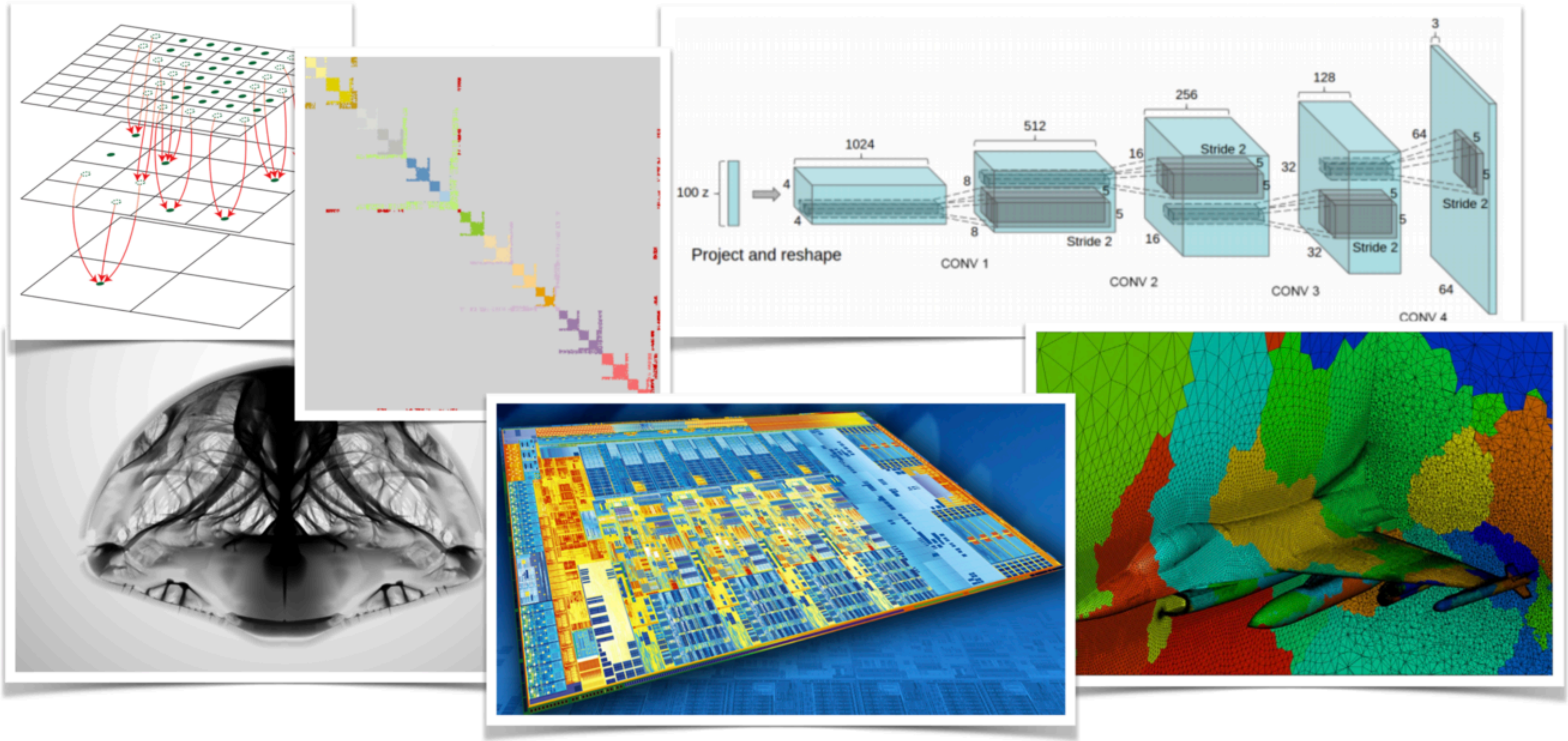


Welcome to CS639!

Undergraduate Topics In Computing: Parallel and Throughput-Optimized Programming

Spring 2020, 2:30-3:45 Tue/Thu

Today's lecture

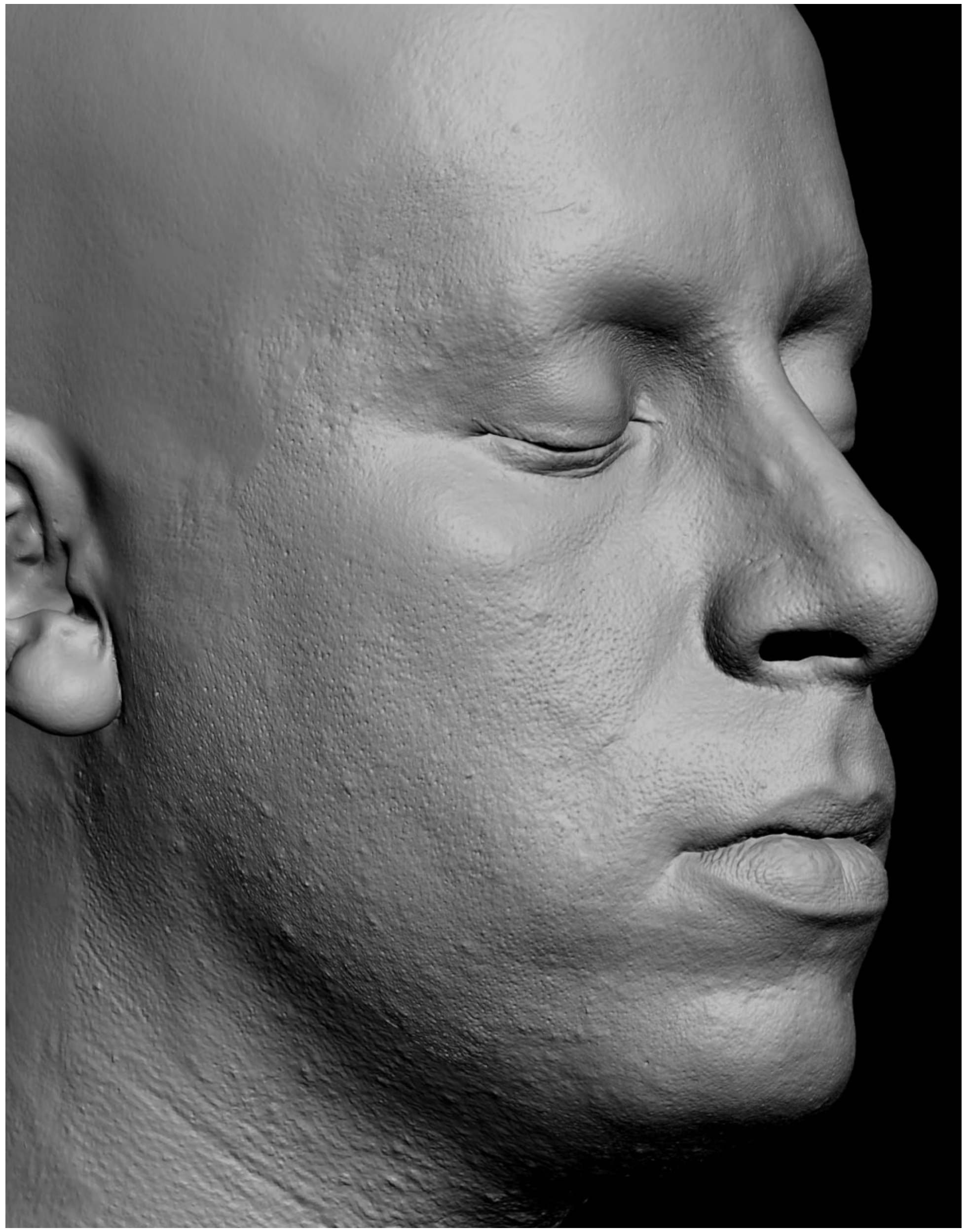
- Introduce the content and motivation for this class
  - What is the technological context?
  - Why care about optimized parallel programming?
  - What methods and applications will we target?
- Discuss class logistics, expected work from students, prerequisites, grading and instructional support
- A few samples of throughput-conscious applications
- Get a first sample of the type of questions we will be addressing, and our design/evaluation philosophy

About the instructor

- Education
  - BSc CS ('00), BSc Math ('02) - Univ of Crete, Greece
  - PhD Computer Science ('07) - Stanford
  - PostDoc CS & Applied Math (07-10) - UCLA
  - At UW since early 2011
- Classes taught:
  - Undergrad : Computer Graphics,
    Intro to Numerical Methods (and now this class!)
  - Graduate : Advanced Computer Graphics,
    Physics-Based Modeling & Simulation

