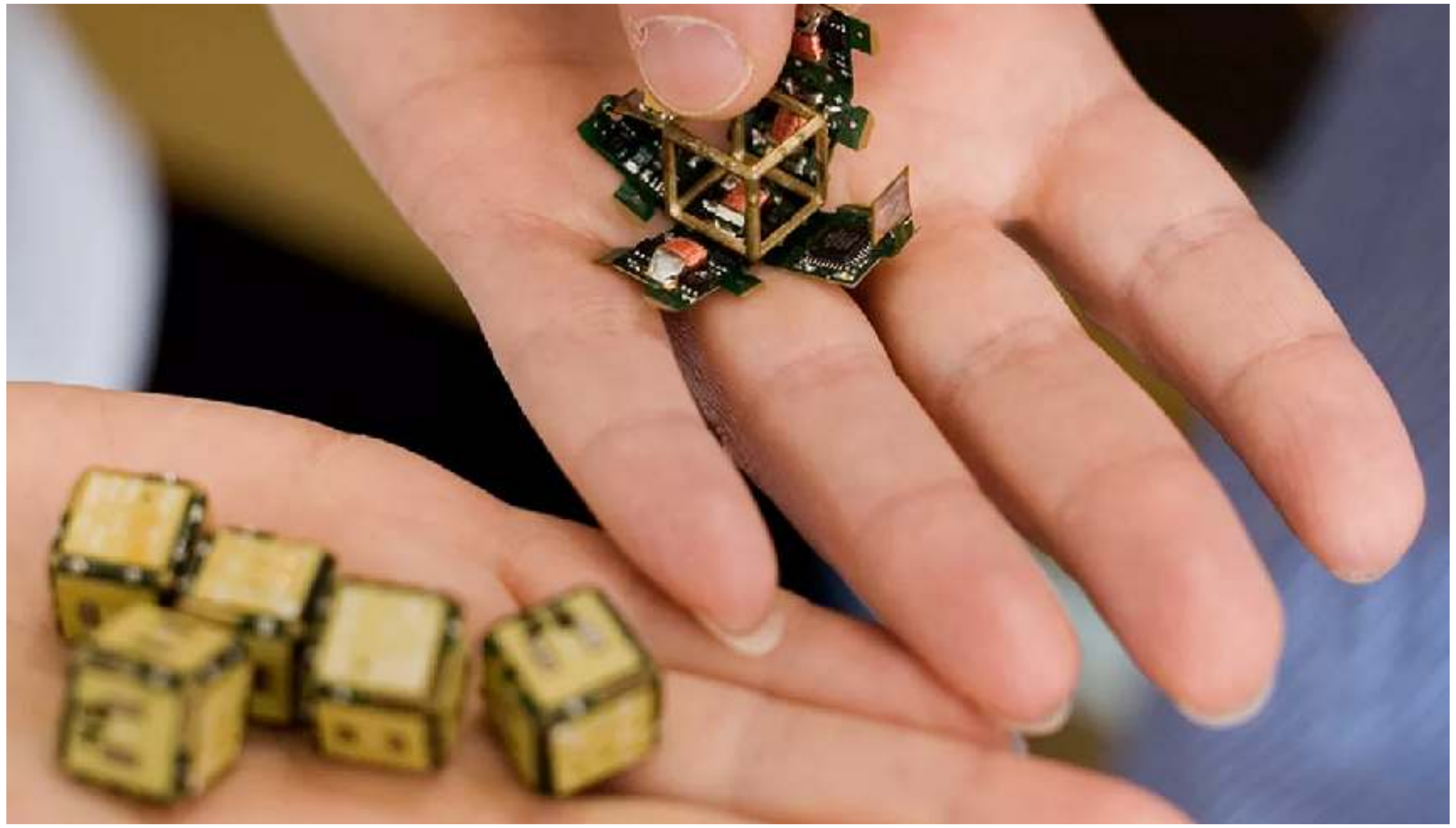
The continuum between "things" and "stuff" [source: Zooids, Le Goc et al. 2016]

Q&A: Miniaturization: Towards mm-scale

wireless power transformation

[IMWUT'18] Luciola : A Millimeter-Scale Light-Emitting Particle Moving in Mid-Air Based On Acoustic Levitation and Wireless Powering, Uno et al.

