

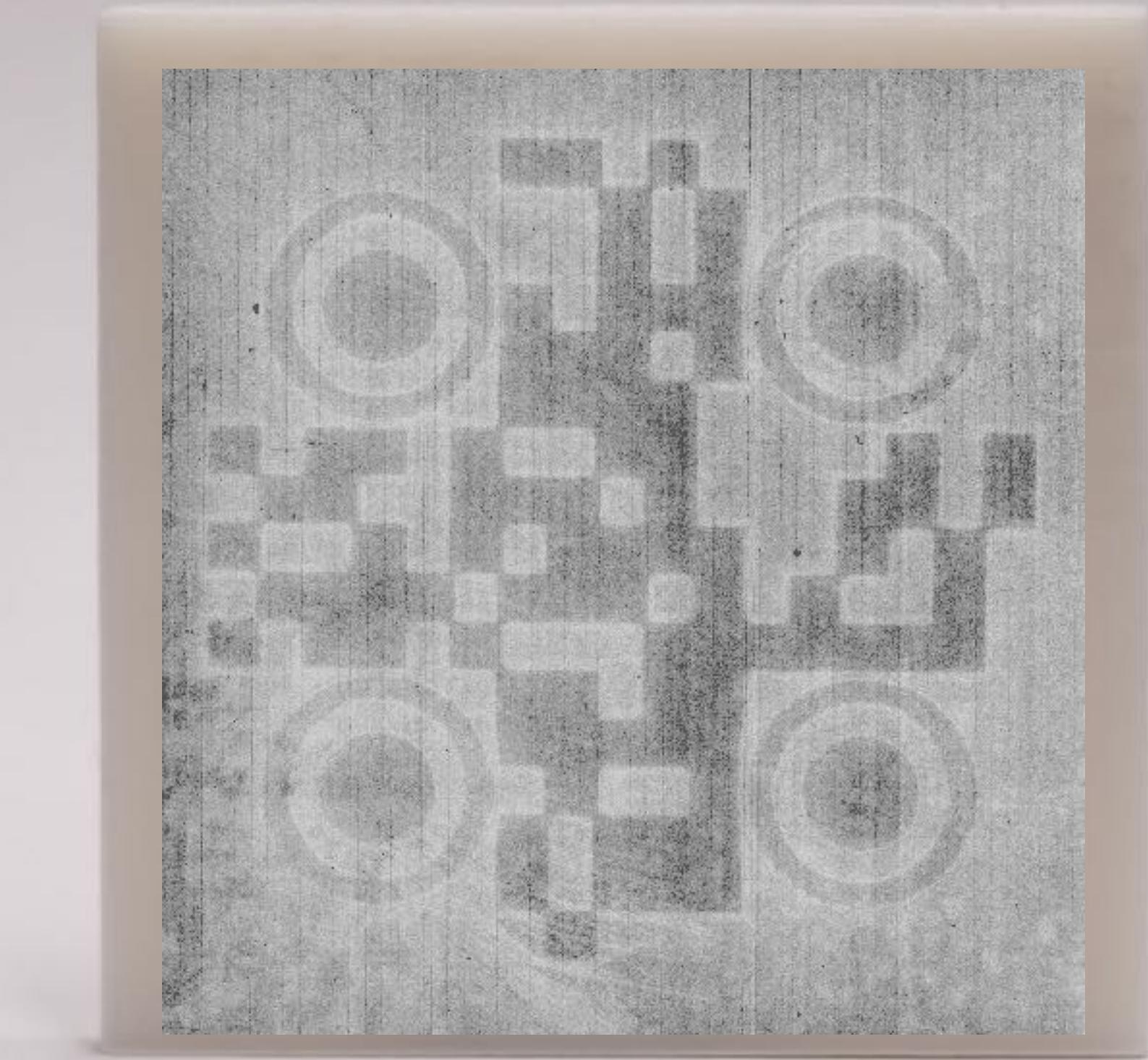
AirCode: Unobtrusive Physical Tags for Digital Fabrication

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Shree K. Nayar

Changxi Zheng



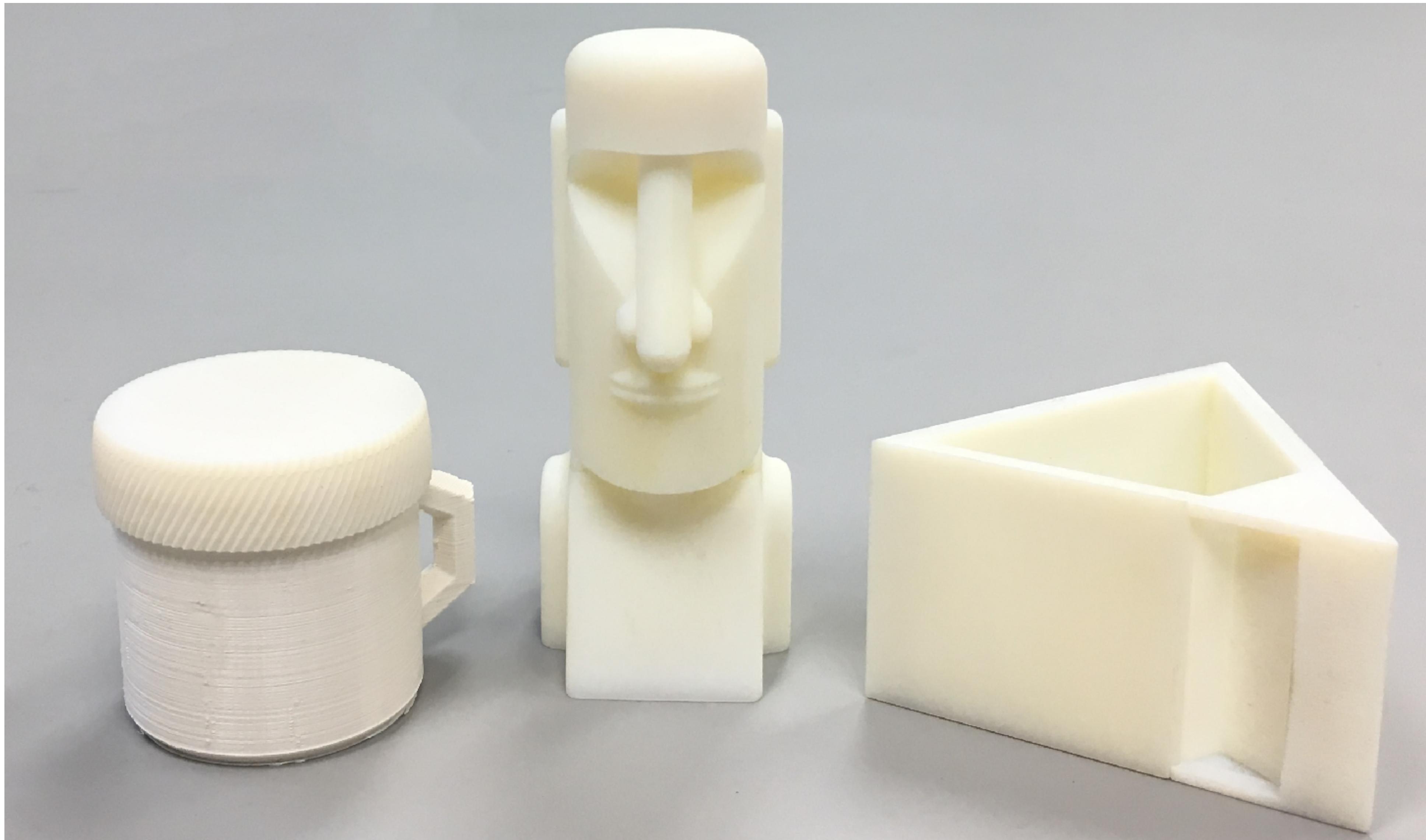
Tags are everywhere.



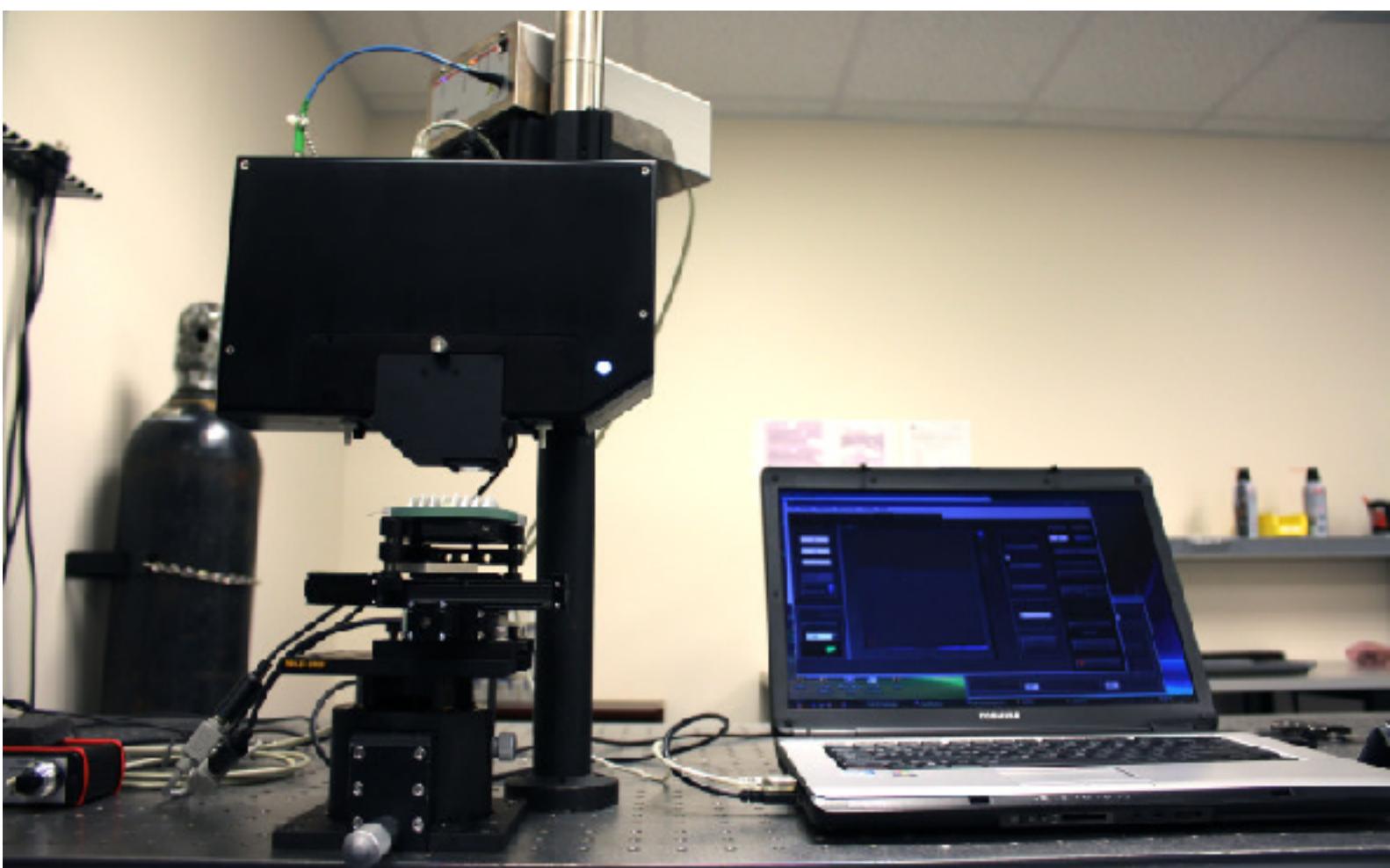
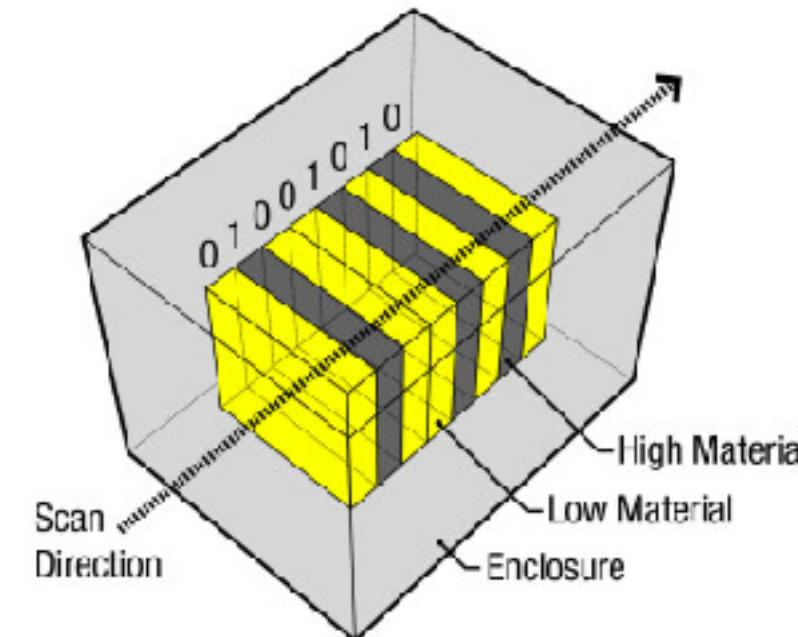
Compromises on Aesthetics