About the instructor

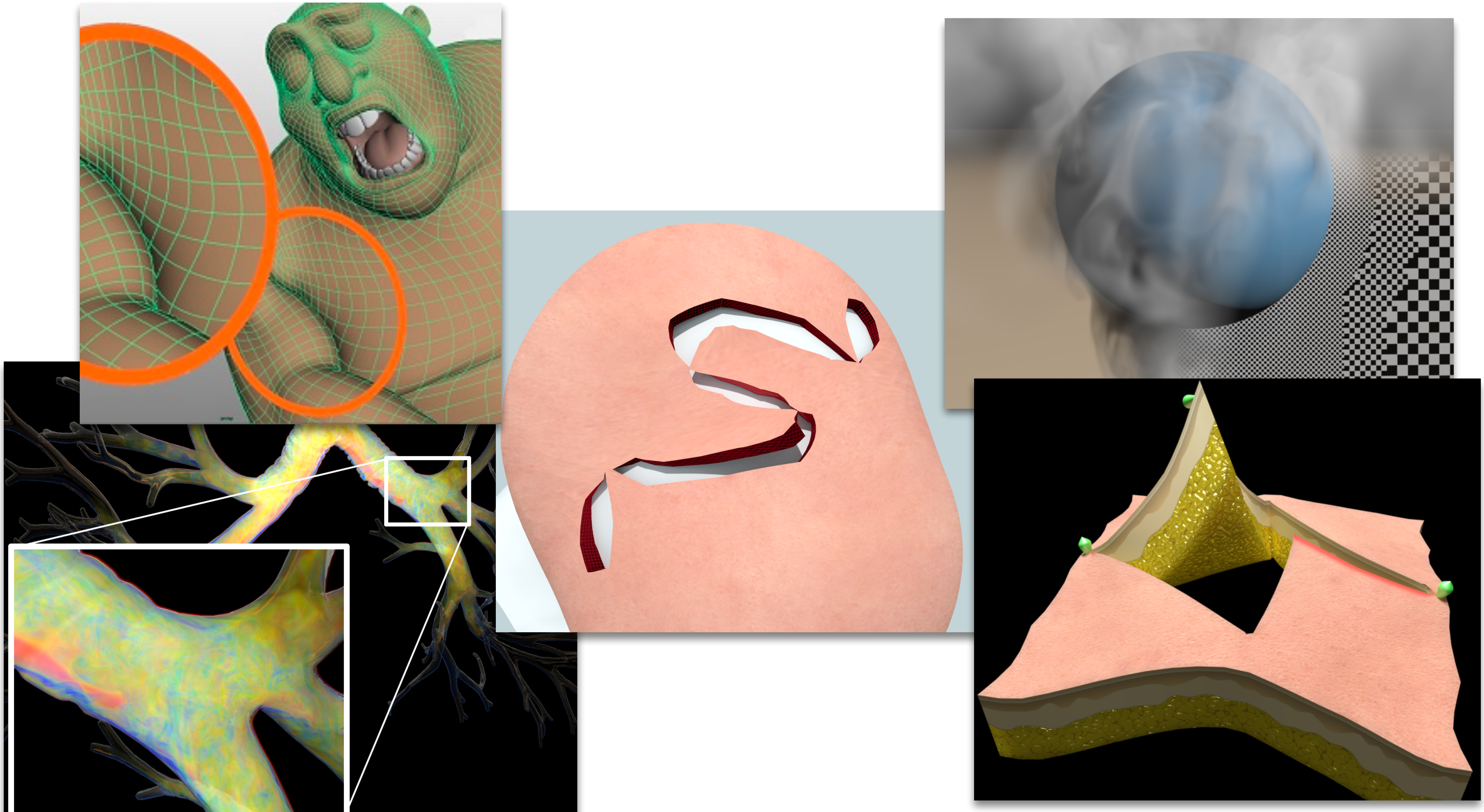
- Research Interests
  - Physics-Based Modeling
  - Digital Humans
  - Visual Simulation (natural phenomena)
  - Biomechanics
  - Visual effects
  - Fast math (in general)



- Current Company affiliations
  - Weta Digital, Disney Research|Studios

About the instructor

- Research Interests



(we'll talk about some of these later)

Motivation for this class

- Modern computers have vastly higher performance potential
  - Modern desktop vs. 2010's cluster
  - $30k Server today vs. 2012-era supercomputer
  - Drastically improved opportunities for high-performance computation

- Performance *potential vs. guarantee*
  - Programming such platforms is much more intricate (you need to be very conscious of platform quirks)
  - Accelerating legacy algorithms is highly nontrivial
  - Hardware and APIs becoming more specialized

Motivation for this class

- Should you care?
  (i.e. is this your problem to figure out?)
  - Everybody cares about performance and scalability (better productivity, improved capabilities, improved user experience)
  - If you are a developer of a performance-sensitive software library or application, chances are you *should* care (too much performance left on the table if you don't)
  - If you are predominantly a *user* of optimized APIs and software libraries, you might not need to get hand dirty … … still a valuable skill to be able to understand what a modern platform *should* be able to do for you (even if somebody else implements it)

Motivating Applications

- What motivated *your instructor* to offer this class? (although somewhat "outside" my core research area …)
  - A distillation of lessons learned through nearly 20 years of development of scale/performance-sensitive applications
  - (Selfish reason) The skills that I wish new students working for me could easily obtain through a formal class
  - In the new era of parallel computing (post-Moore's law) performance advances require buy-in from application specialists vs. just better compilers & hardware
    (this is shaping to be a near-consensus view …)

How did this journey start … ?

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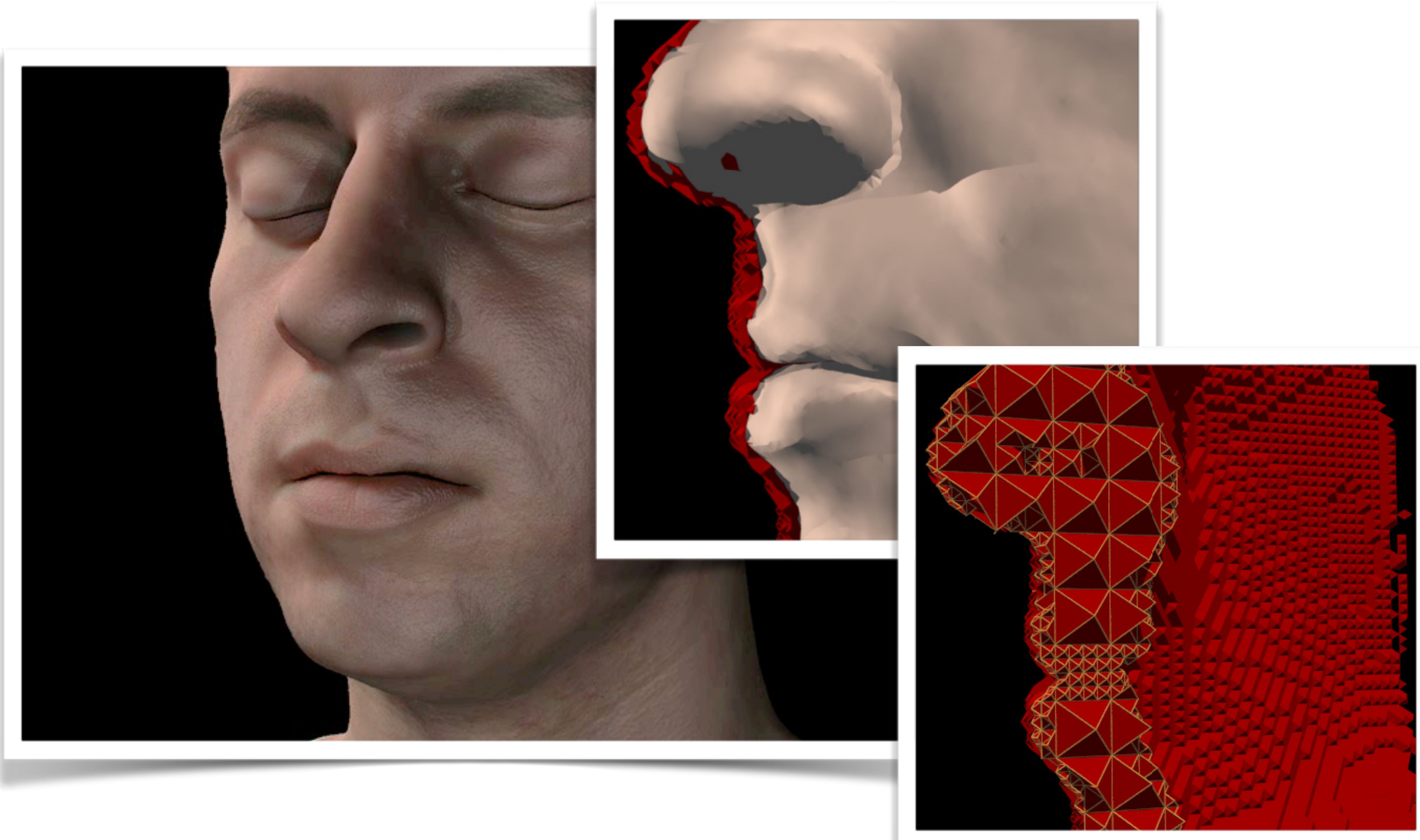