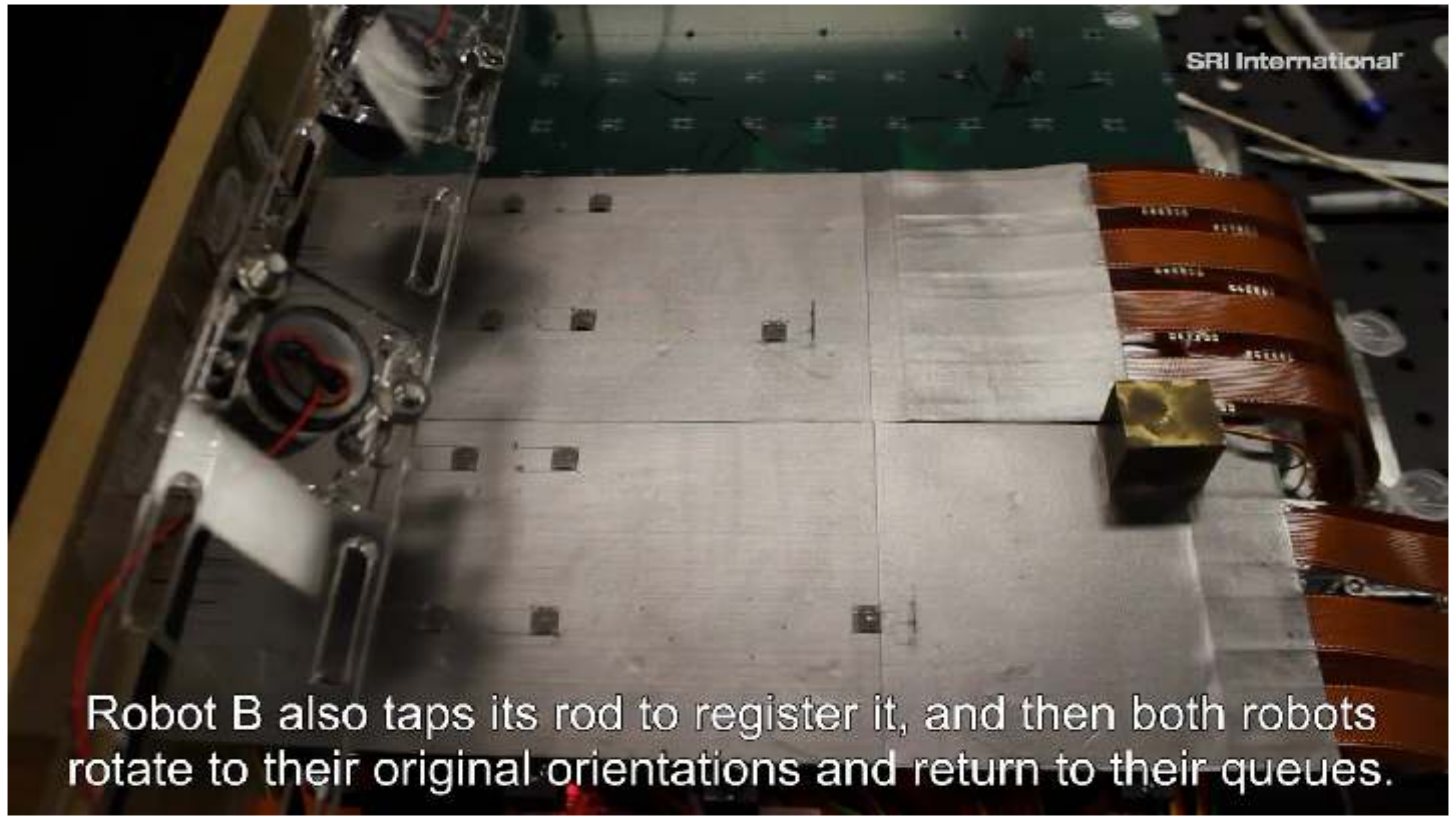
electro-permanent magnets



[ICRA'10] Robot pebbles: One centimeter modules for programmable matter through self-disassembly, Gilpin