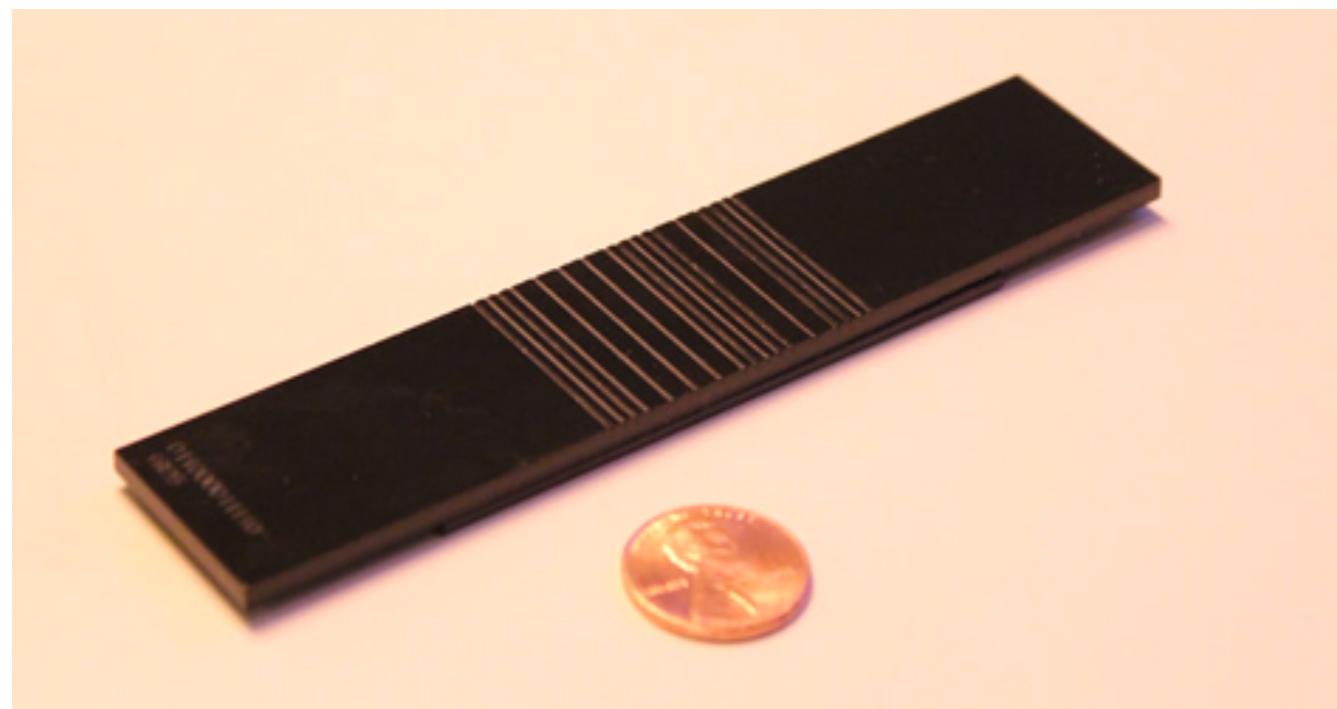
Unobtrusive Tagging for Fabrication



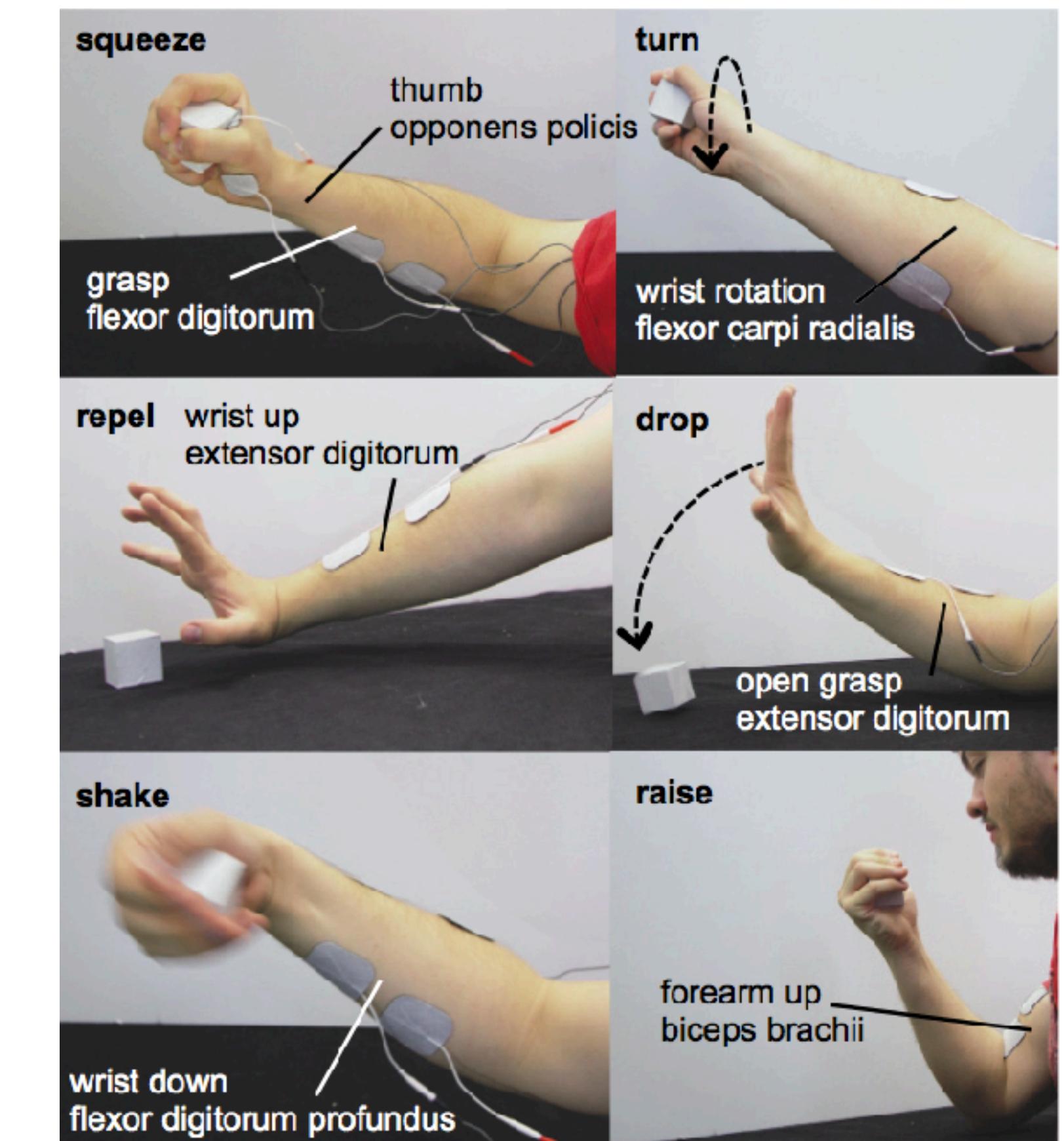
Related Work



InfraStructs - Terahertz
[Willis et al., SIGGRAPH 2013]



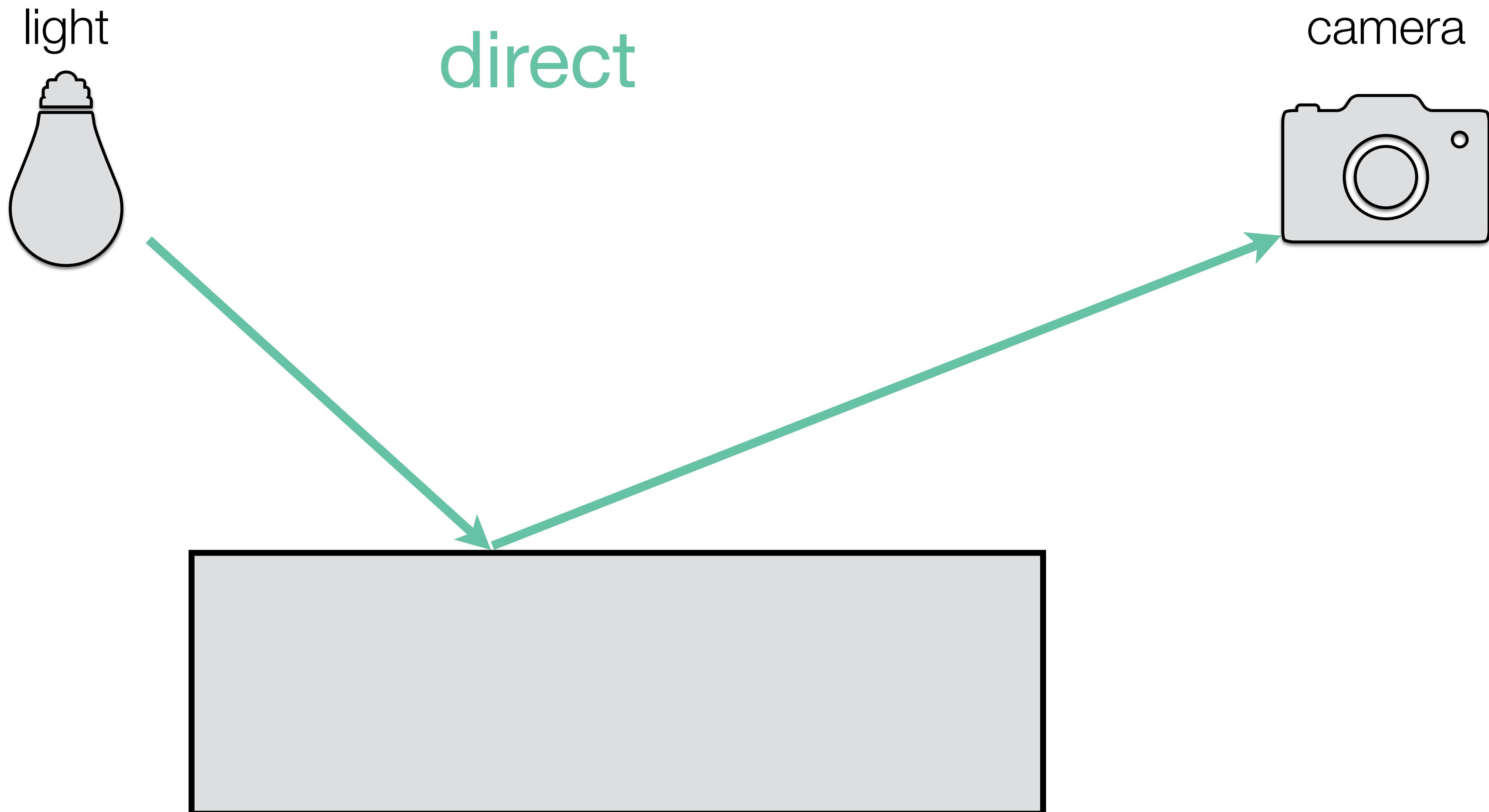
Acoustic Barcodes
[Harrison et al., UIST 2012]



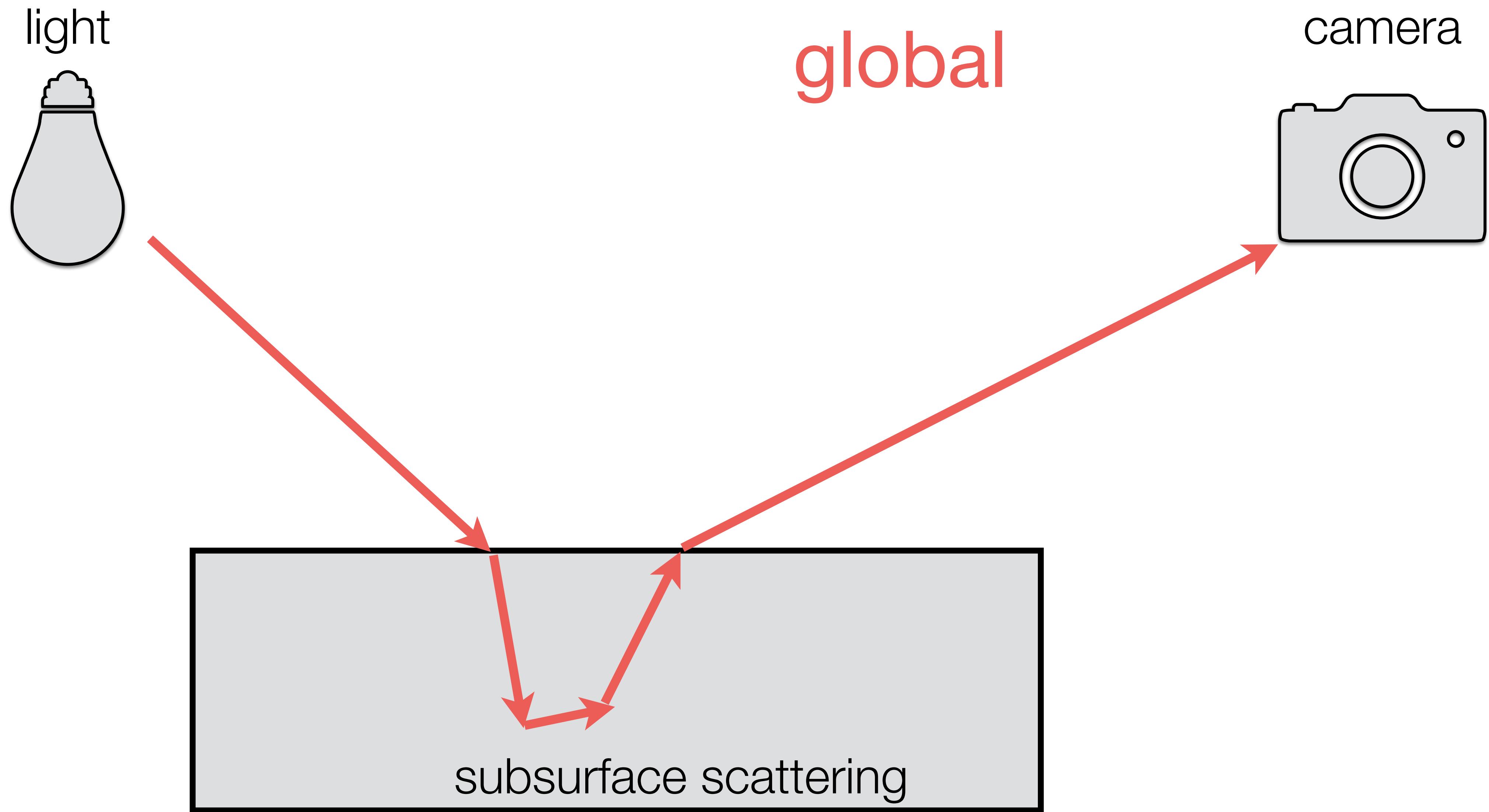
Affordance++ - Stimulating
[Lopes et al., CHI 2015]