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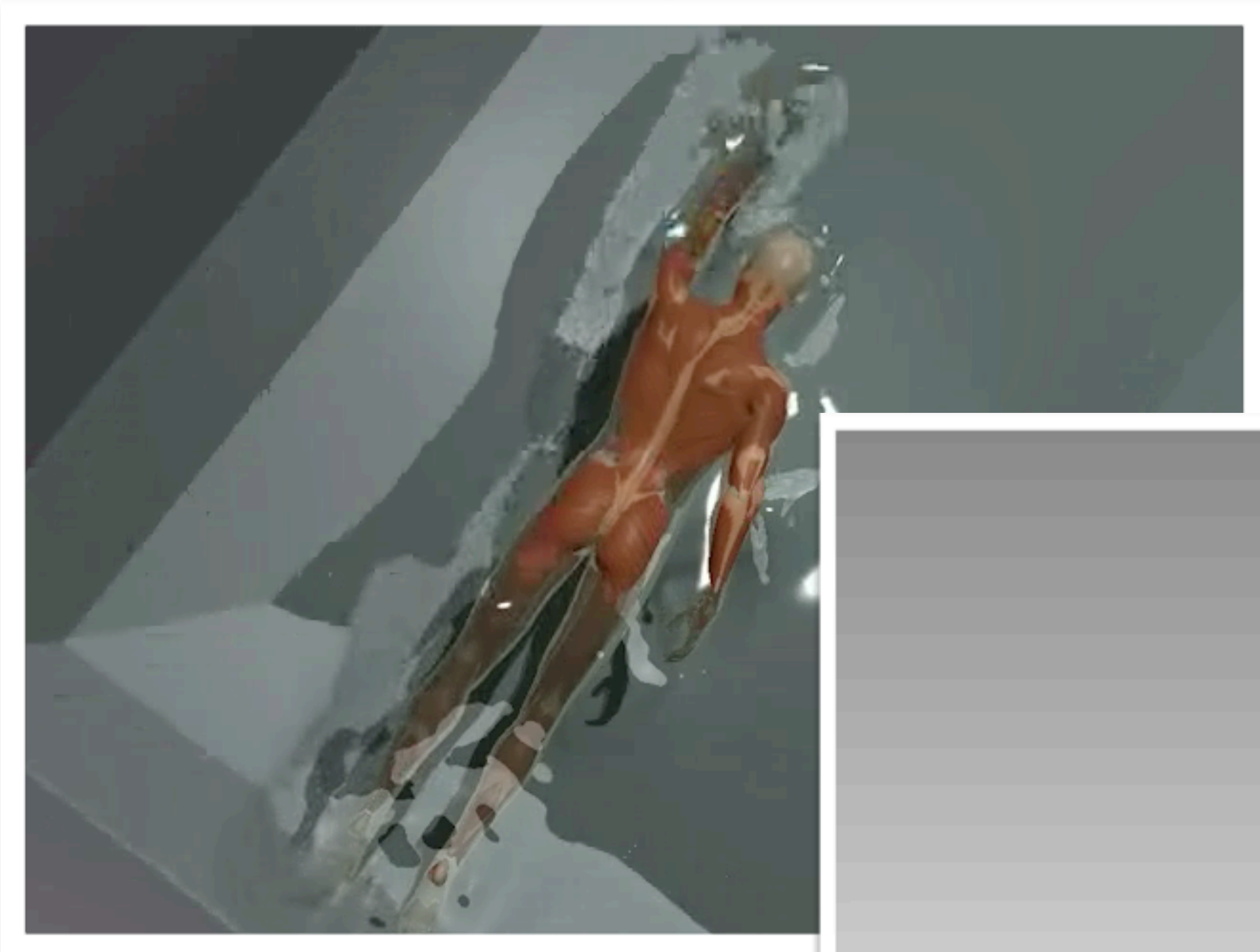

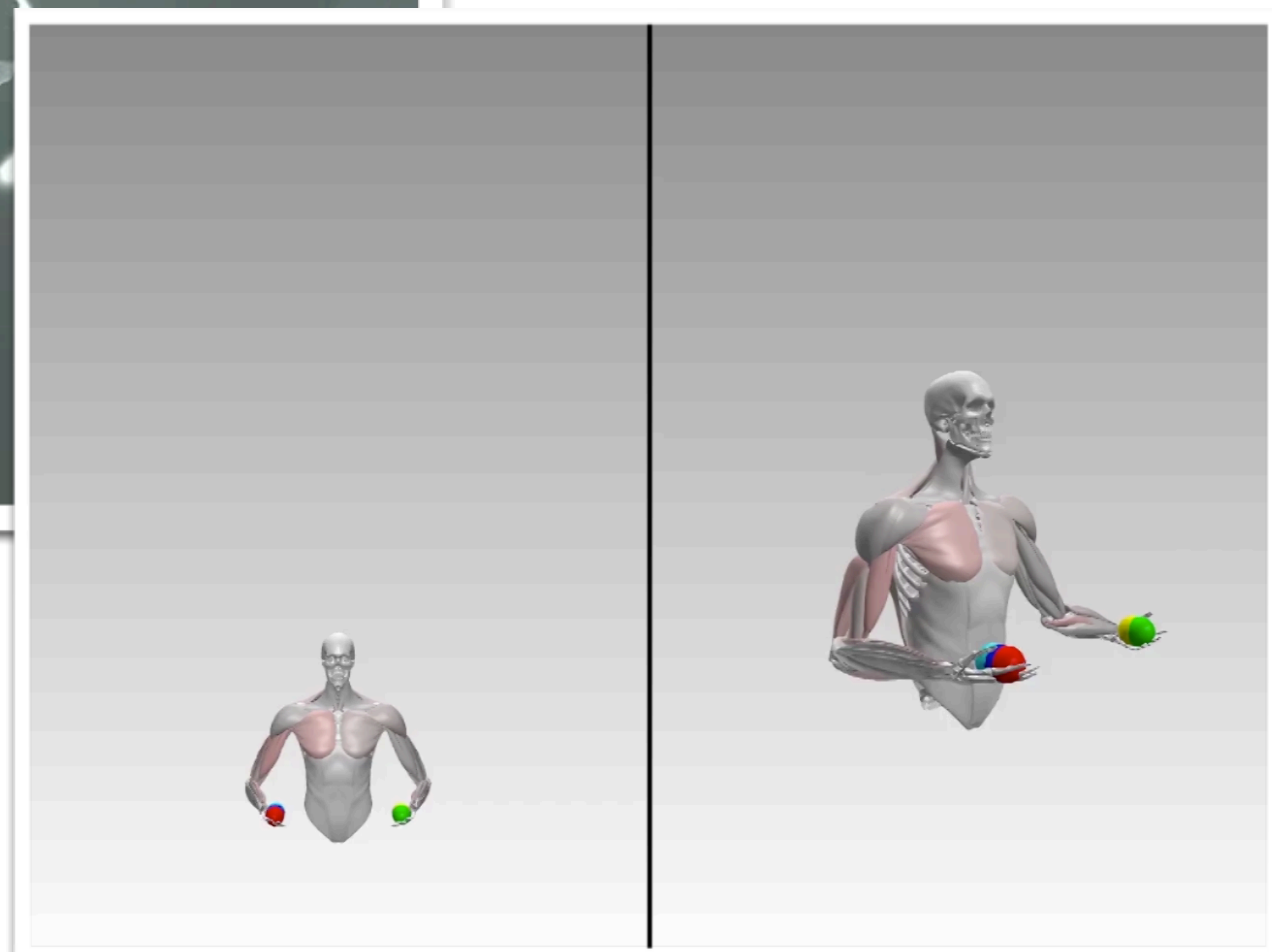

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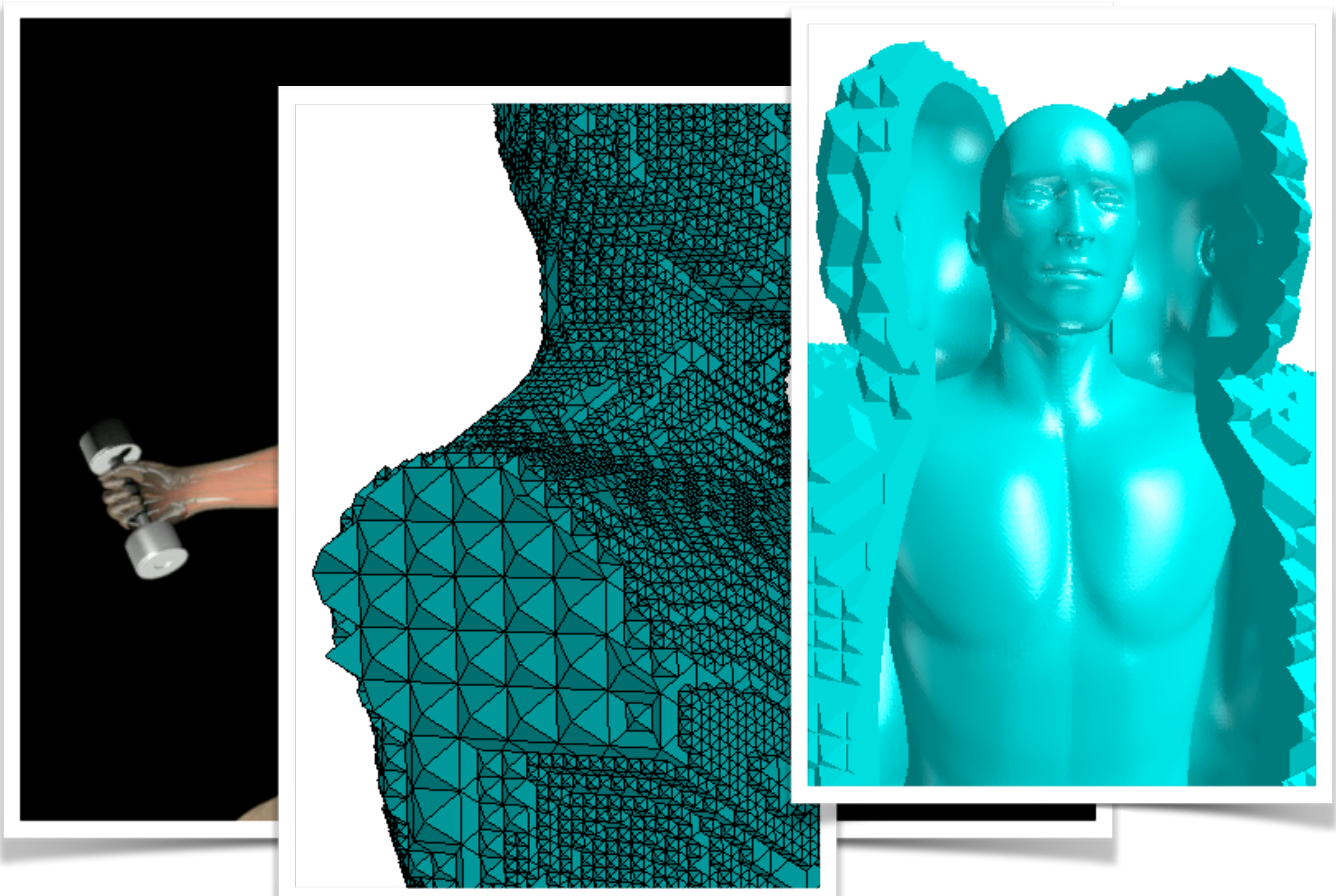