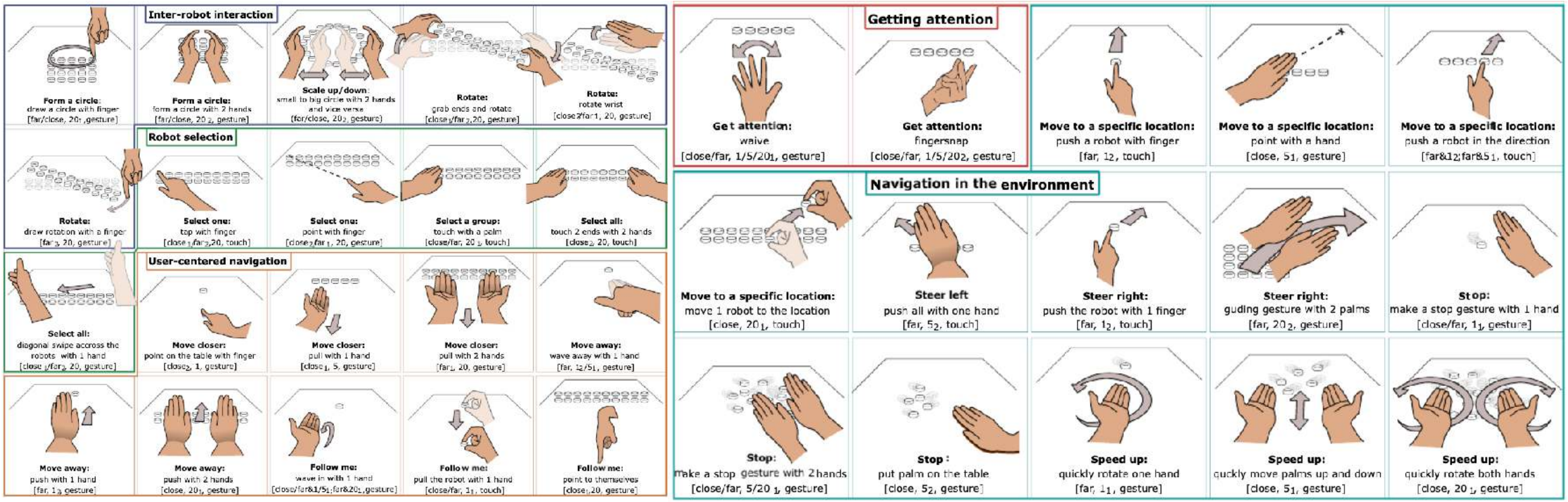
Q&A: Miniaturization: Towards mm-scale

e.g., Universal Planar Manipulator by Dan Reznik