Light Transport

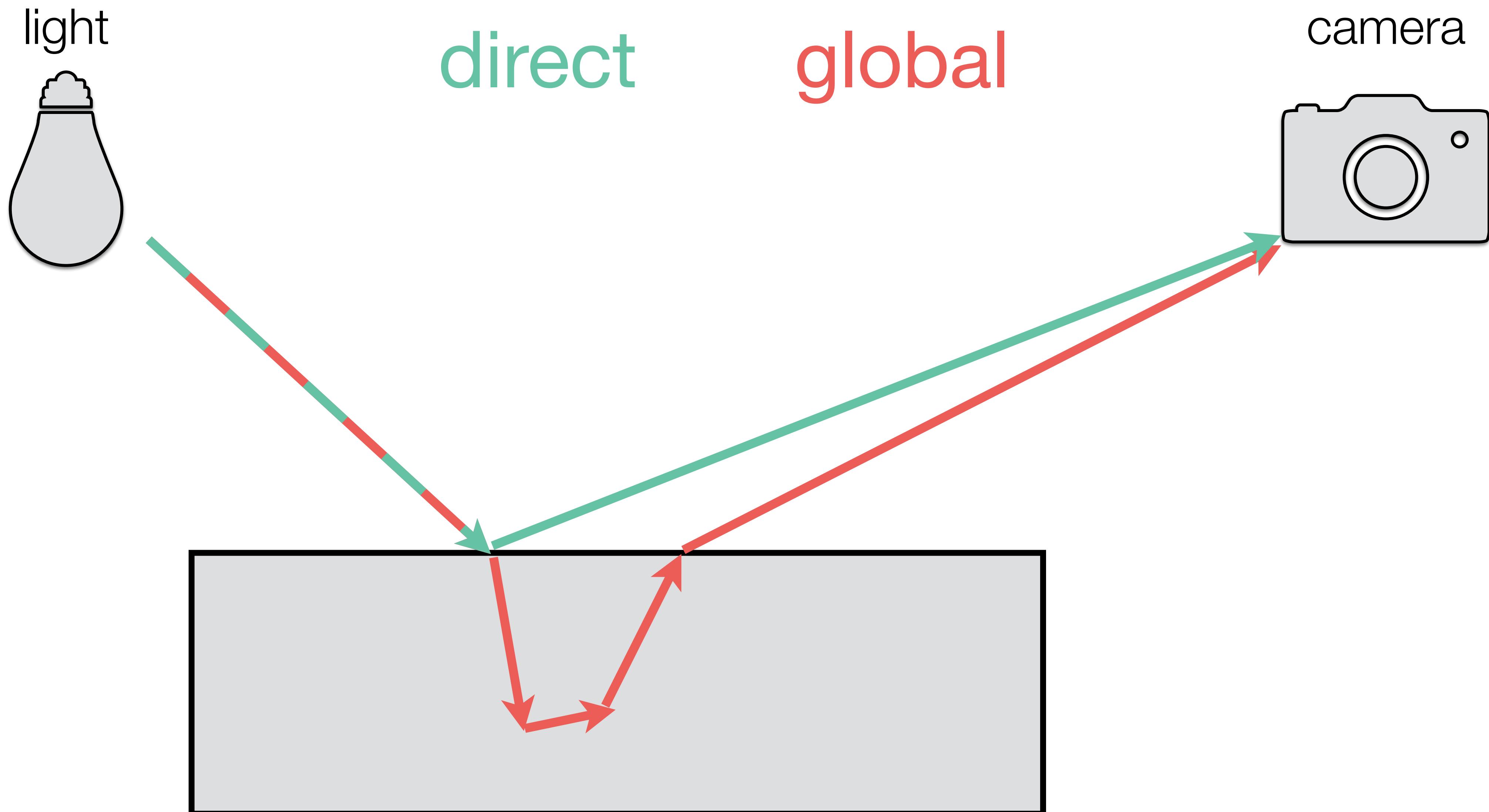
Light Transport



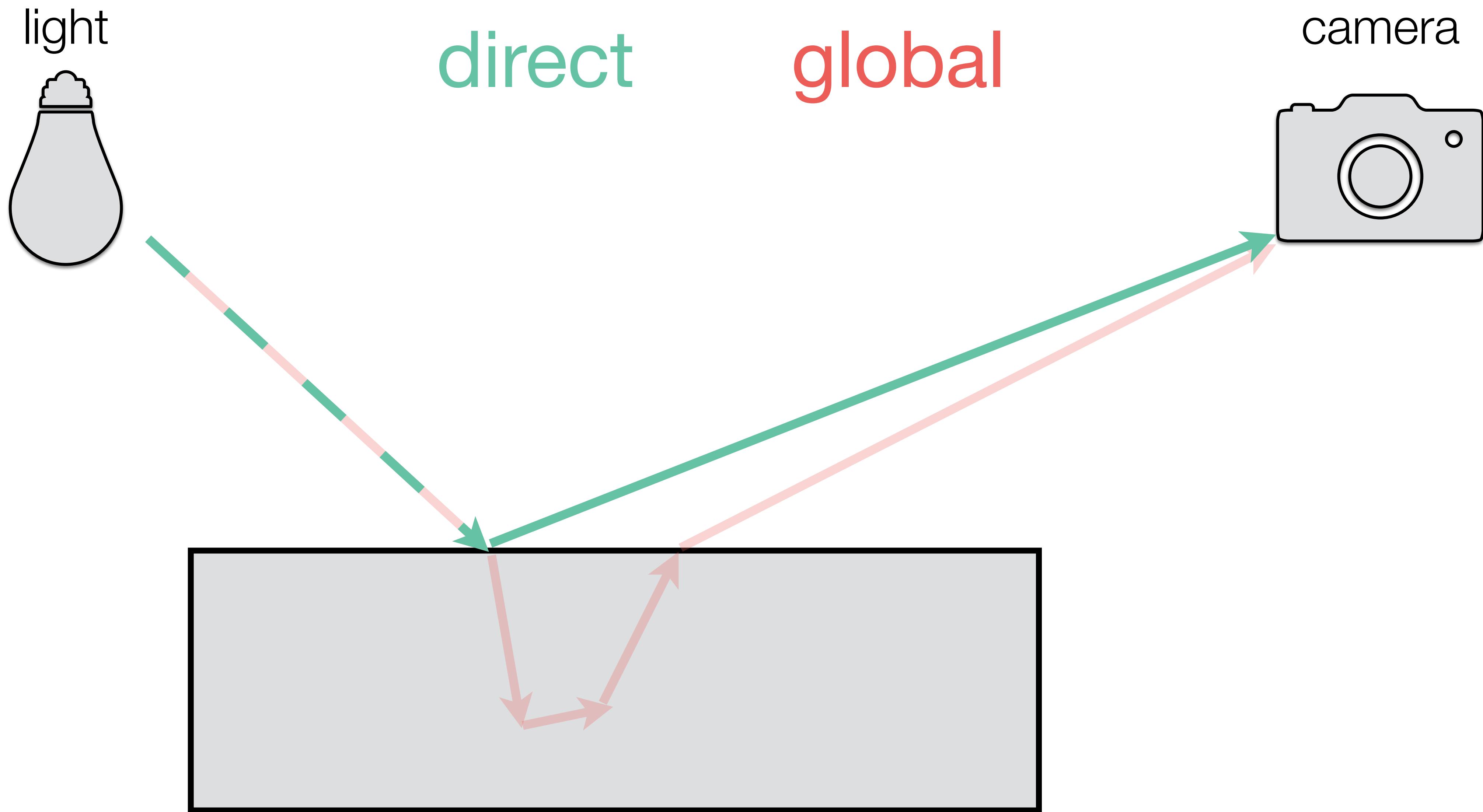
Light Transport



Combined



Combined



Visual Appearance

idea: embed unobtrusive tags in the global component

1. How to guarantee the tags are invisible?
2. How to detect the global component?

Separate Global Component

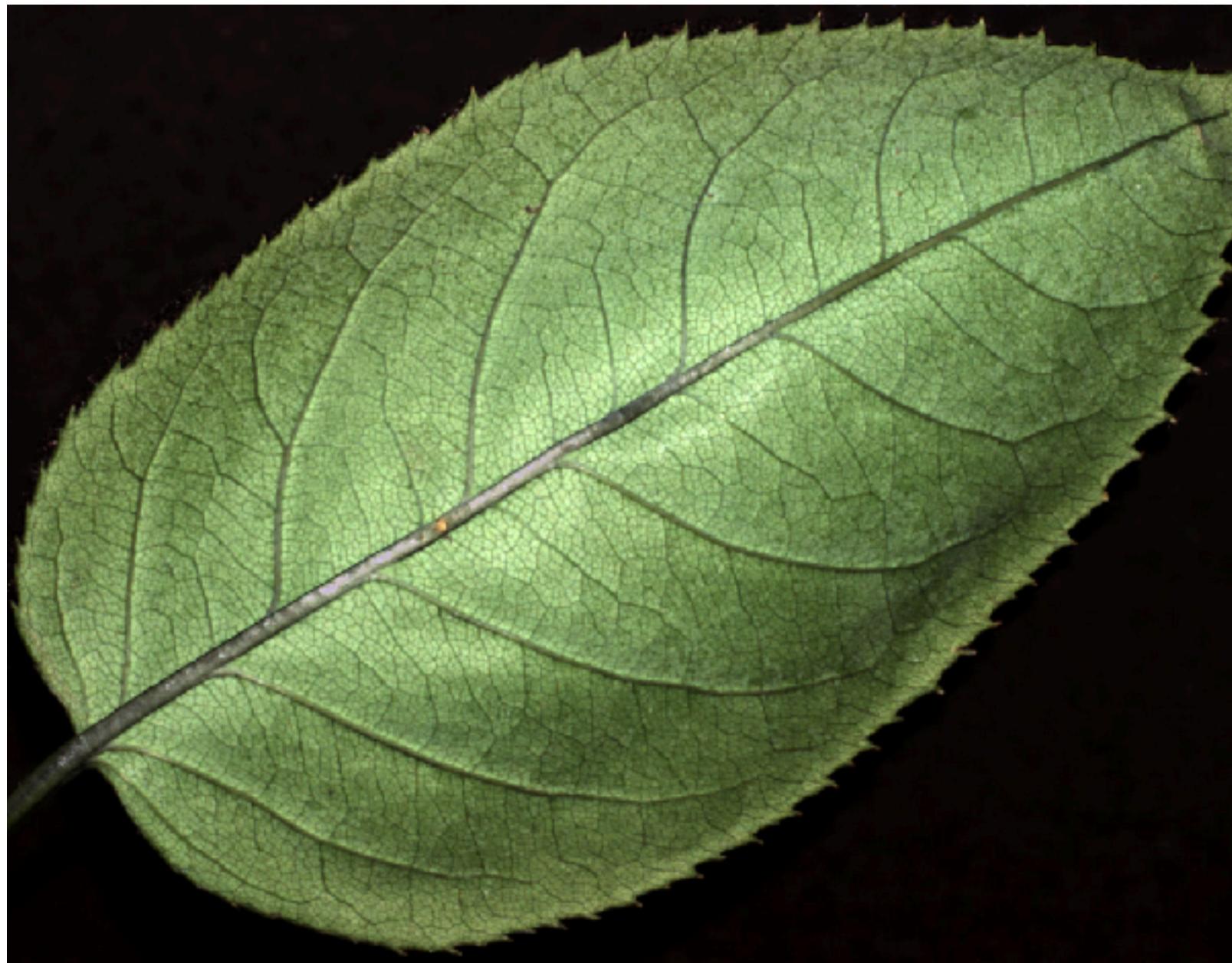
[Nayar et al., SIGGRAPH 2006]



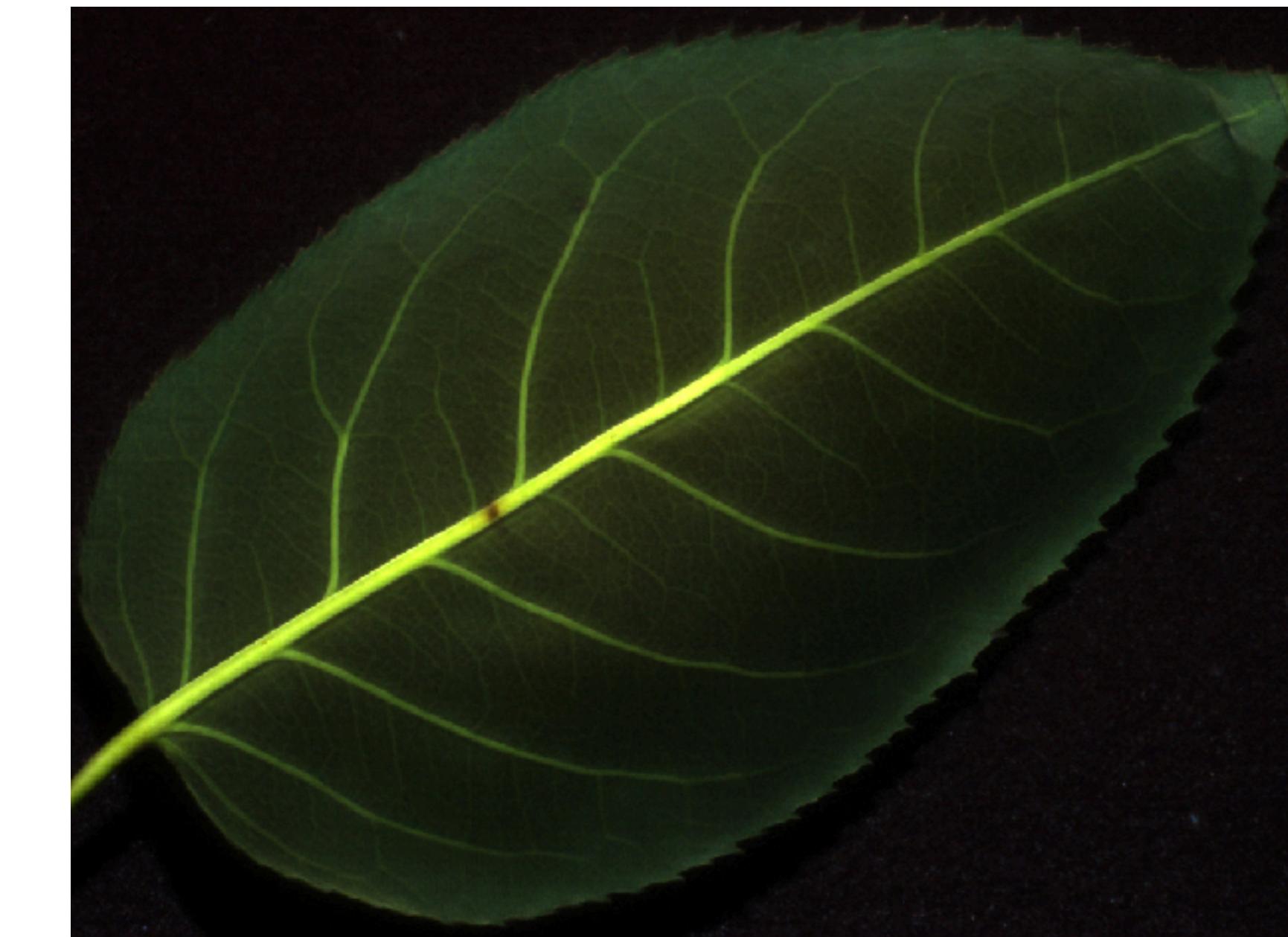


[Nayar et al., SIGGRAPH 2006]