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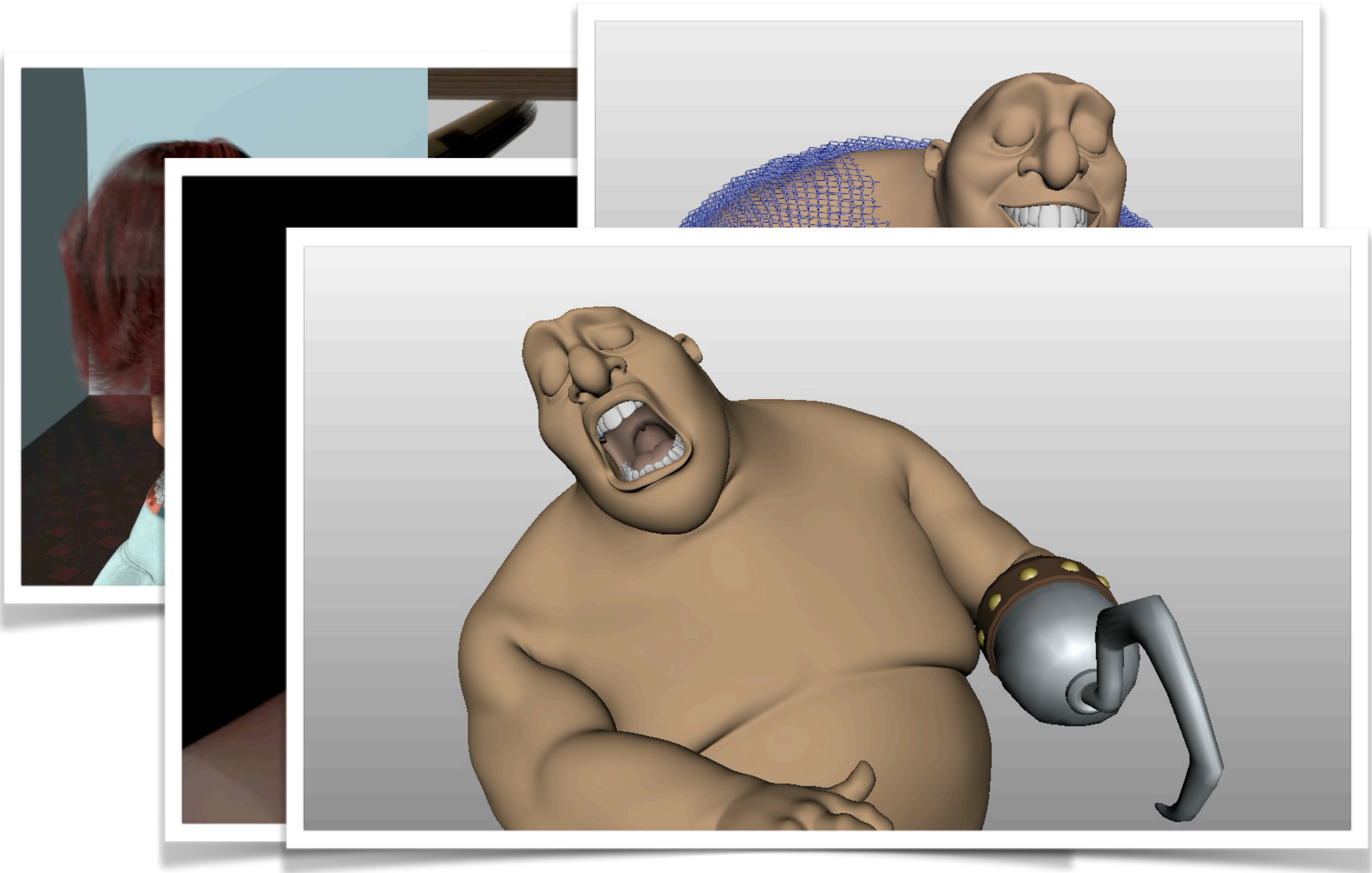

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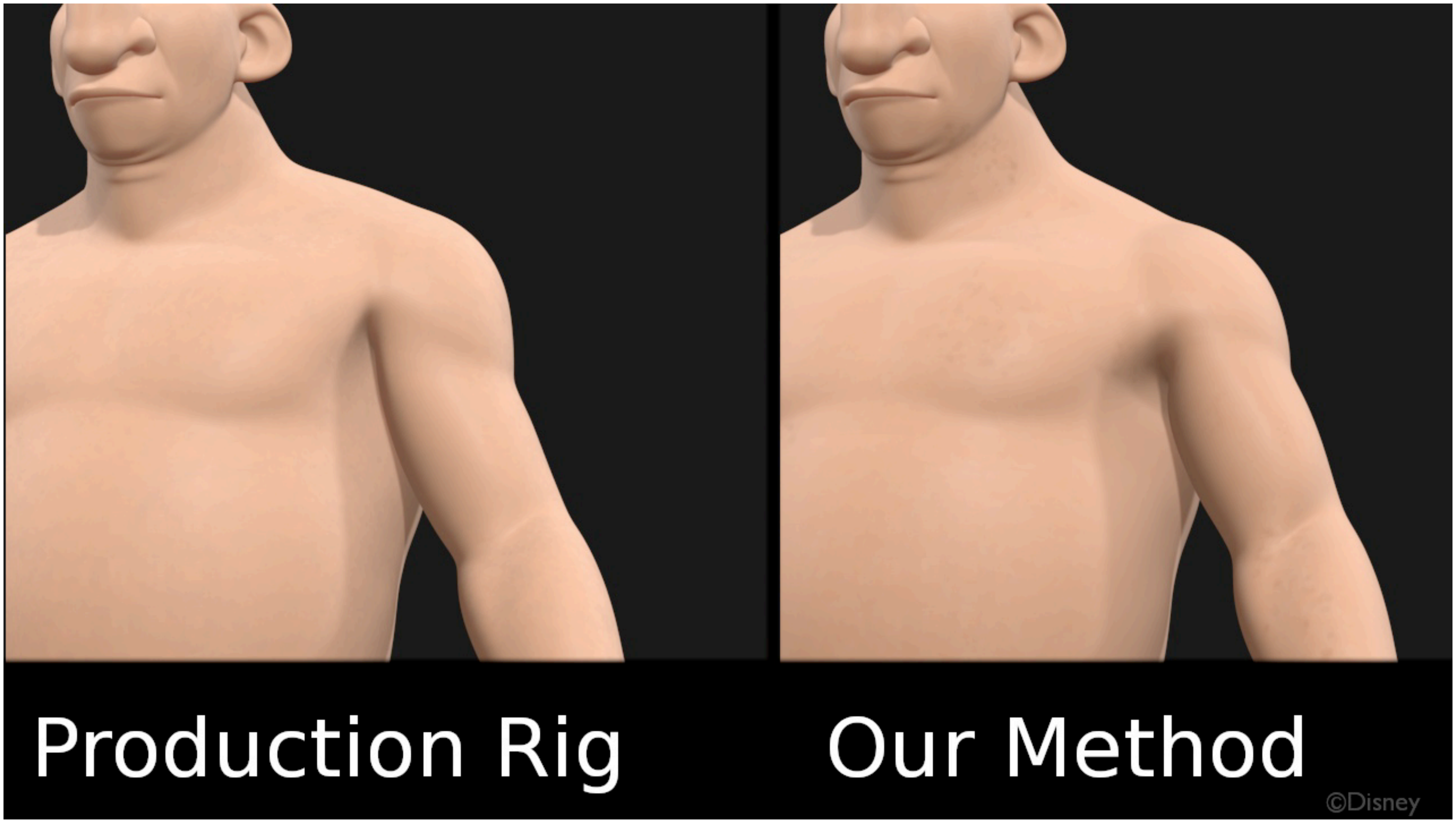