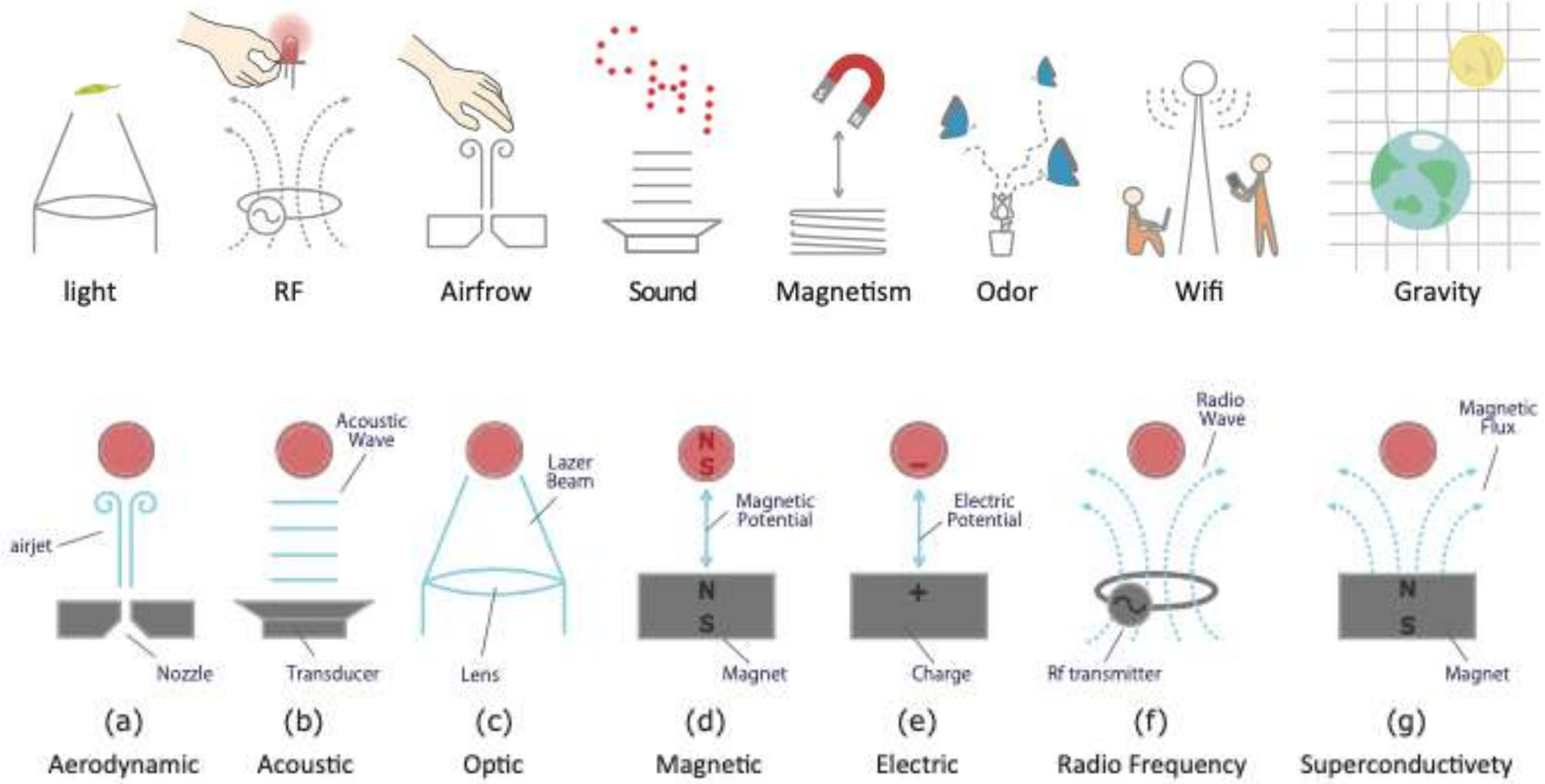
e.g., SRI micro factory

Q&A: Interactions



e.g., Kim et al. User-defined Swarm Robot Control [CHI'20]