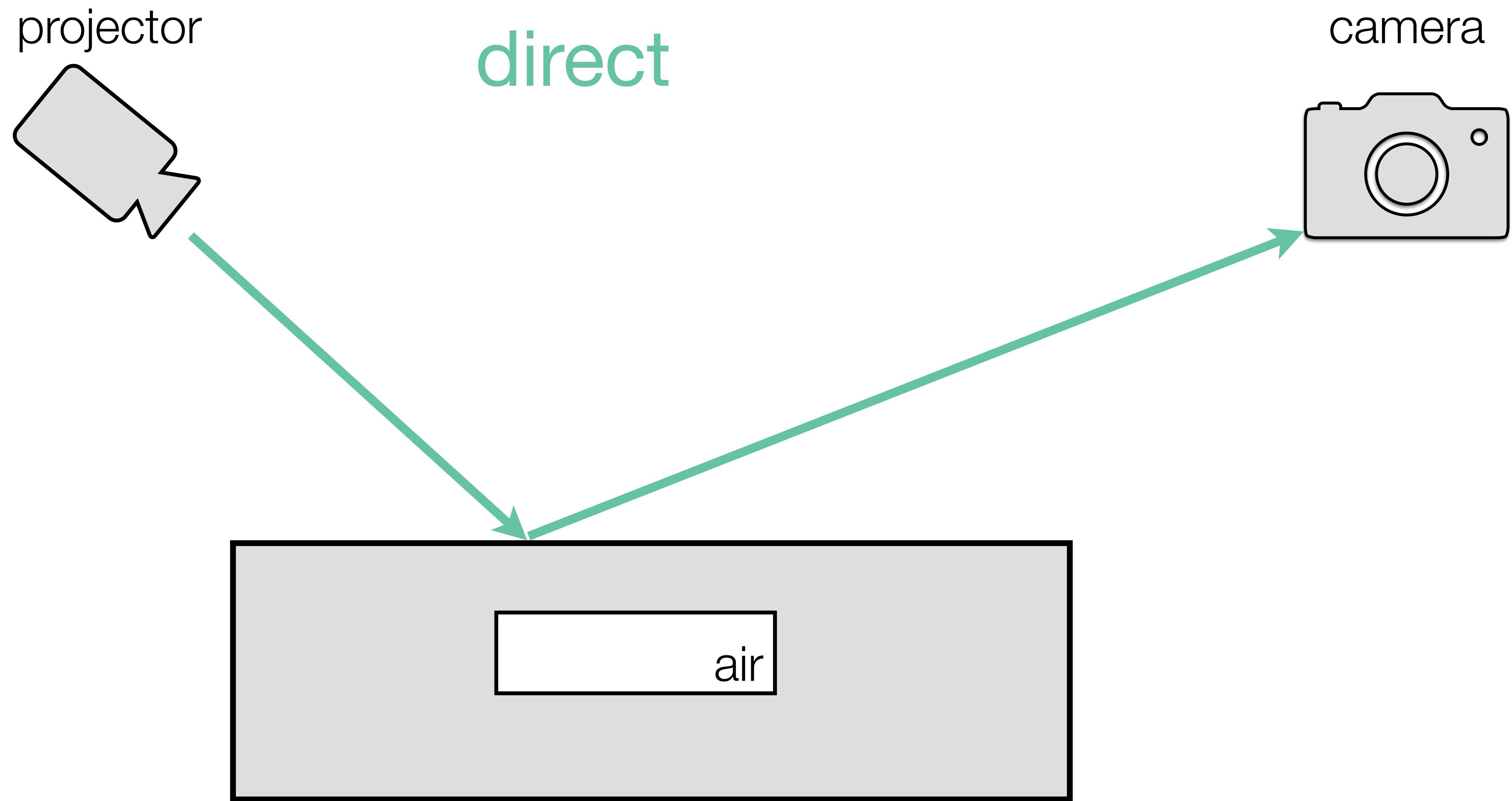
direct



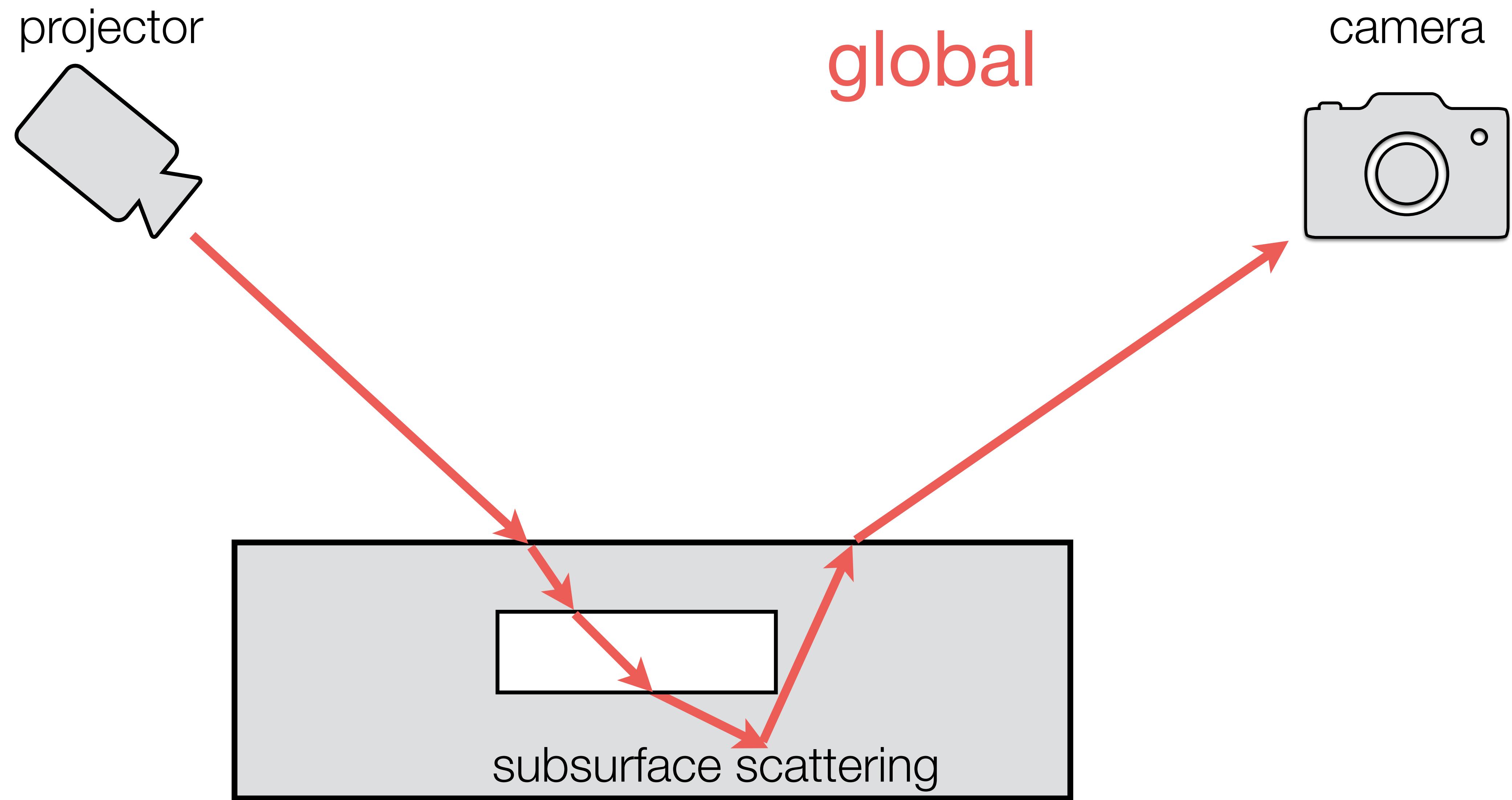
global



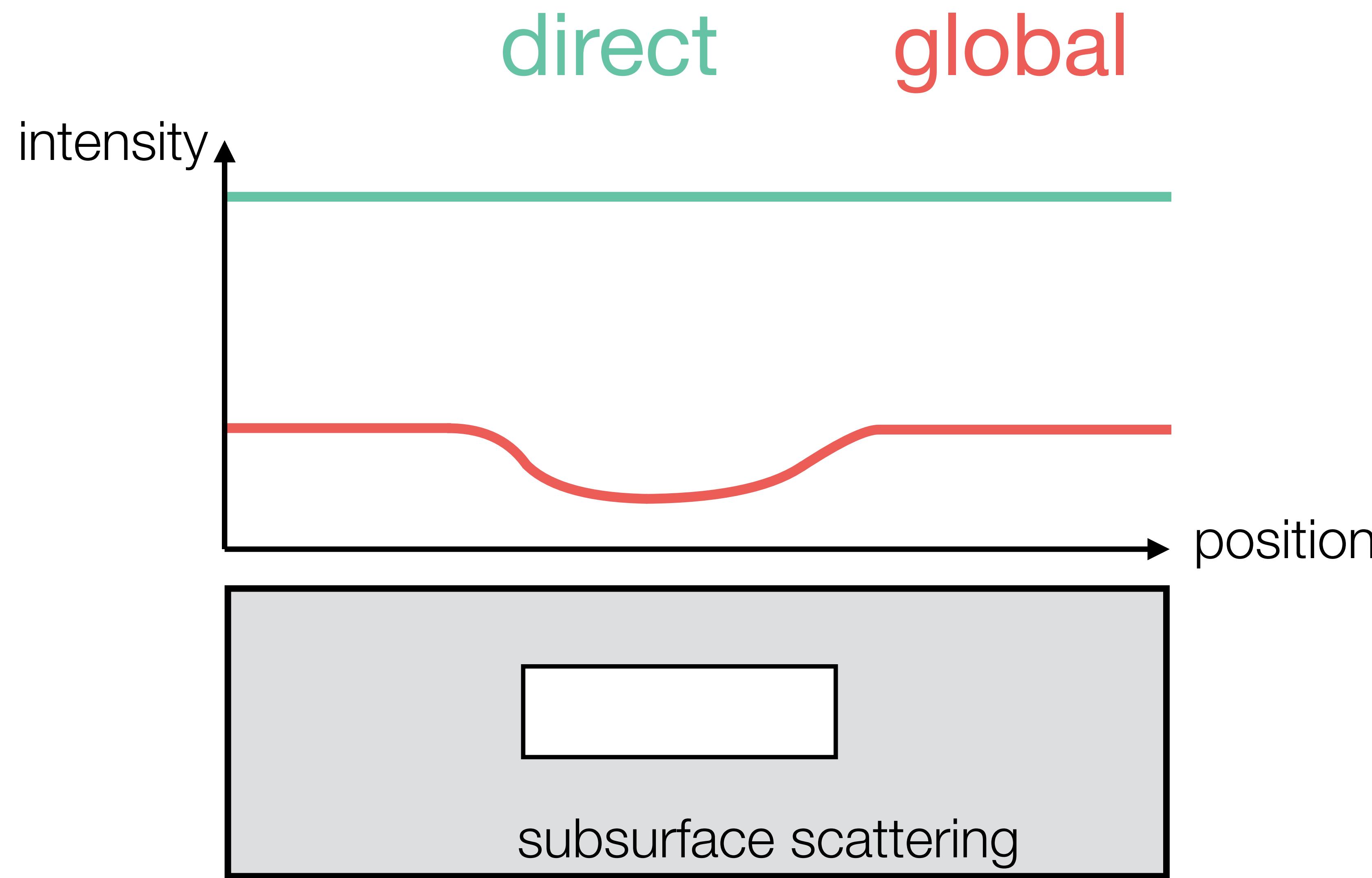
Air Pockets



Air Pockets

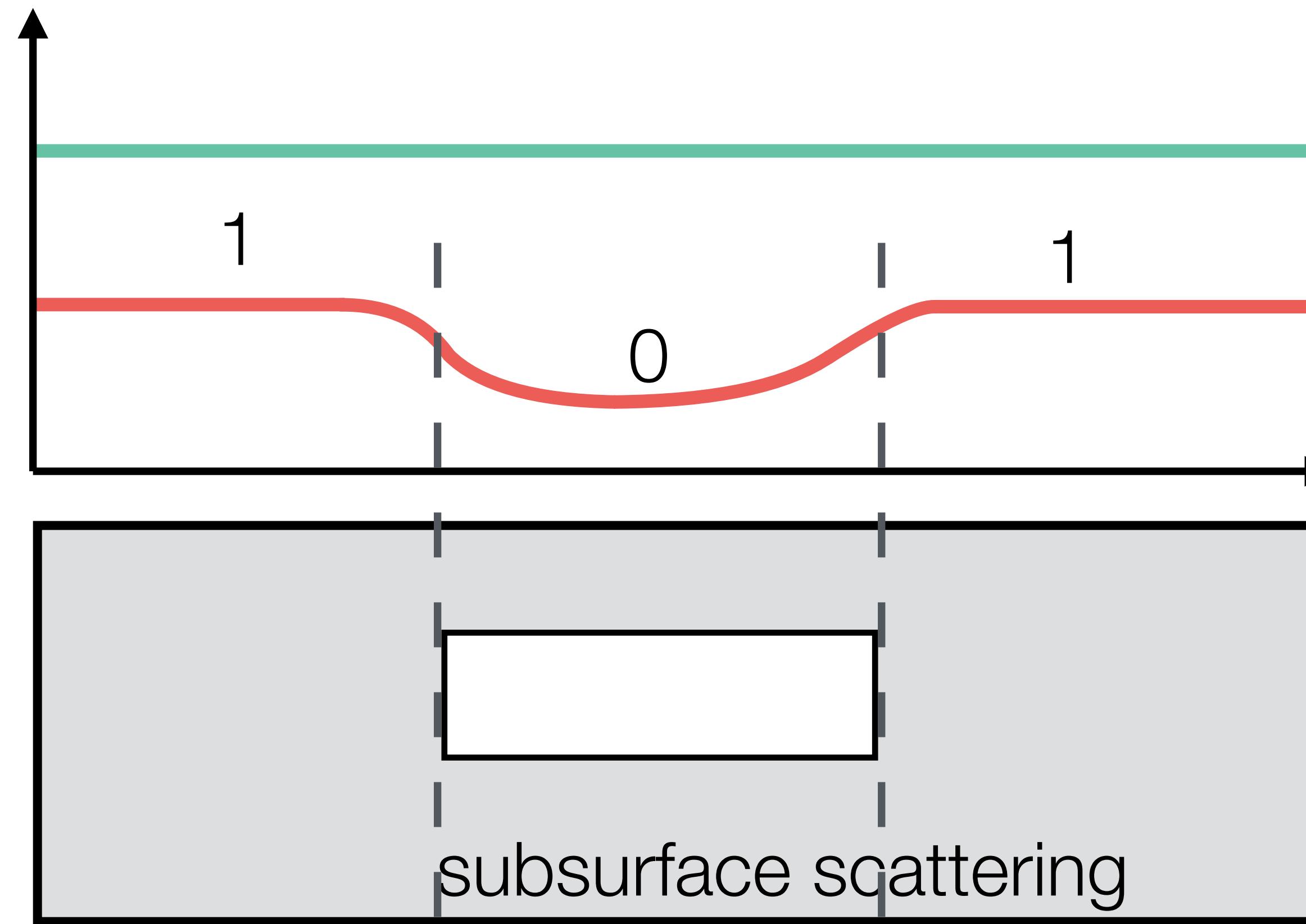


Air Pockets



Air Pockets

direct global



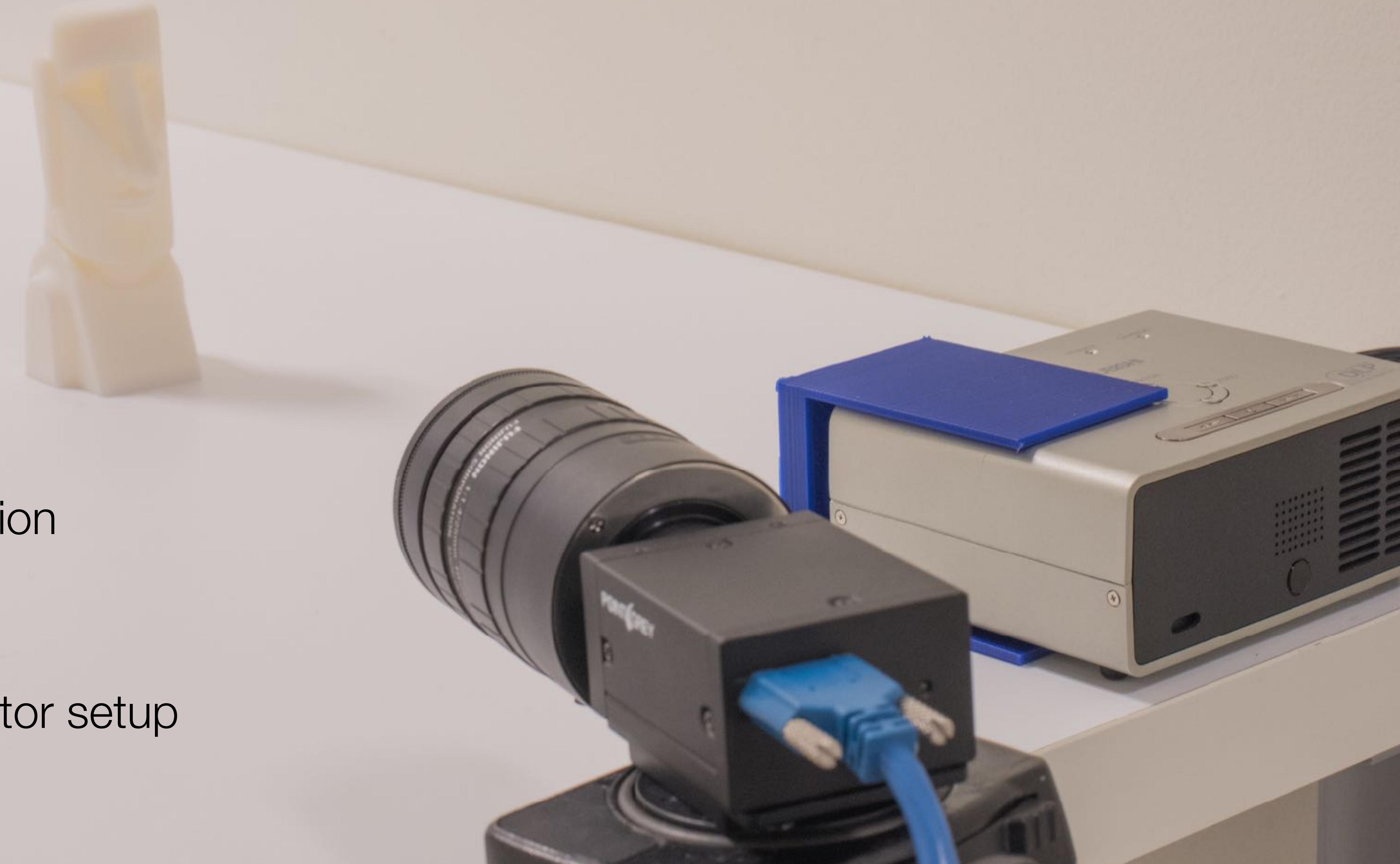
AirCode Layout

1 0 1

→ Markers
→ Data Bits
→ Calibration Bits

AirCode Benefits

- during fabrication
- invisible
- camera/projector setup



Invisibility: Contrast Threshold

Contrast threshold is the minimal contrast required to see the target reliably.

Invisibility: Contrast Threshold

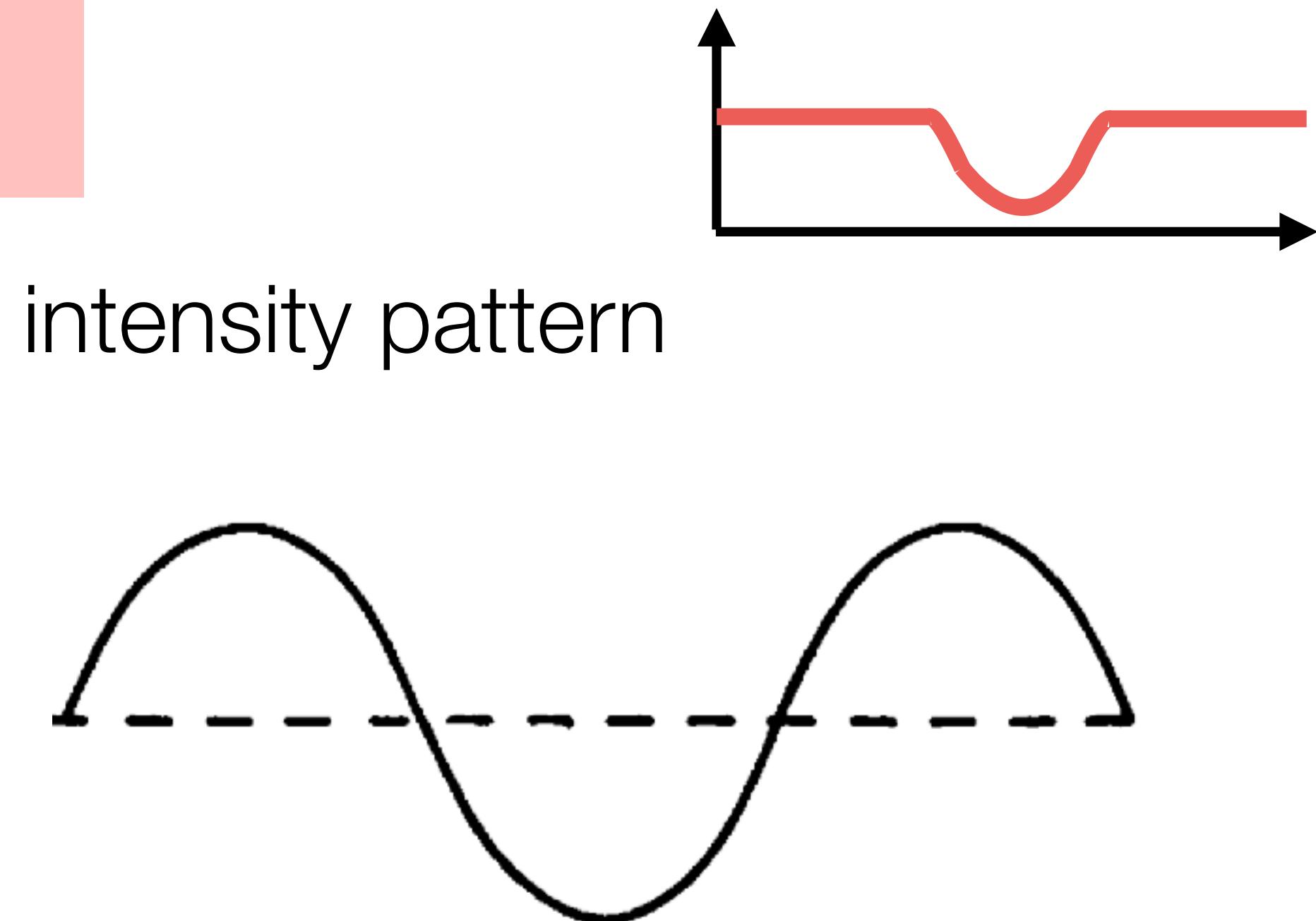
Contrast threshold is the minimal contrast required to see the target reliably.

contrast

$$= \frac{L_{max} - L_{min}}{\bar{L}}$$

0.1% - 10%

intensity pattern

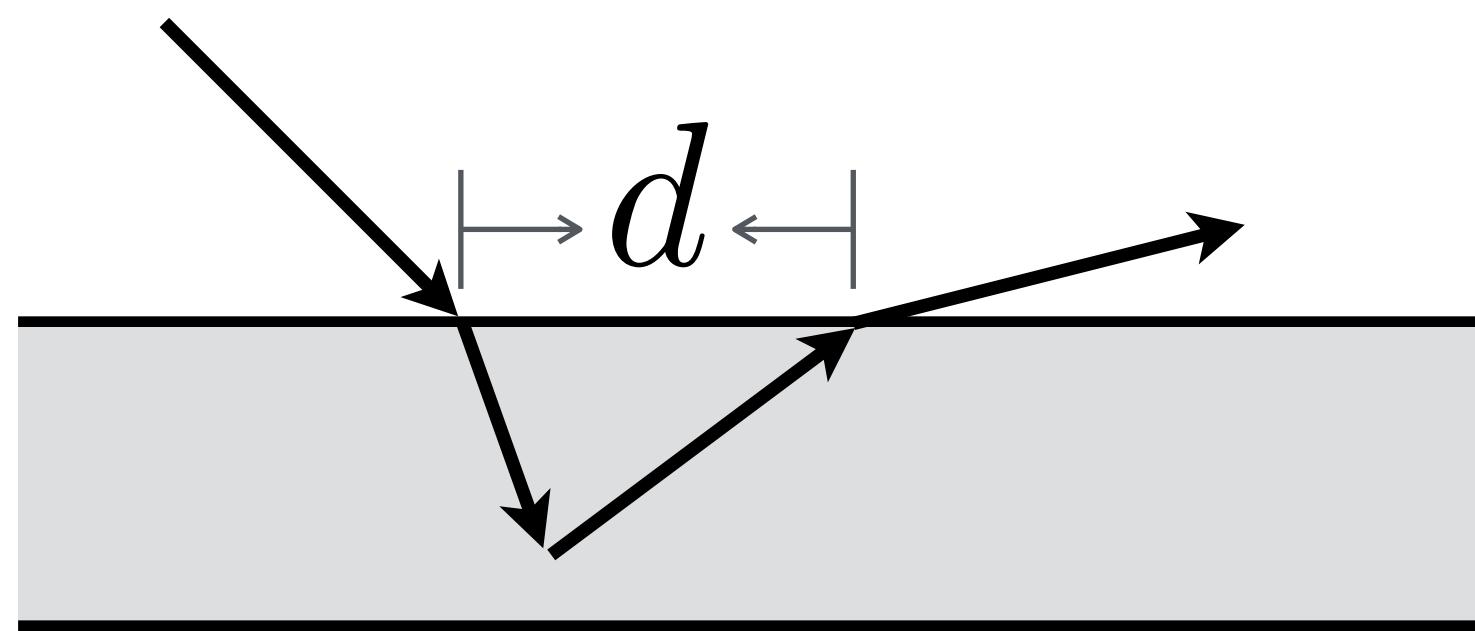


[Campbell and Robson, Journal of Physiology 1968]