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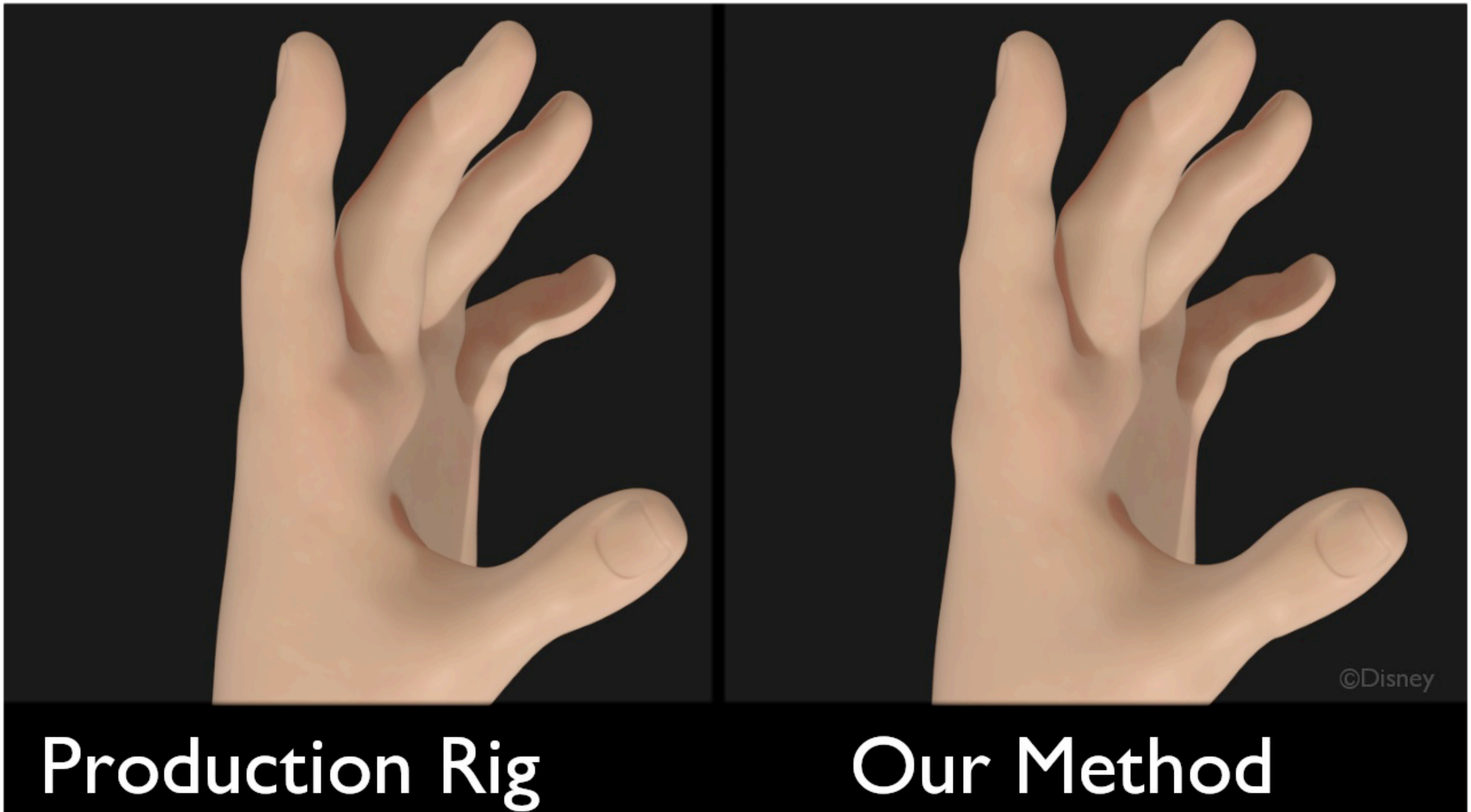

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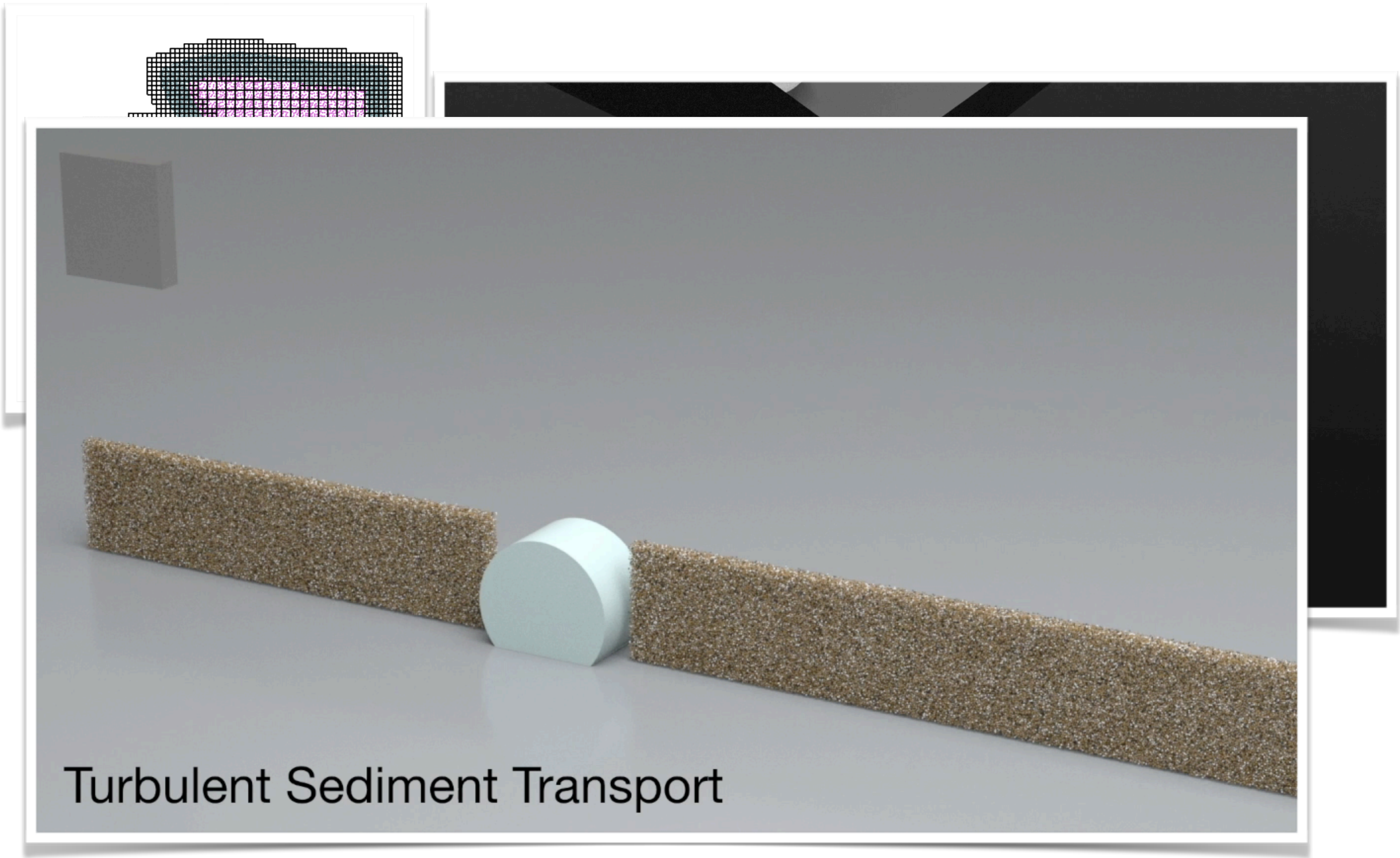

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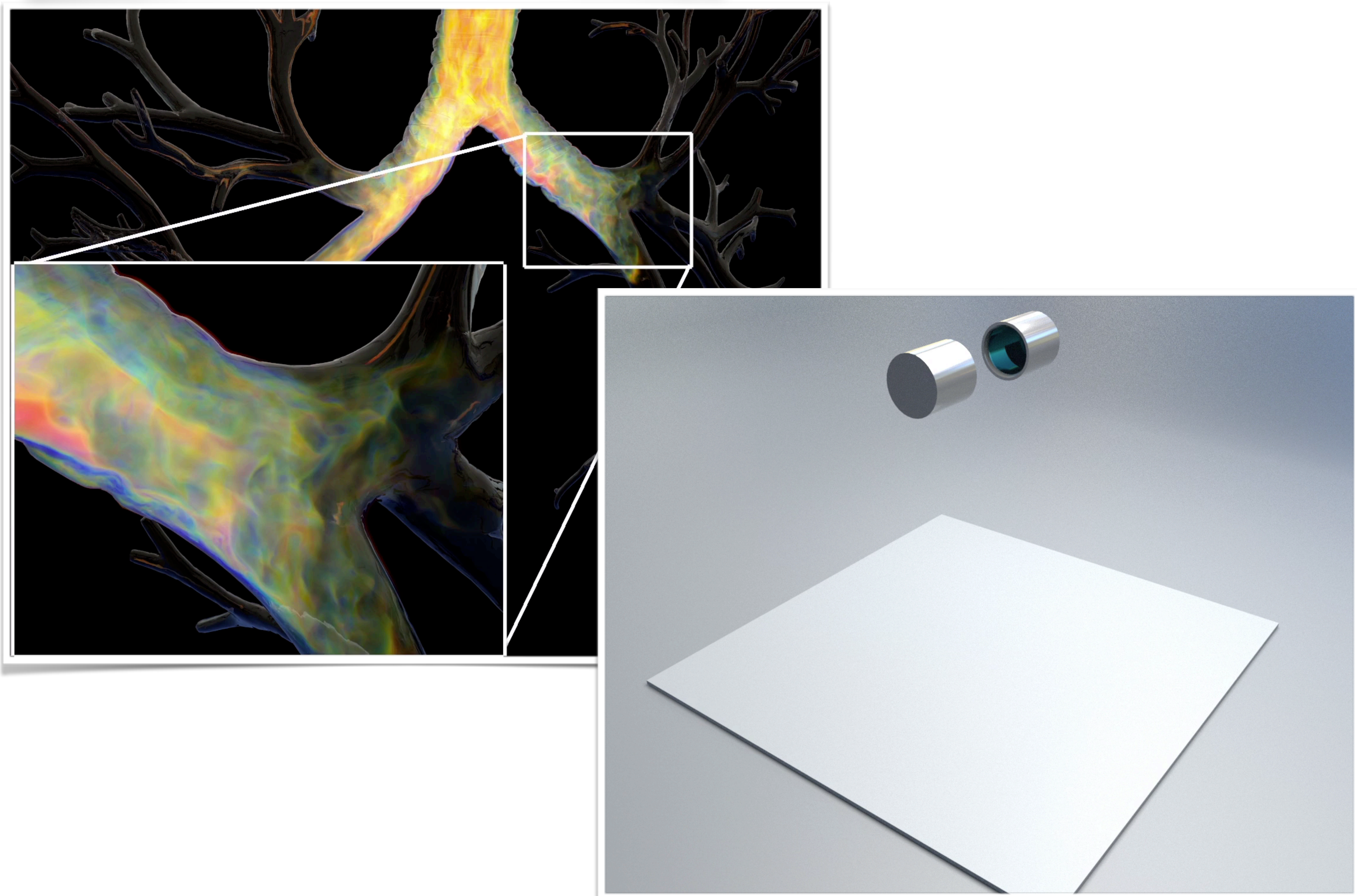