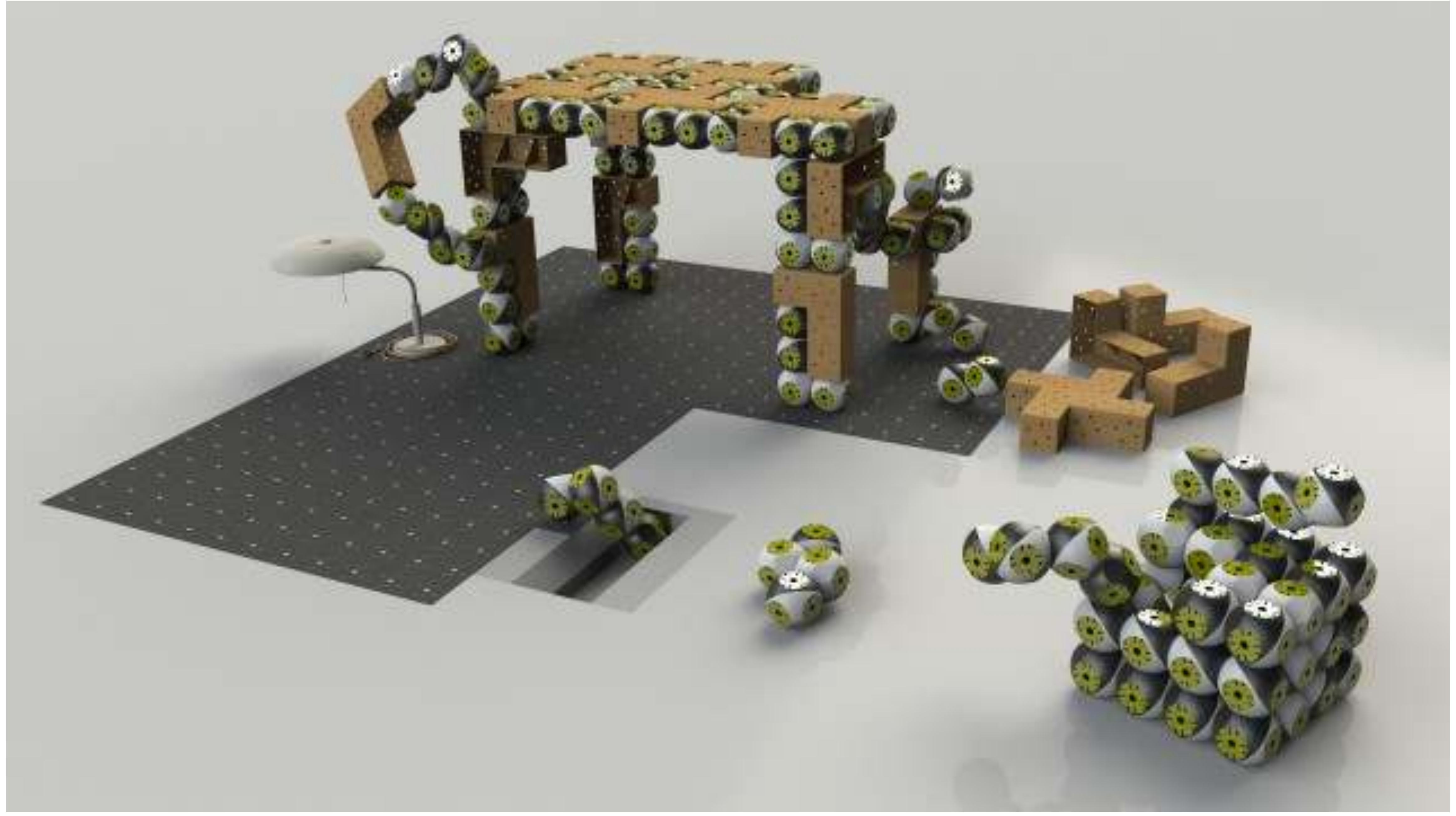
Q&A: Design / Technology Choice



Ochiai, Graphics by Computational Acoustic Fields

Q&A: Self-assembly vs External Assembly

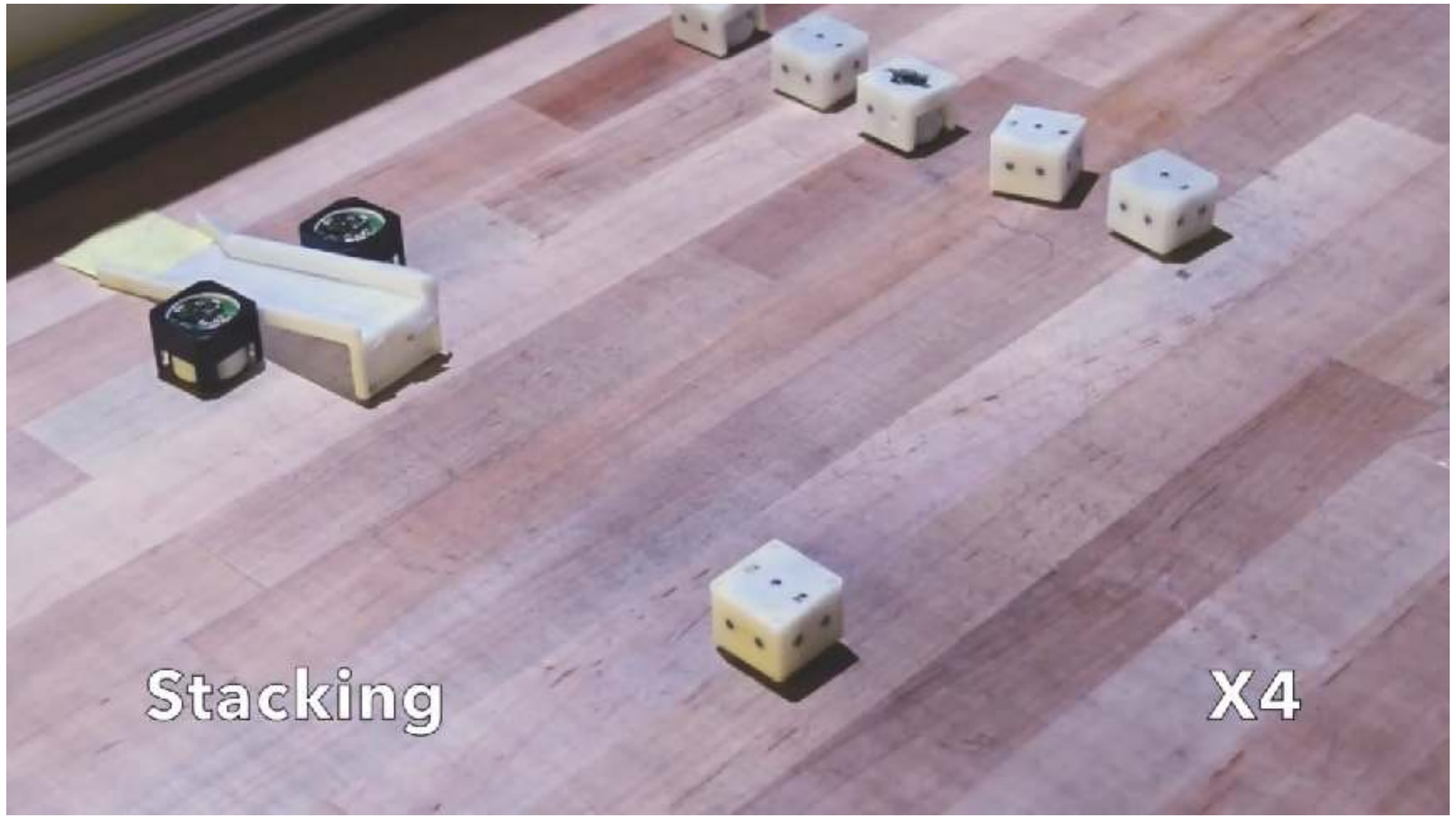
self actuation ⟷ *external actuation*



[ICRA'09] Roombots: Mechanical design of self-reconfiguring modular robots for adaptive furniture, Sprowitz et al.

BioMolecular Self-Assembly, Tibbits et al.

Q&A: Self-assembly vs External Assembly



[ISS'17] Robotic Assembly of Haptic Proxy Objects for Tangible Interaction and Virtual Reality, Zhao et al.

Q&A: Collective Actuation