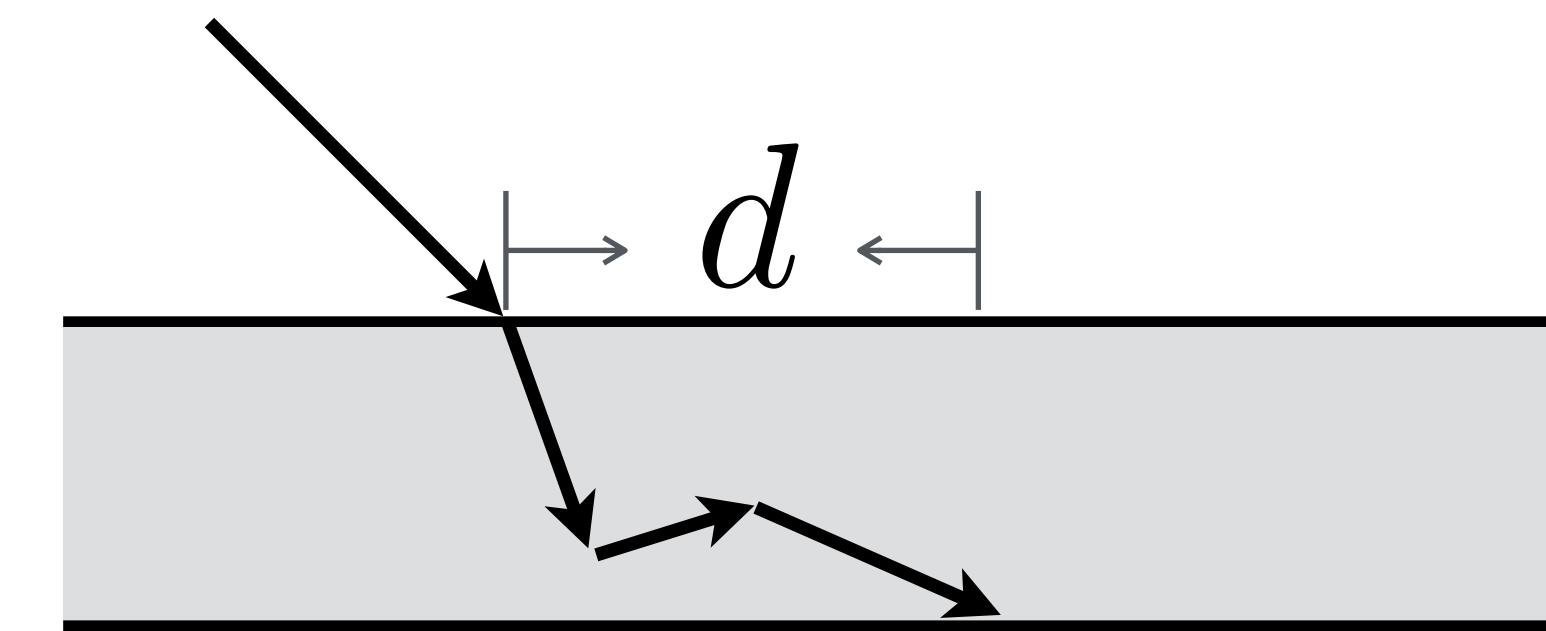
[Bijl et al., Vision Research 1989]

Layered Scattering Model

Reflection profile $R(d)$



Transmission profile $T(d)$



- multi-layer reflection profile

[Donner and Jensen, SIGGRAPH 2005]

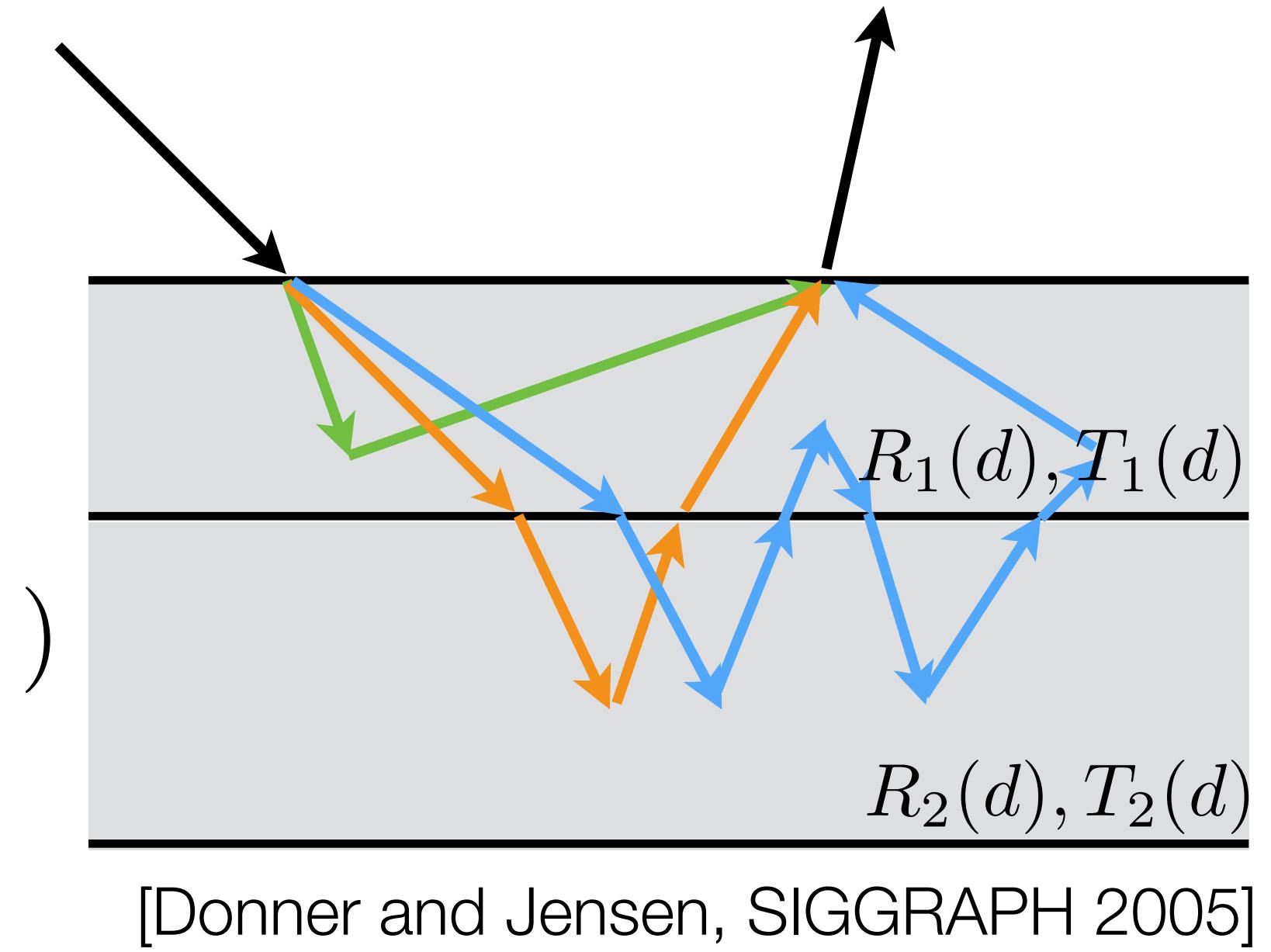
Multi-Layer Profile

$$R(d) = R_1 + T_1 R_2 T_1 + T_1 R_2 R_1 R_2 T_1 + \dots$$

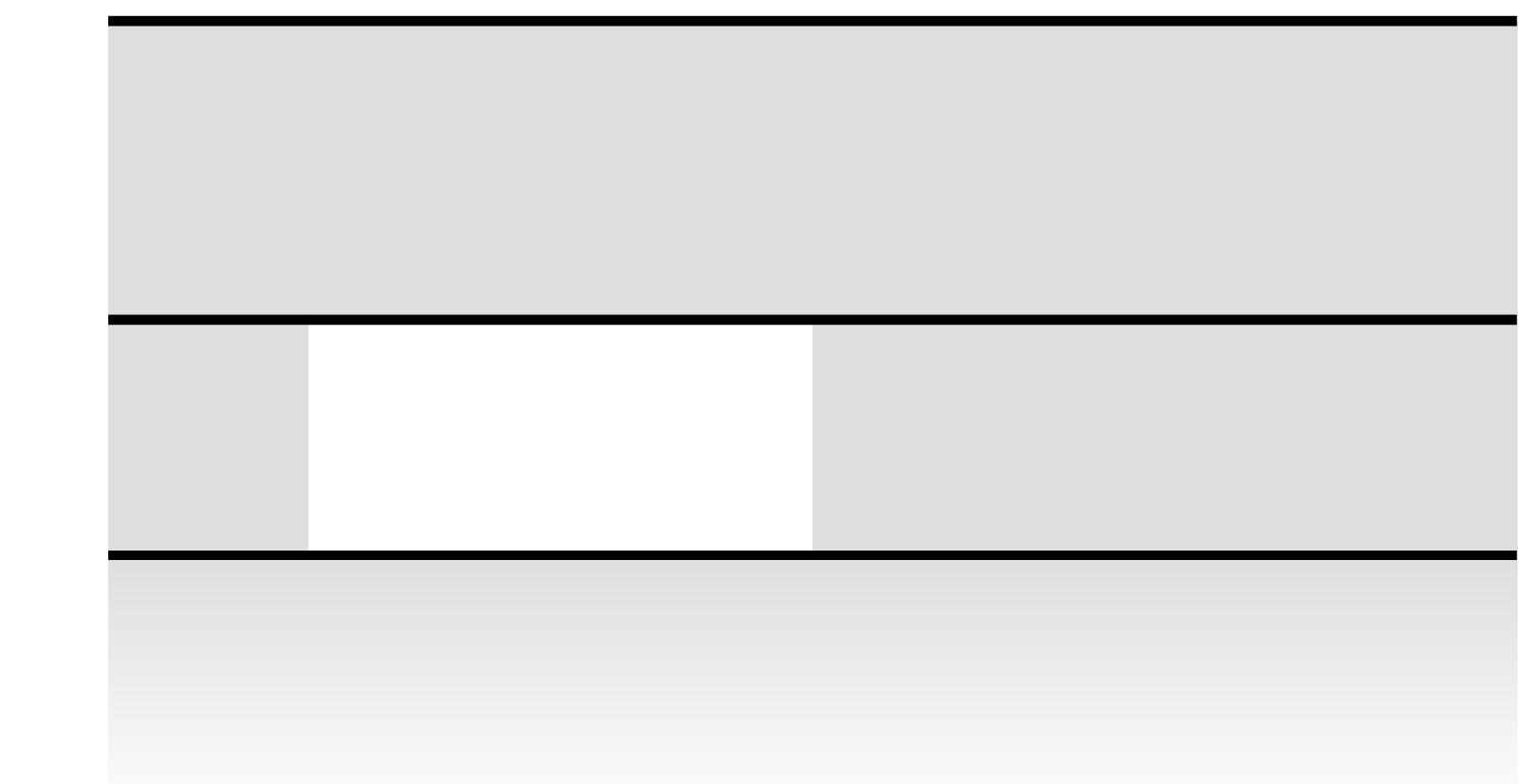
0-bounce 1-bounce 2-bounce

$$= R_1 + T_1 R_2 T_1 (1 + R_1 R_2 + (R_1 R_2)^2 + \dots)$$

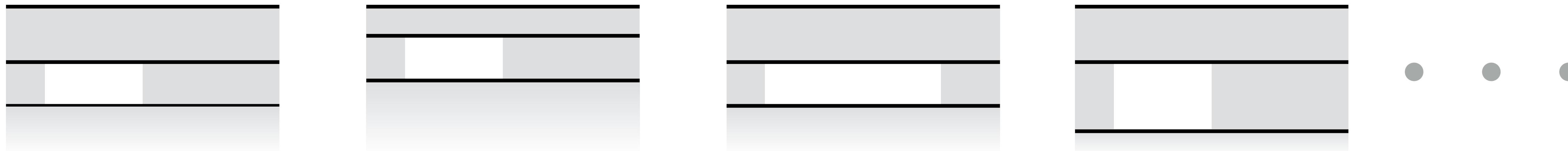
$$= R_1 + \frac{T_1 R_2 T_1}{1 - R_1 R_2}$$



Efficient computation for layered material

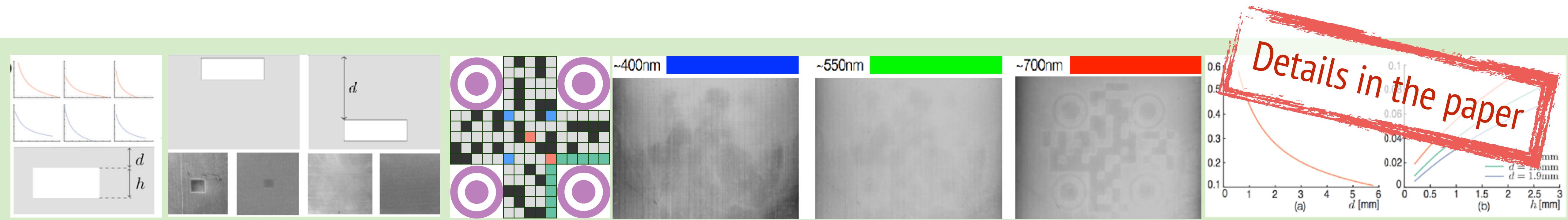


Putting it together



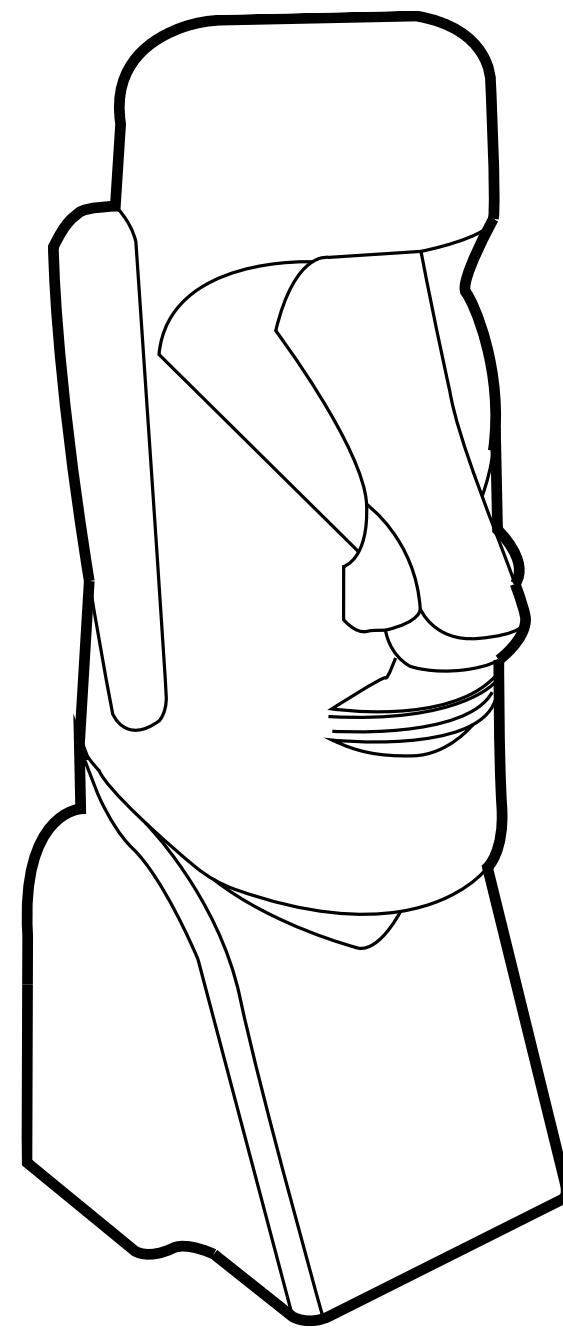
$$R(d) = R_1 + T_1 R_2 T_1 + T_1 R_2 R_1 R_2 T_1 + \dots + 0.1\% - 10\%$$