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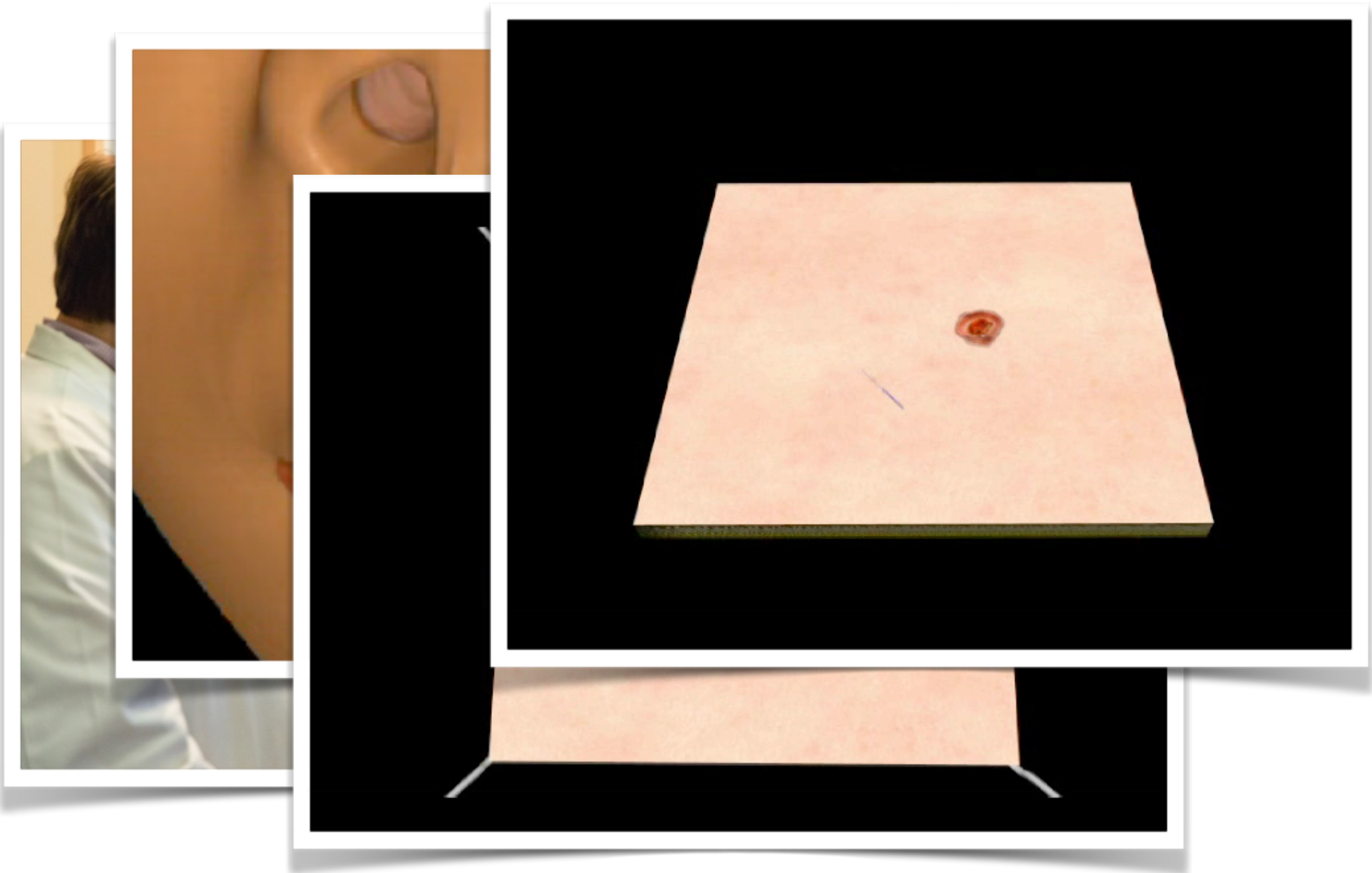
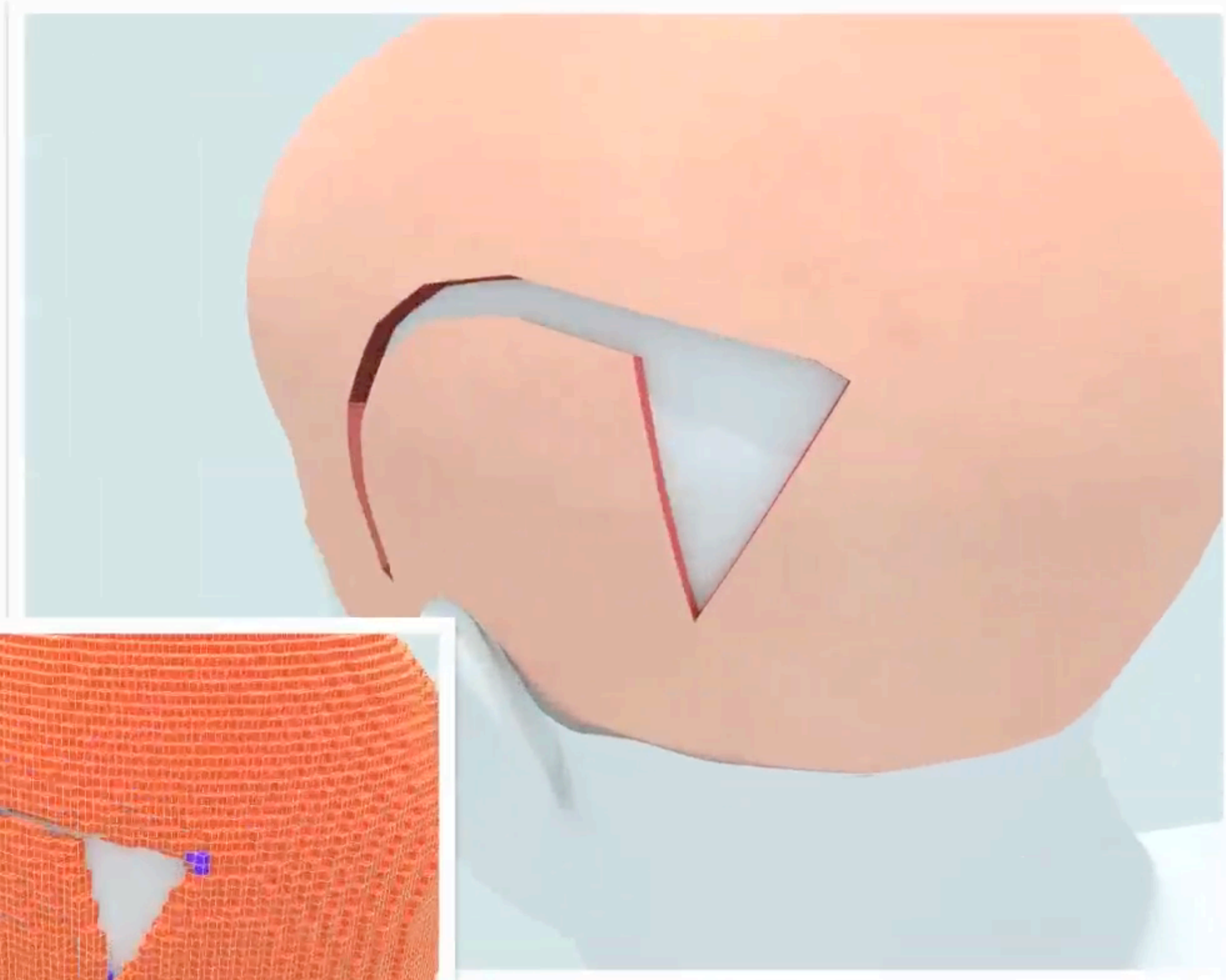
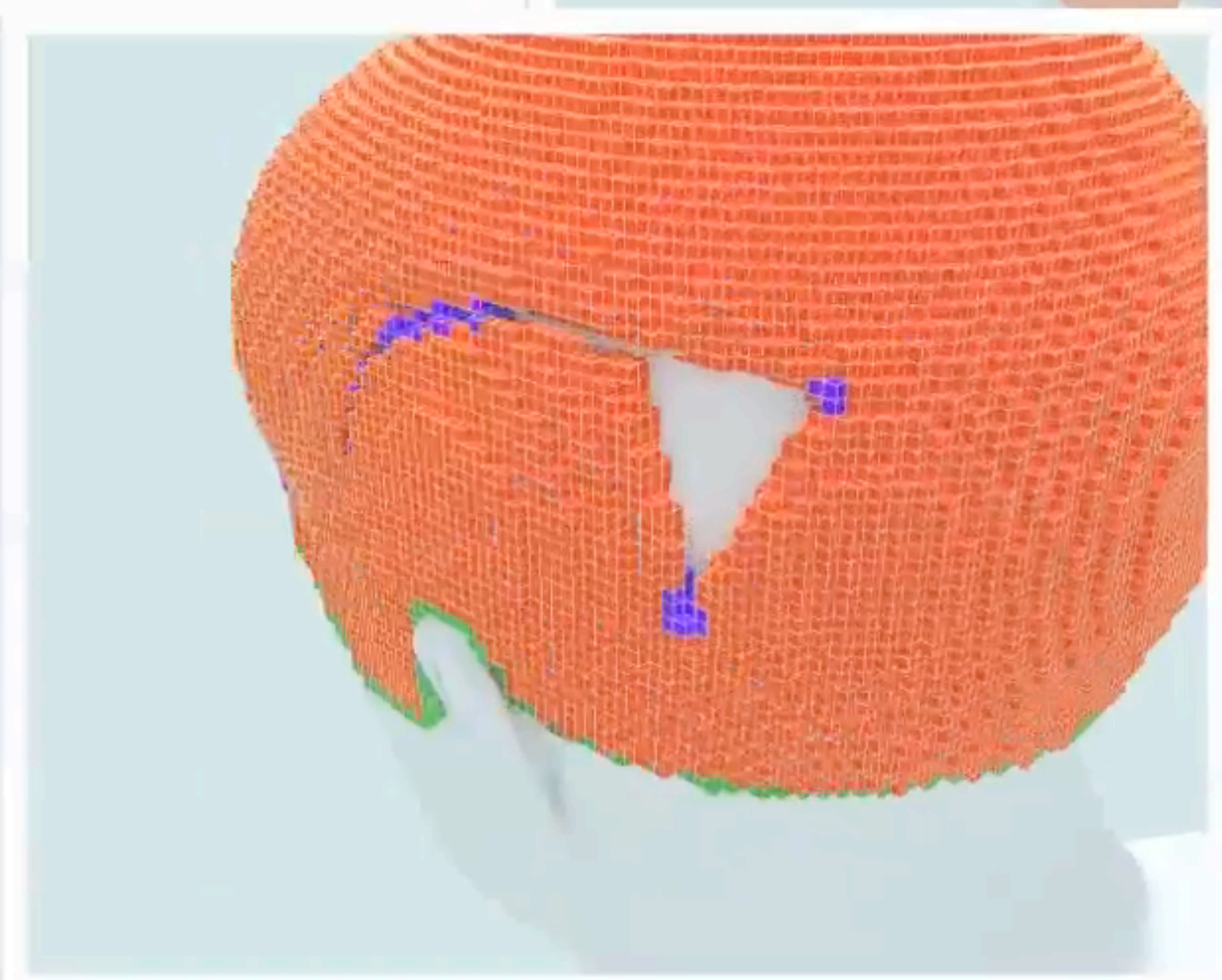
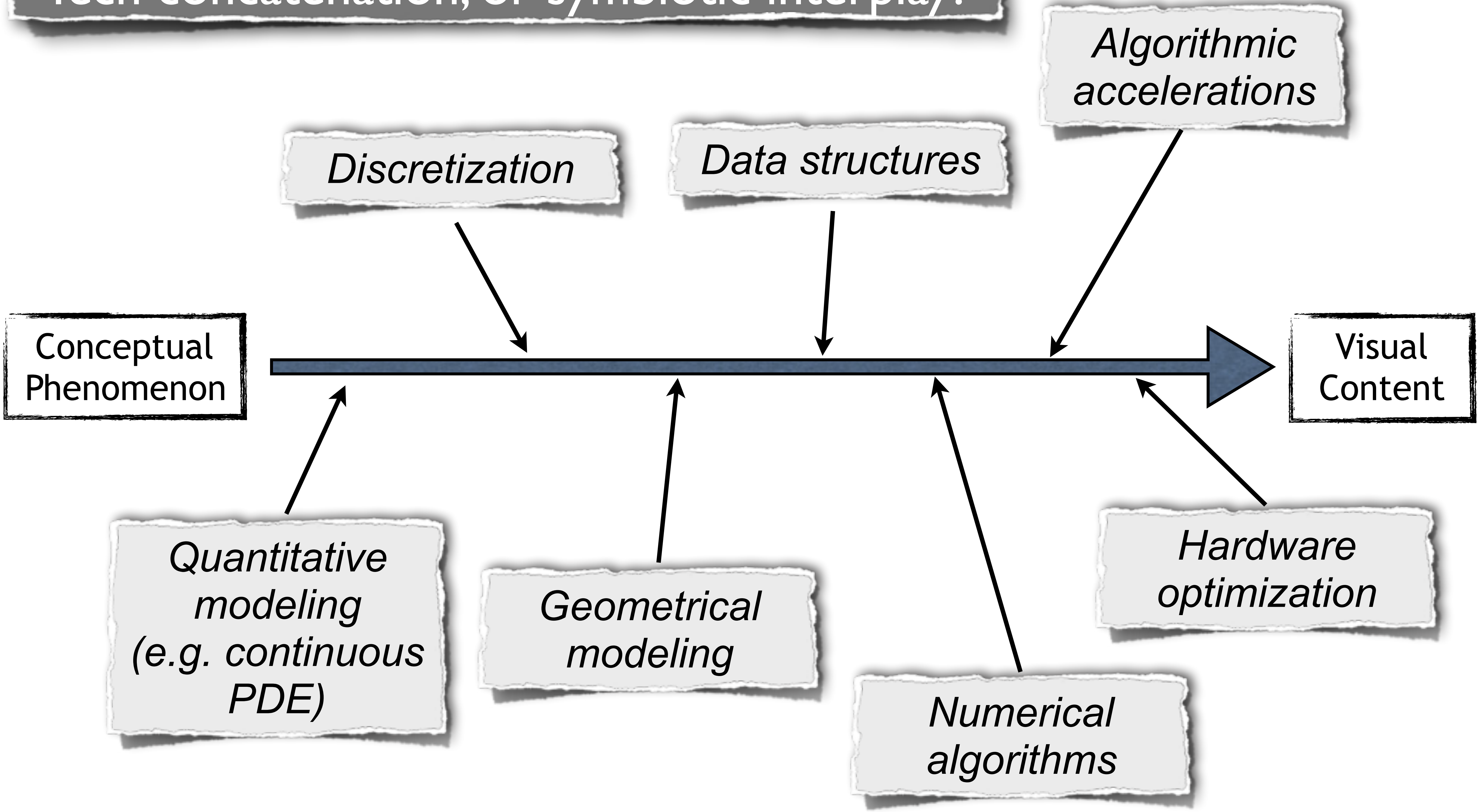
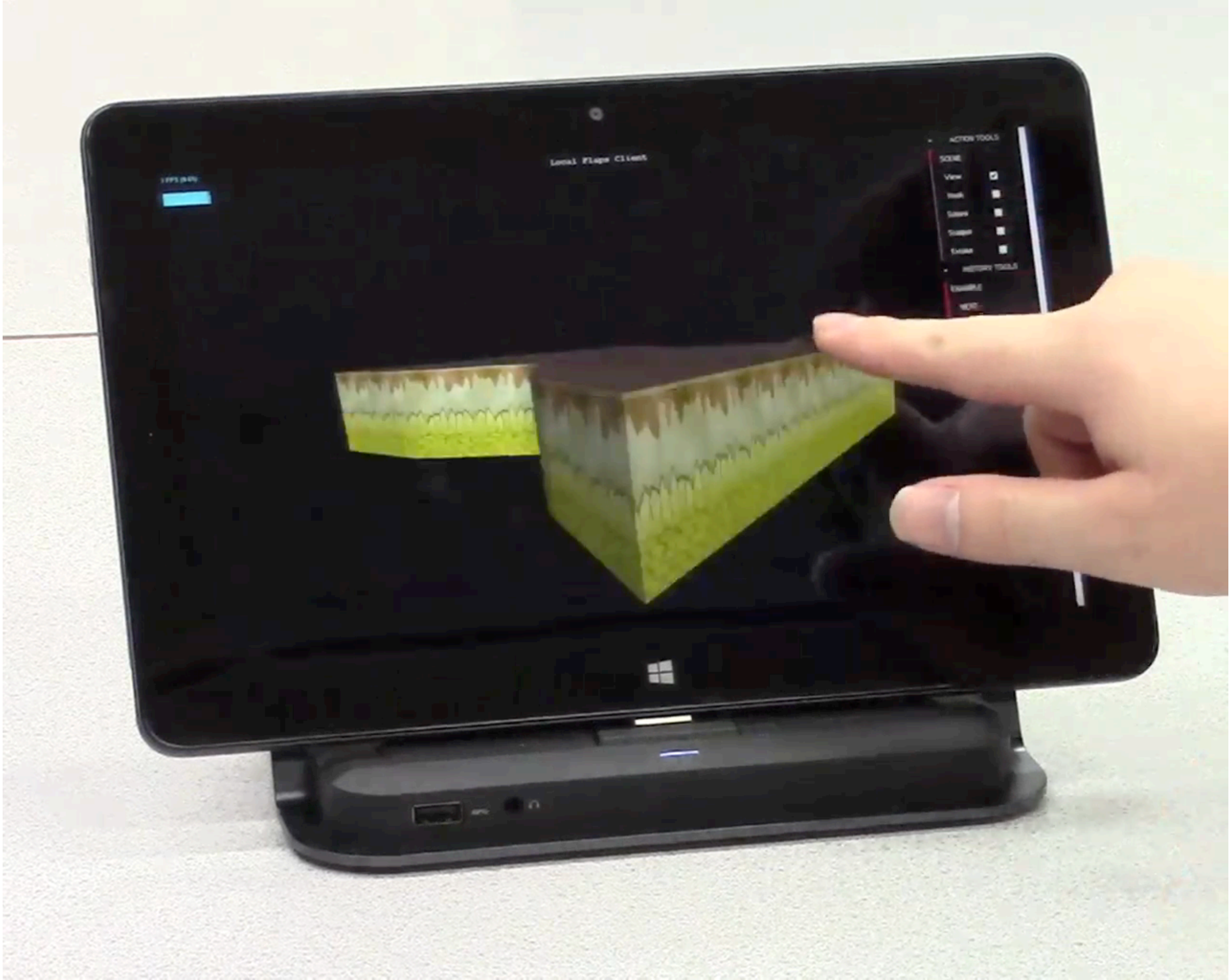