0-bounce 1-bounce 2-bounce

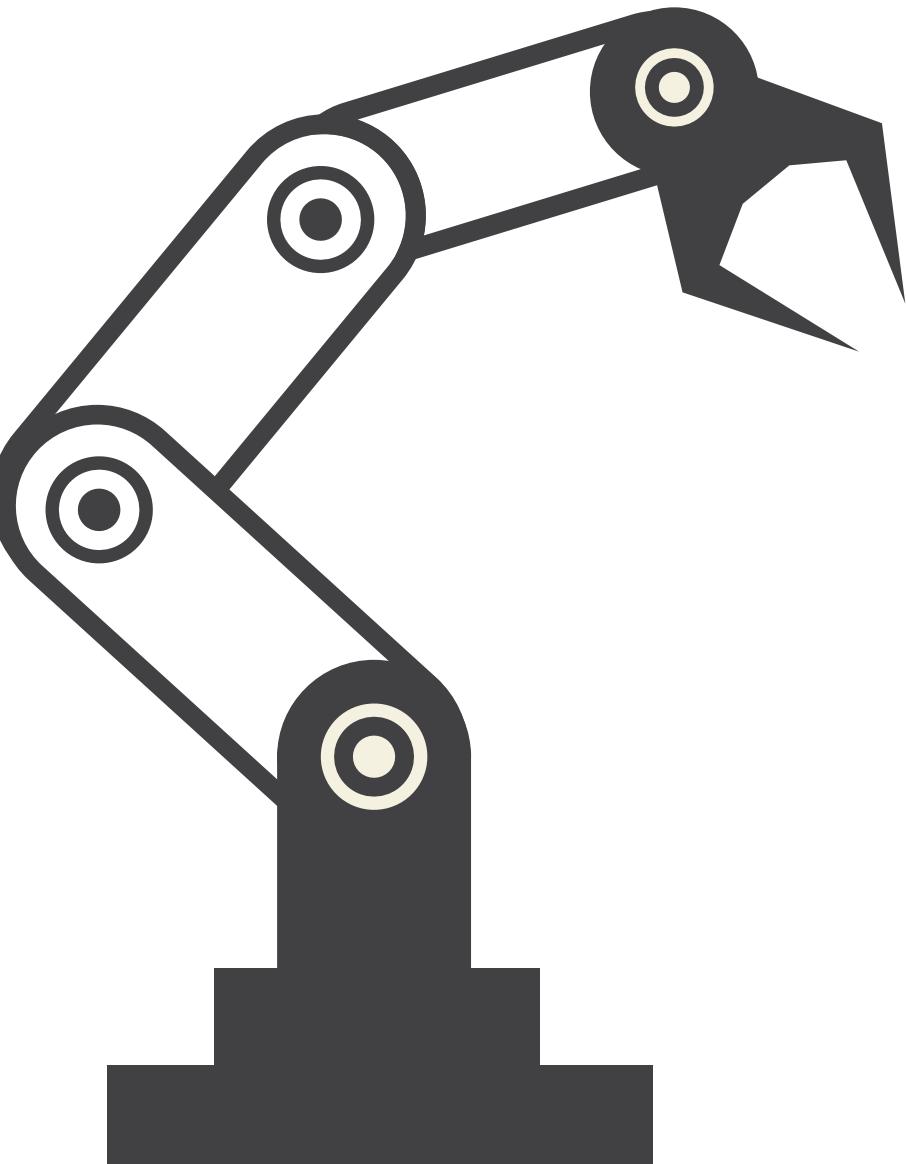


Applications

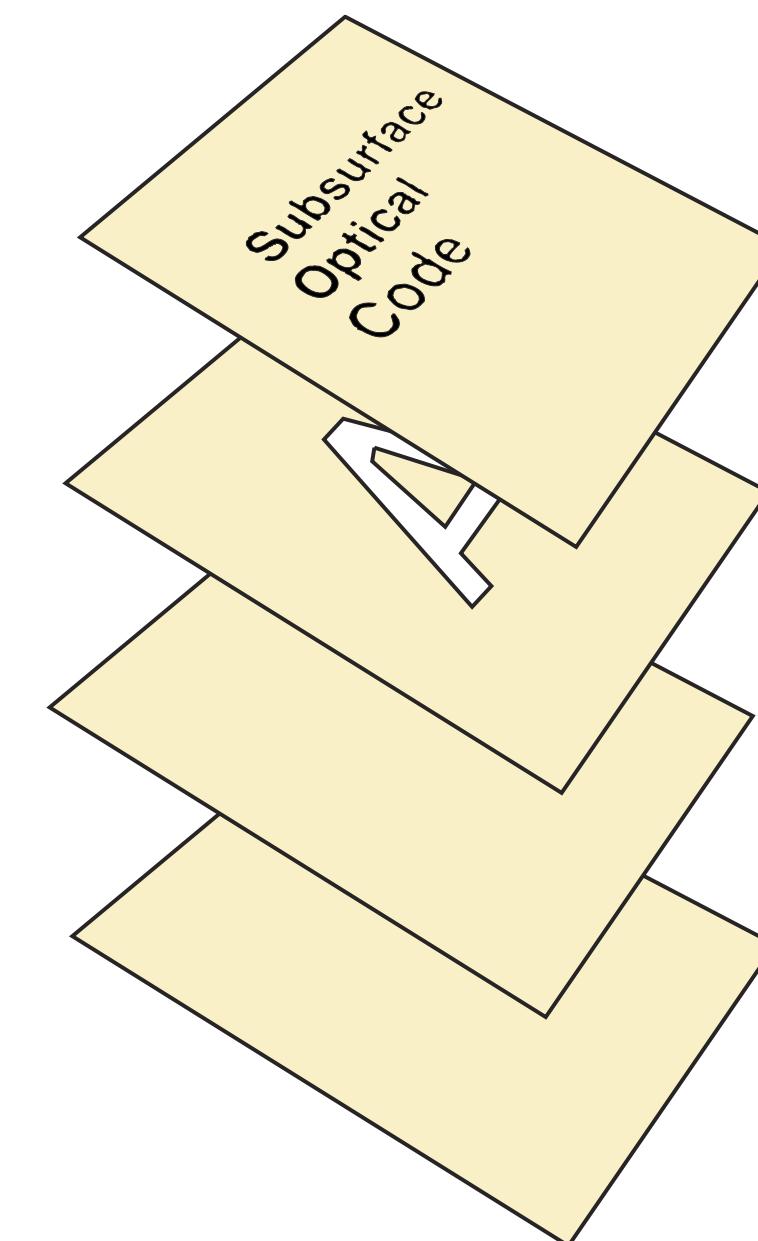
metadata embedding



robotic grasping

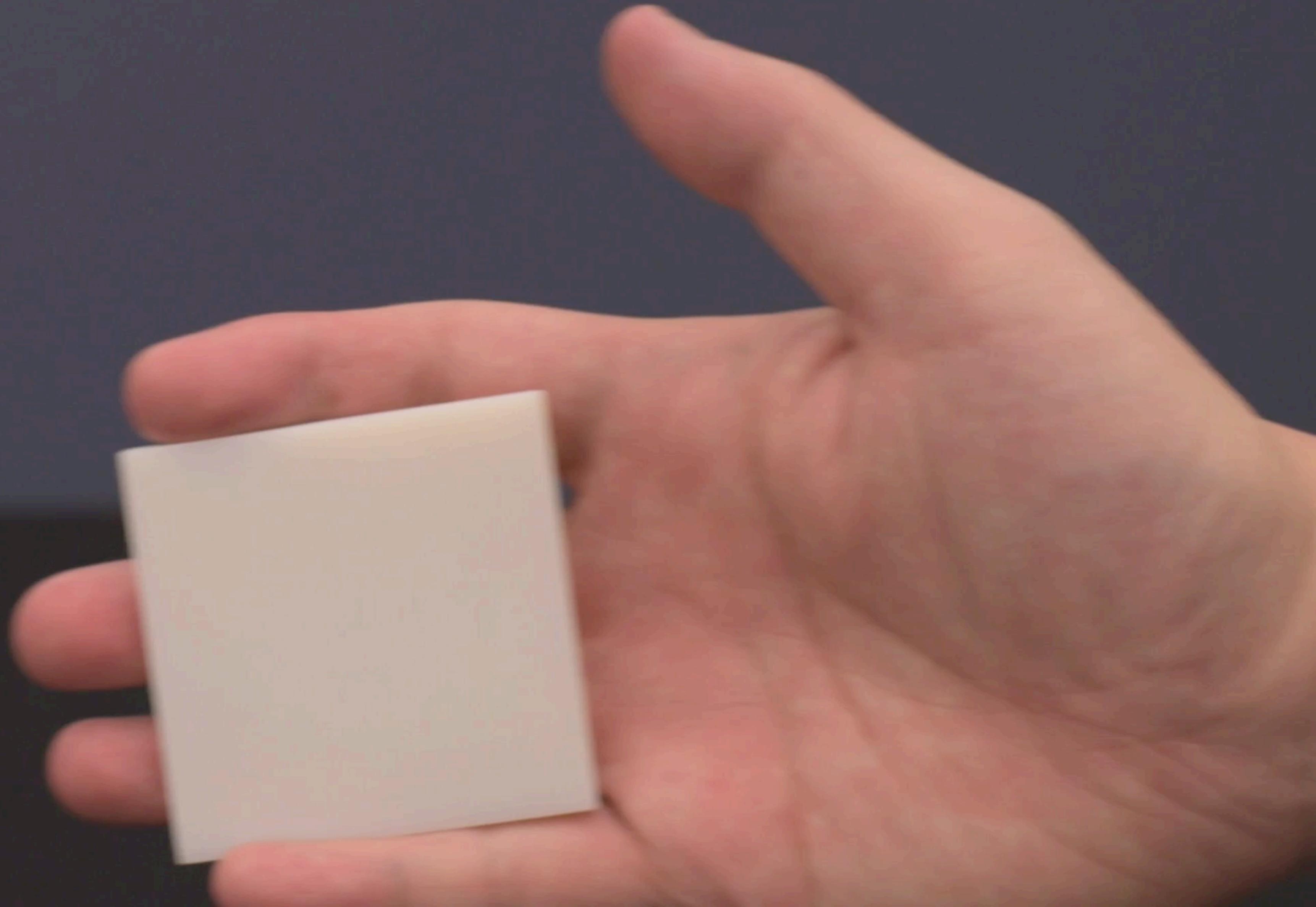


paper watermarking

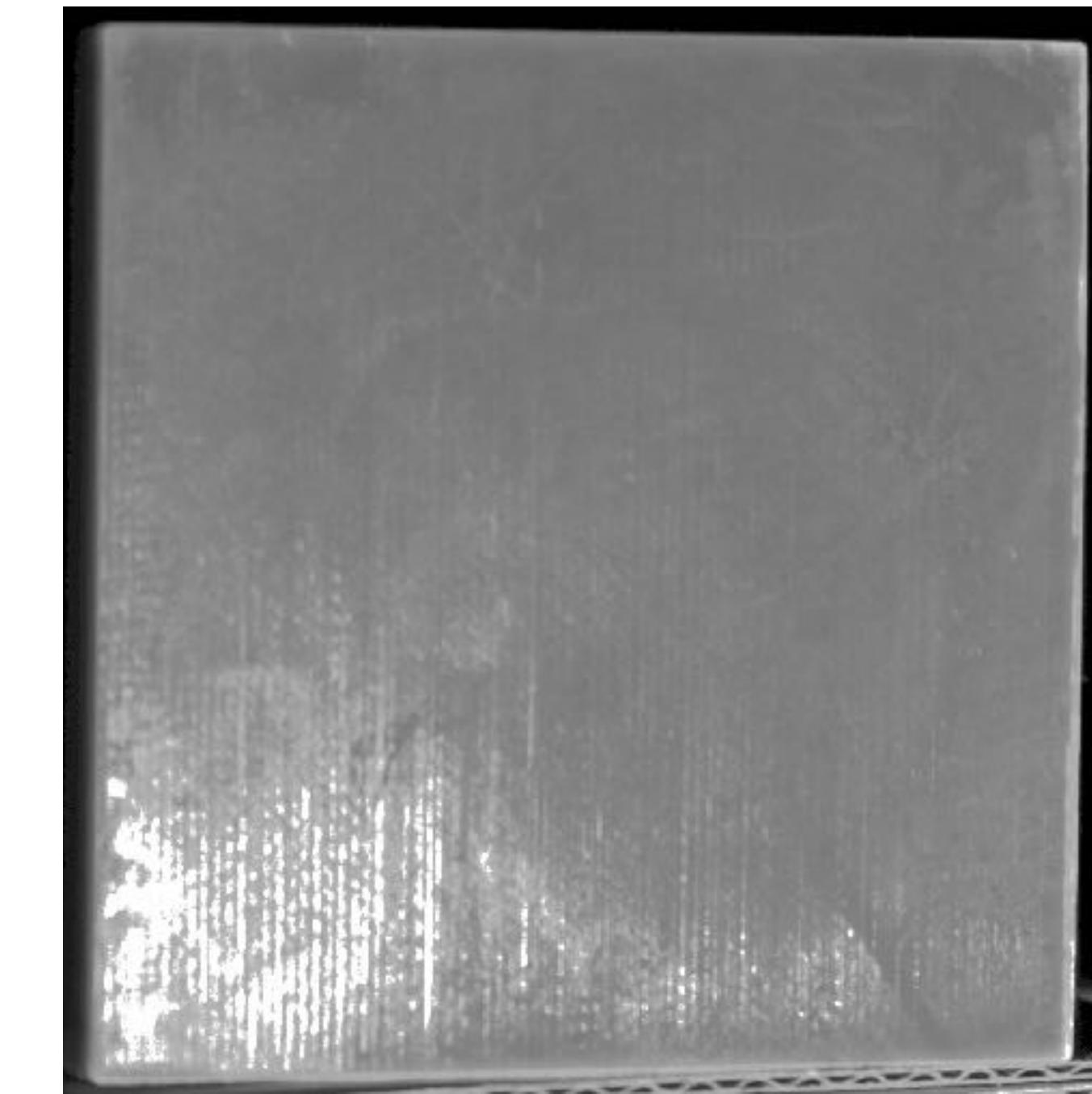
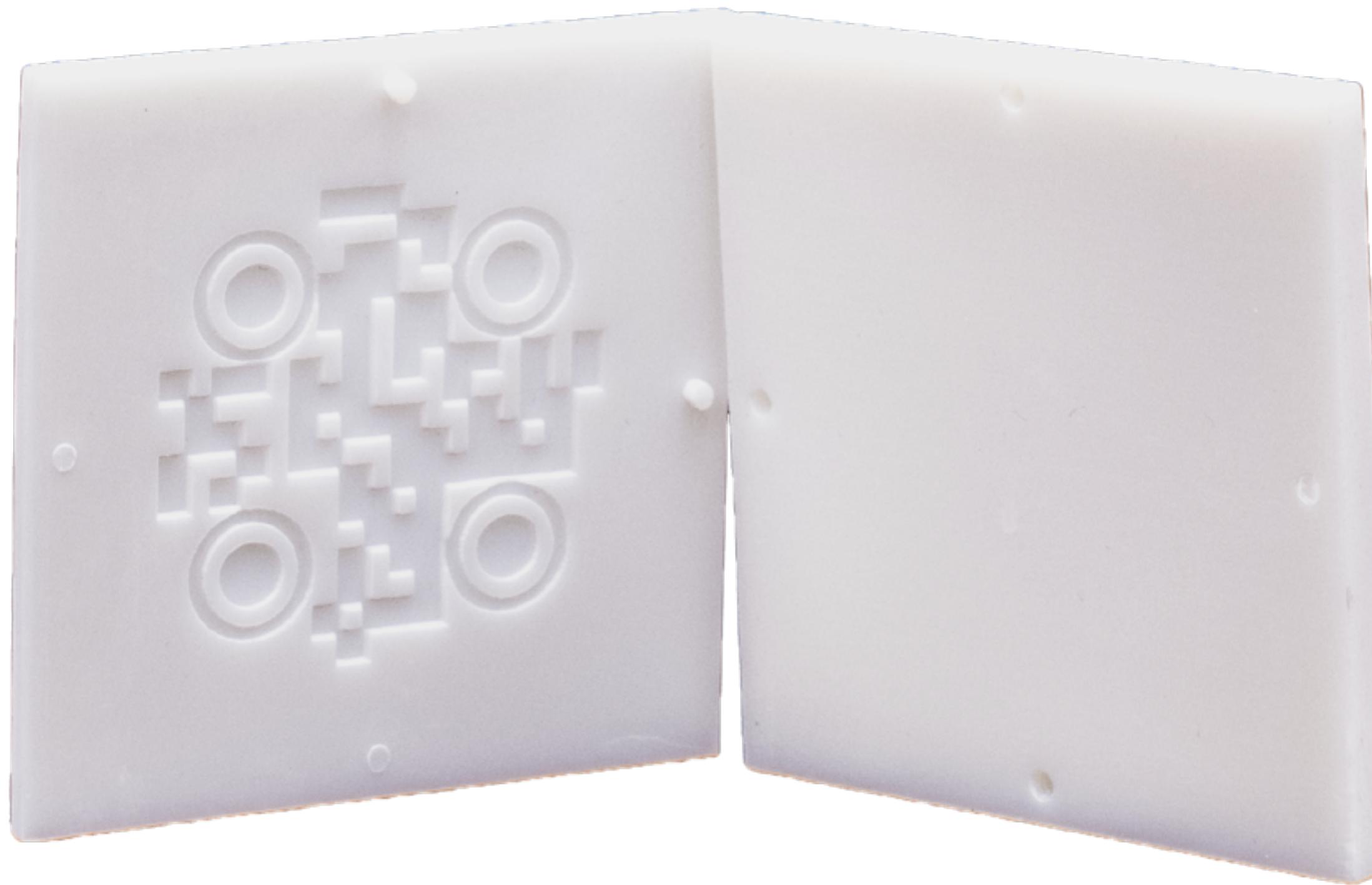


Metadata Embedding

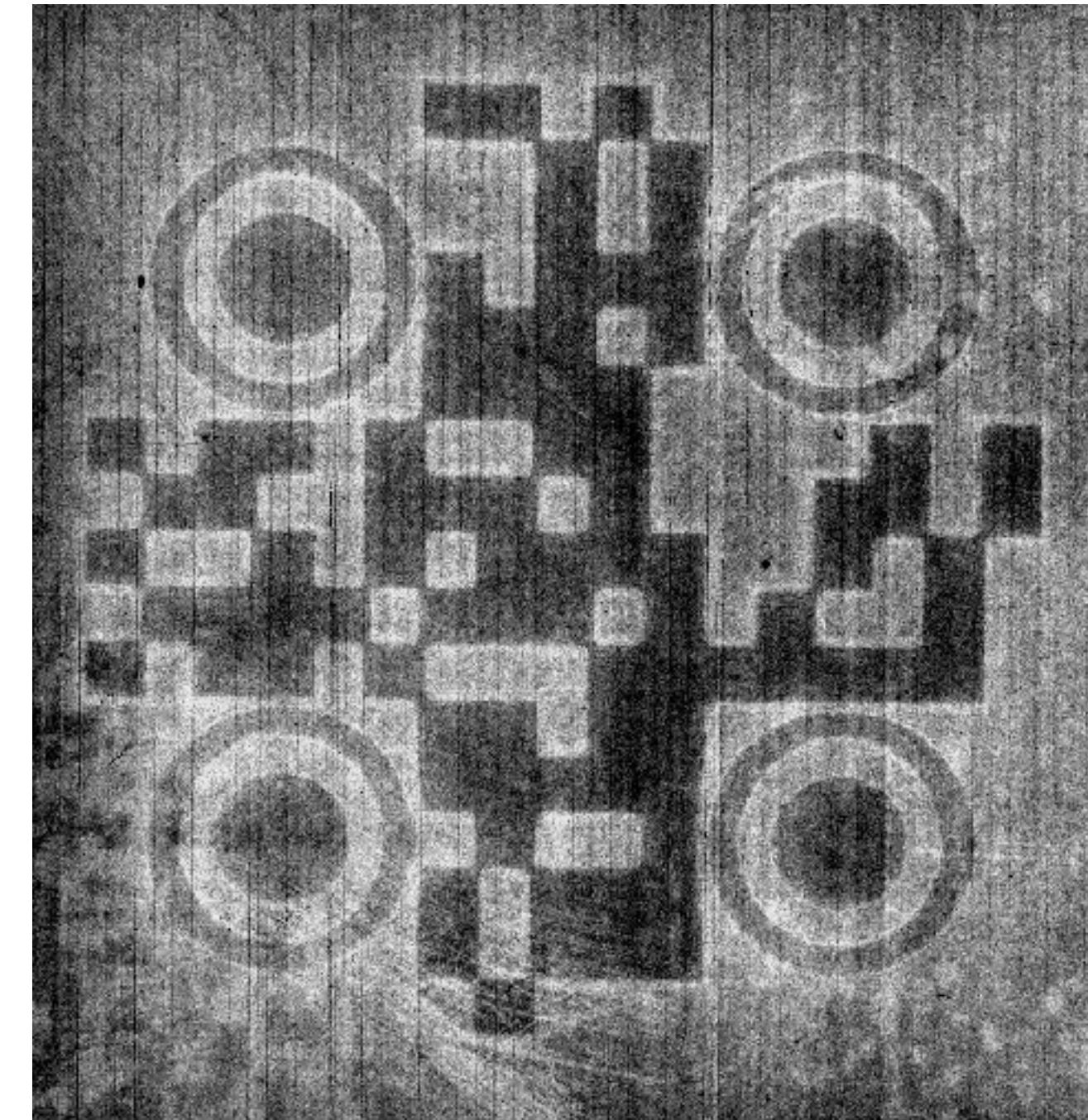
Metadata Embedding



Metadata Embedding



direct

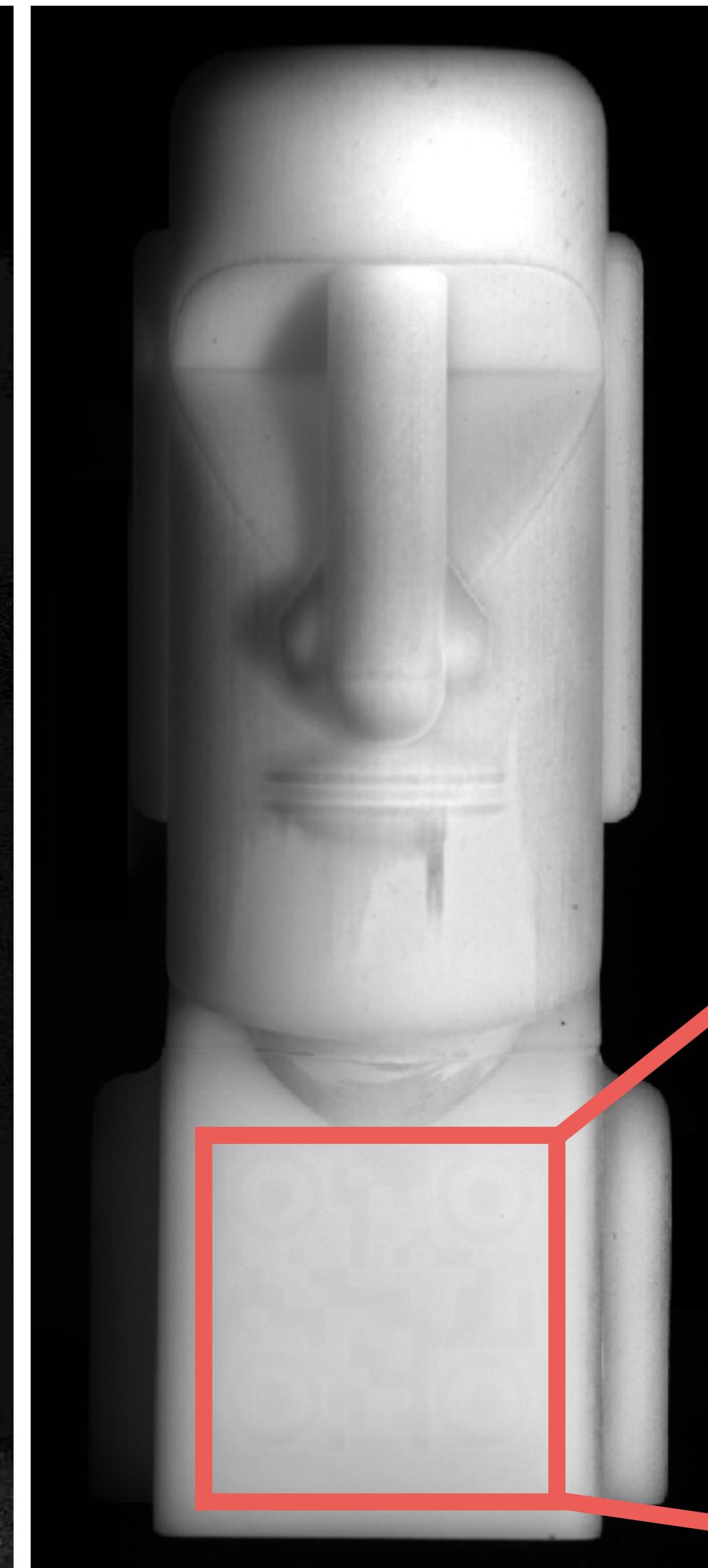
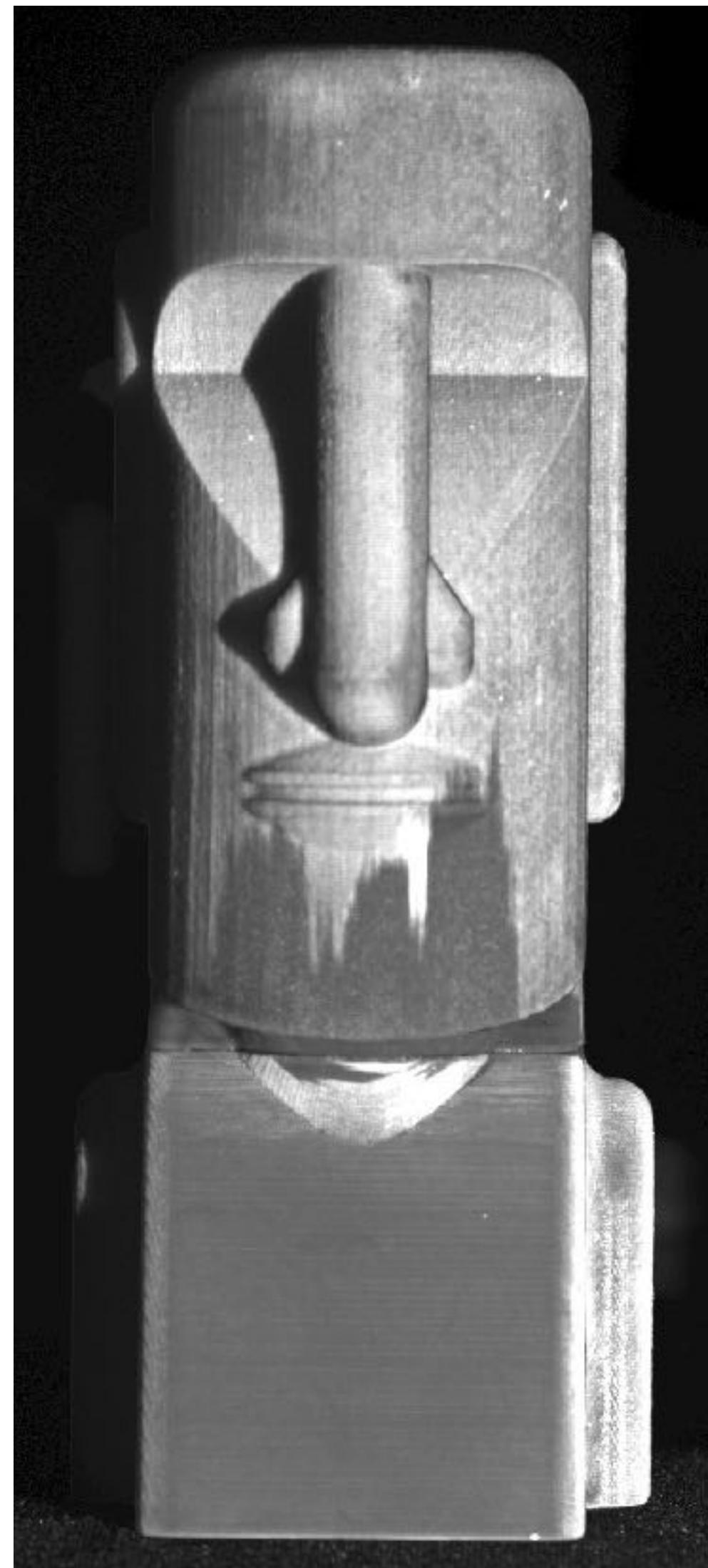


global
“visibility”

Physical Hyperlink



Physical Hyperlink

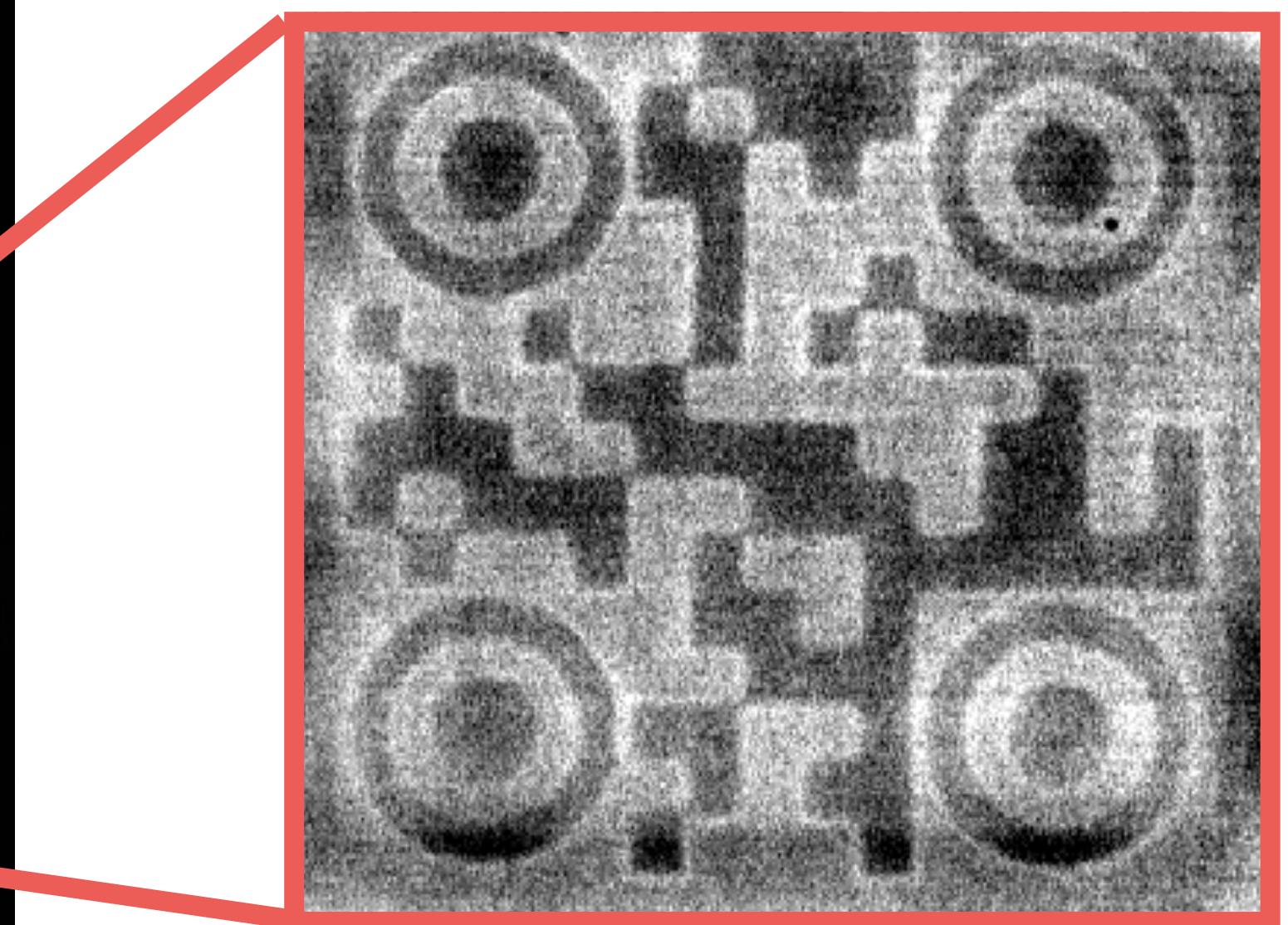


Moai

This article is about the monolithic statues of Easter Island. For other uses, see [Moai \(disambiguation\)](#).

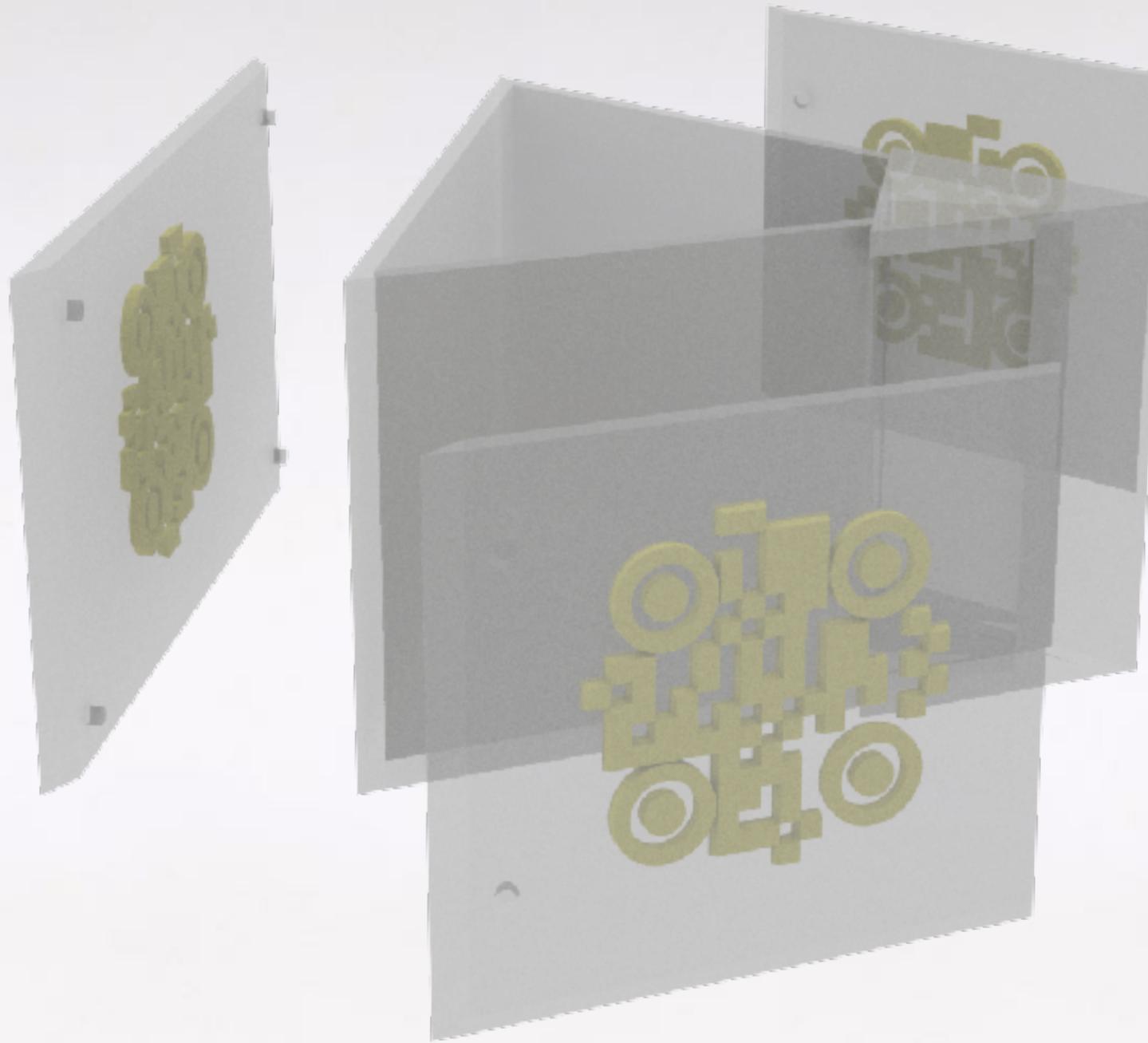
Moai [/moʊ.æɪ/](#), or [mo'āi](#), are monolithic human figures carved by the [Rapa Nui people](#) on [Easter Island](#) in eastern Polynesia between the years 1250 and 1500.^{[1][2]} Nearly half are still at [Rano Raraku](#), the main moai quarry, but hundreds were transported from there and set on stone platforms called [ahu](#) around the island's perimeter. Almost all moai have overly large heads three-eighths the size of the whole statue. The moai are chiefly the living faces (*aringa ora*) of deified ancestors (*aringa ora ata tepuna*).^[3] The statues still gazed inland across their clan lands when Europeans first visited the island in 1722, but all of them had fallen by the latter part of the 19th century.^[4]

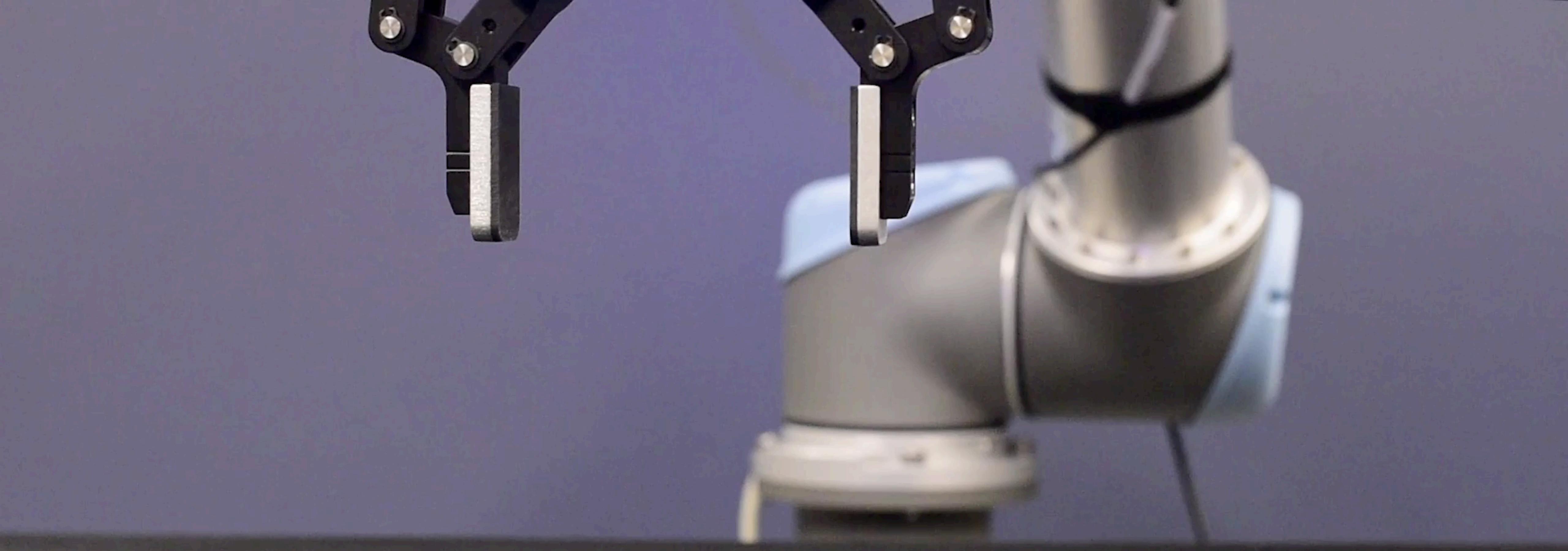
 Moai facing inland at [Ahu Tongariki](#), restored by Chilean archaeologist Claudio Cristino in the 1990s

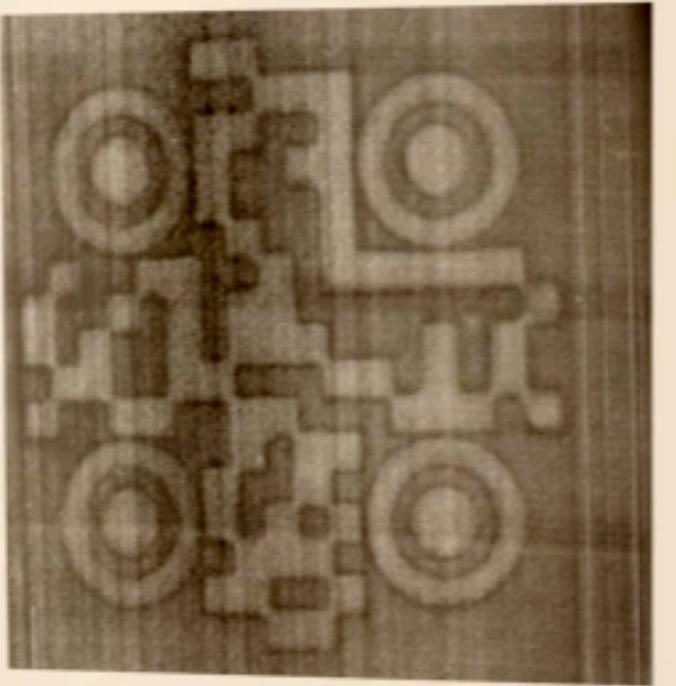


Robotic Grasping

recognition - pose estimation - grasping location







Beyond 3D Printing Materials



Paper Watermarking

Can you see the text?

Can you see the text?

global component

Air Pockets in Paper

Separation Results

imperceptible
adjective
impossible to perceive.

subsurface
adjective
located beneath a surface.

code
noun
a system of words, letters, figures, or other symbols substituted for other words, letters, etc., especially for the purposes of secrecy.

direct

imperceptible
adjective
impossible to perceive.

subsurface
adjective
located beneath a surface.

code
noun
a system of words, letters, figures, or other symbols substituted for other words, letters, etc., especially for the purposes of secrecy.

global

Separation Results

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subsurface
adjective
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noun
a system of words, letters, figures, or other symbols substituted for other words, letters, etc., especially for the purposes of secrecy.

mask

imperceptible
adjective
impossible to perceive.

subsurface
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located beneath a surface.

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noun
a system of words, letters, figures, or other symbols substituted for other words, letters, etc., especially for the purposes of secrecy.

global

Separation Results

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code
noun
a system of words, letters, figures, or other symbols substituted for other words, letters, etc., especially for the purposes of secrecy.

mask



filtered global

Conclusion

AirCode to Tag Physical Objects

embedded during fabrication

unobtrusive

robust decoding with camera/projector

non-opaque material

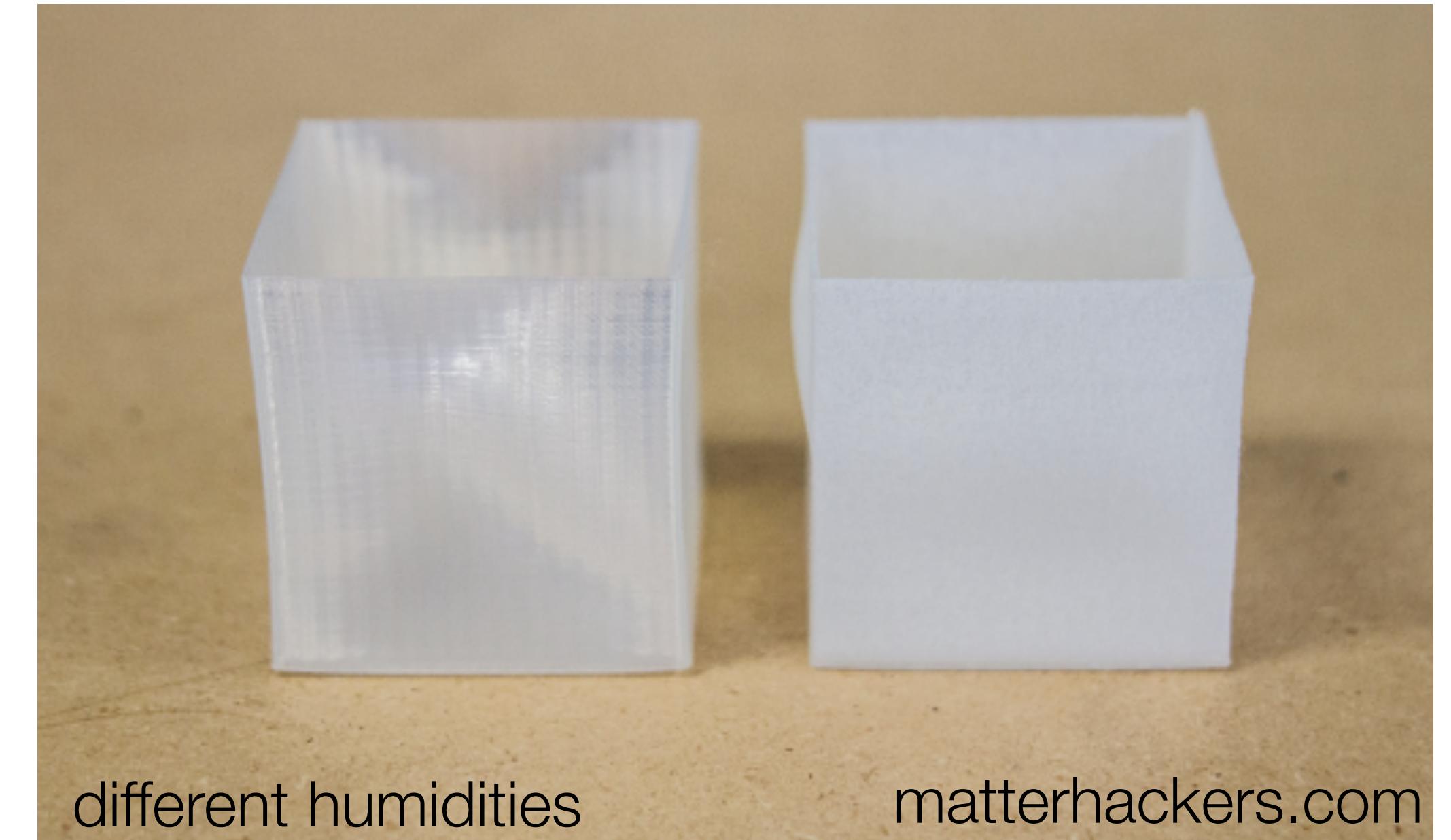
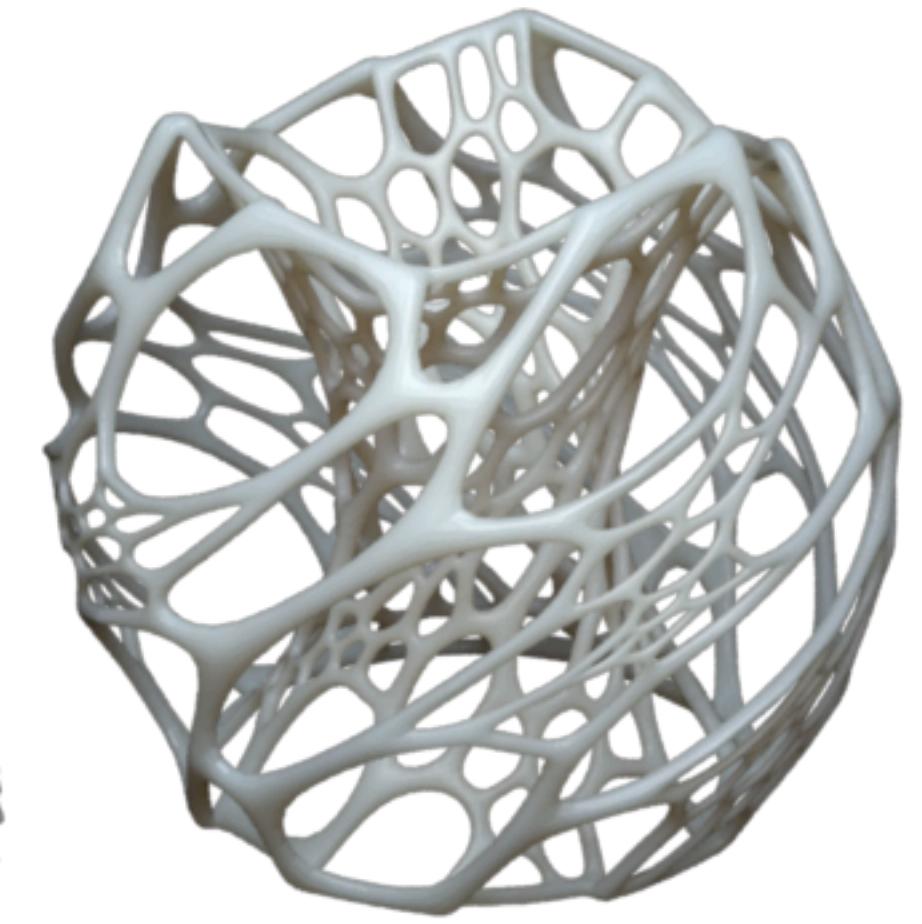
Limitations and Future Work

capture time

non-smooth surface

long-term preservation

changeability



matterhackers.com

Acknowledgement

Arthur Autz, Daniel Miau, Brian A. Smith, Henrique Teles Maia, Yonghao Yue,
Shuang Zhao, Clint Qinami, Anne Fleming, Daniel Sims, Jason Hollaway

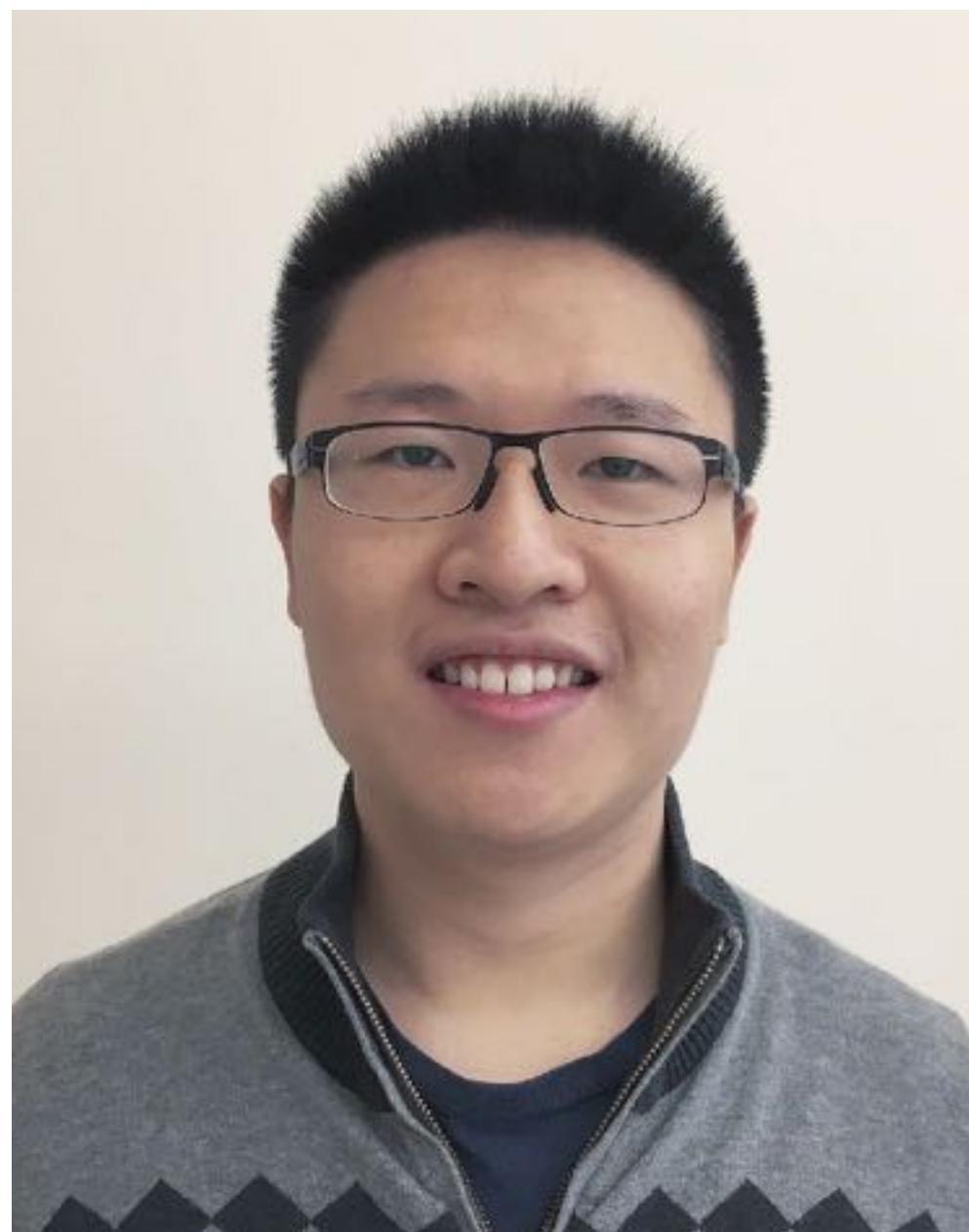
Thingiverse.com users: Filar3D, mbeyerle116, gravityisweak, Tinyeyes,

National Science Foundation (CAREER-1453101)
Adobe PhD Research Fellowship



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<http://ding.fyi/aircode>



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