Tech concatenation, or symbiotic interplay?



Software engineering, programming models, computation delivery ...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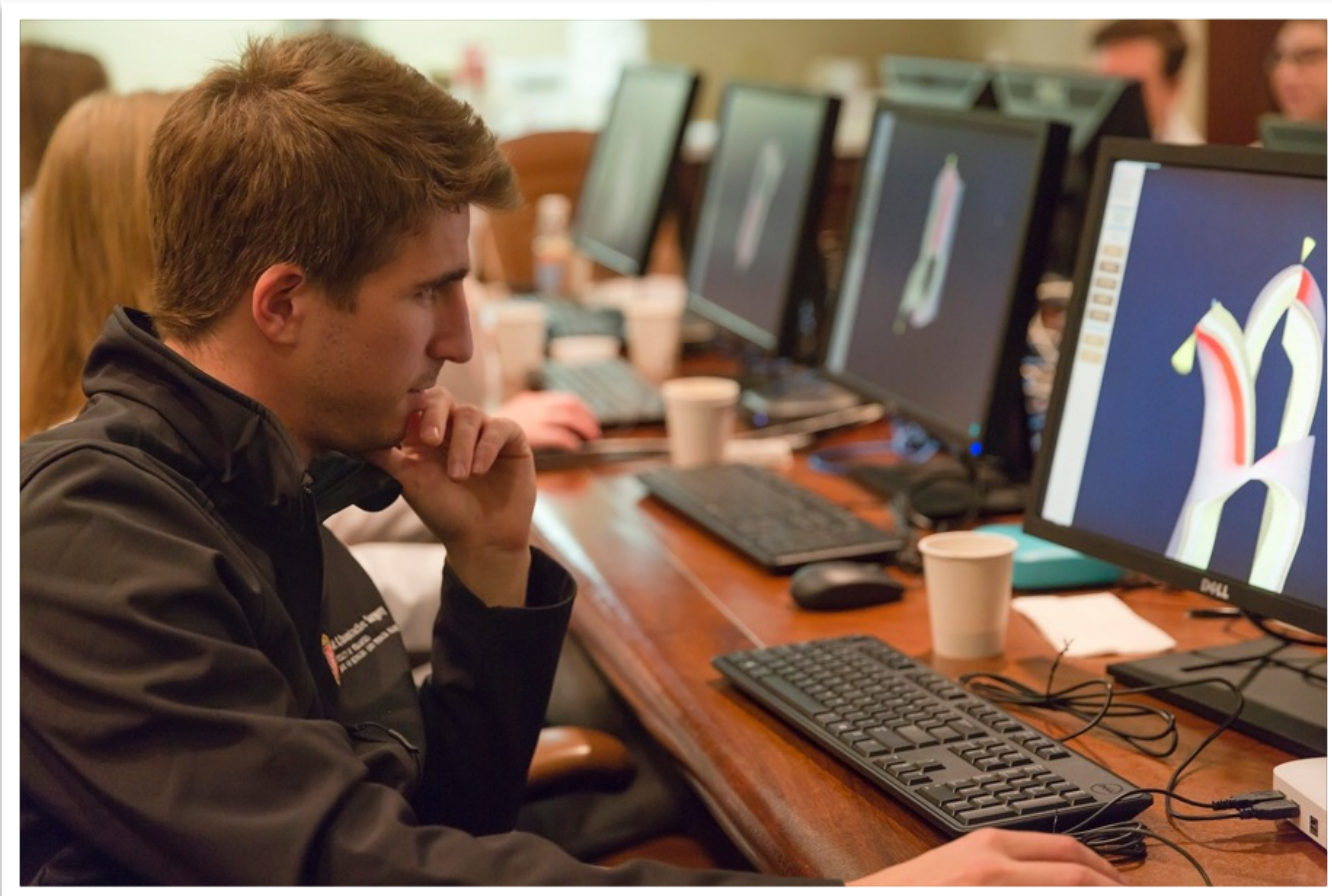
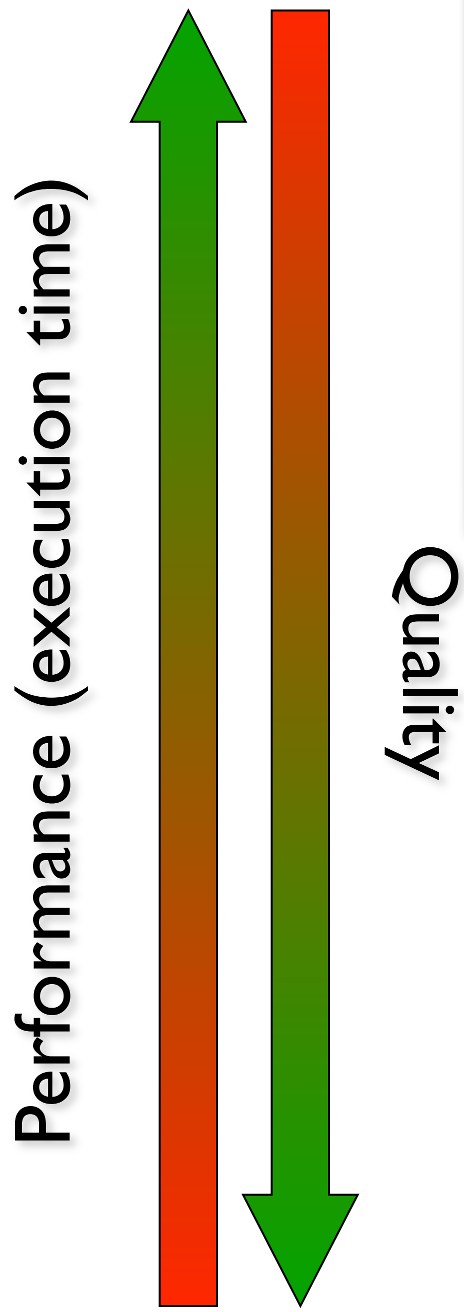
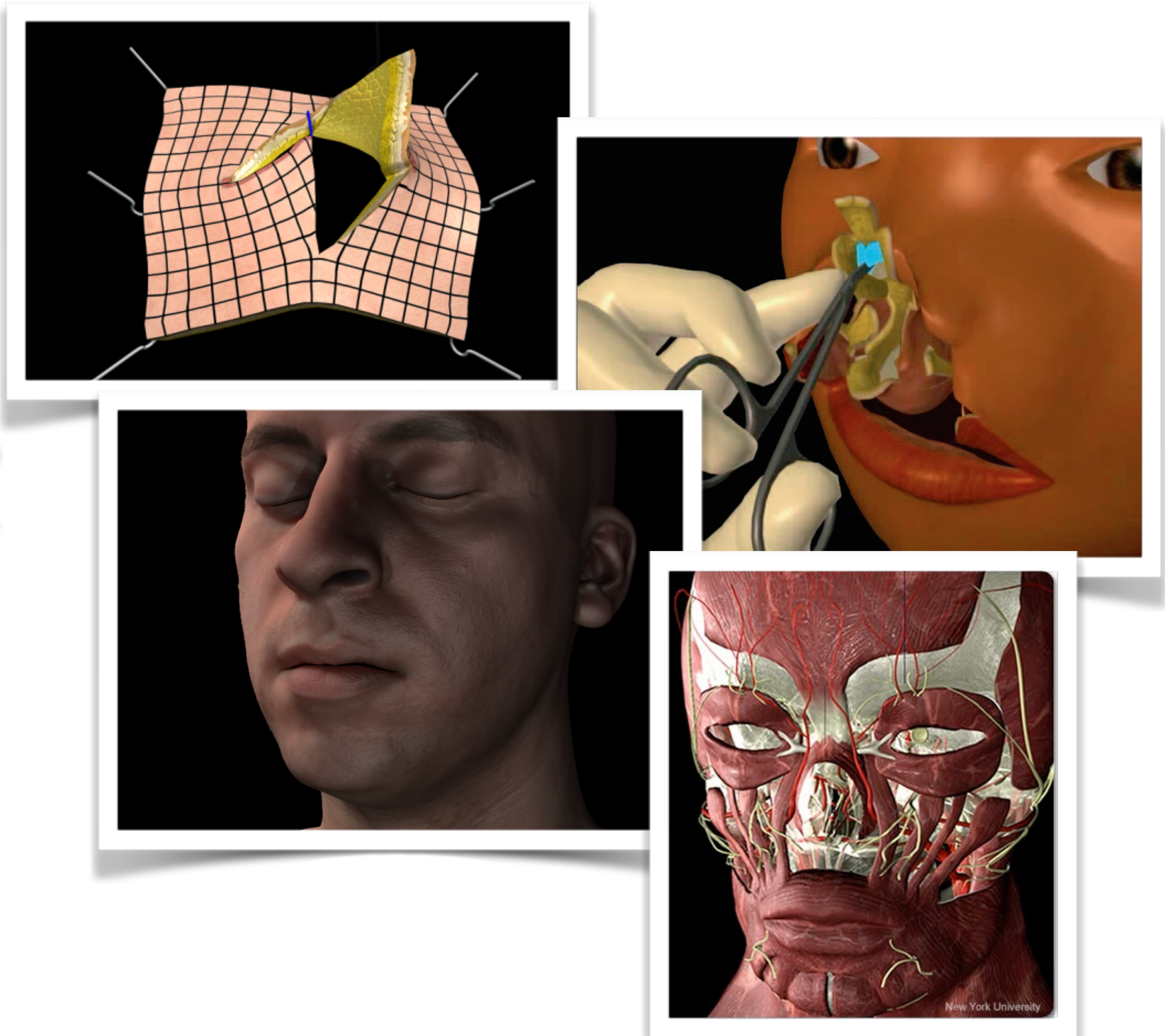
ACTION TOOLS
SCENE
View
HISTORY TOOLS


DELL

Performance : Incremental benefit or critical feature?





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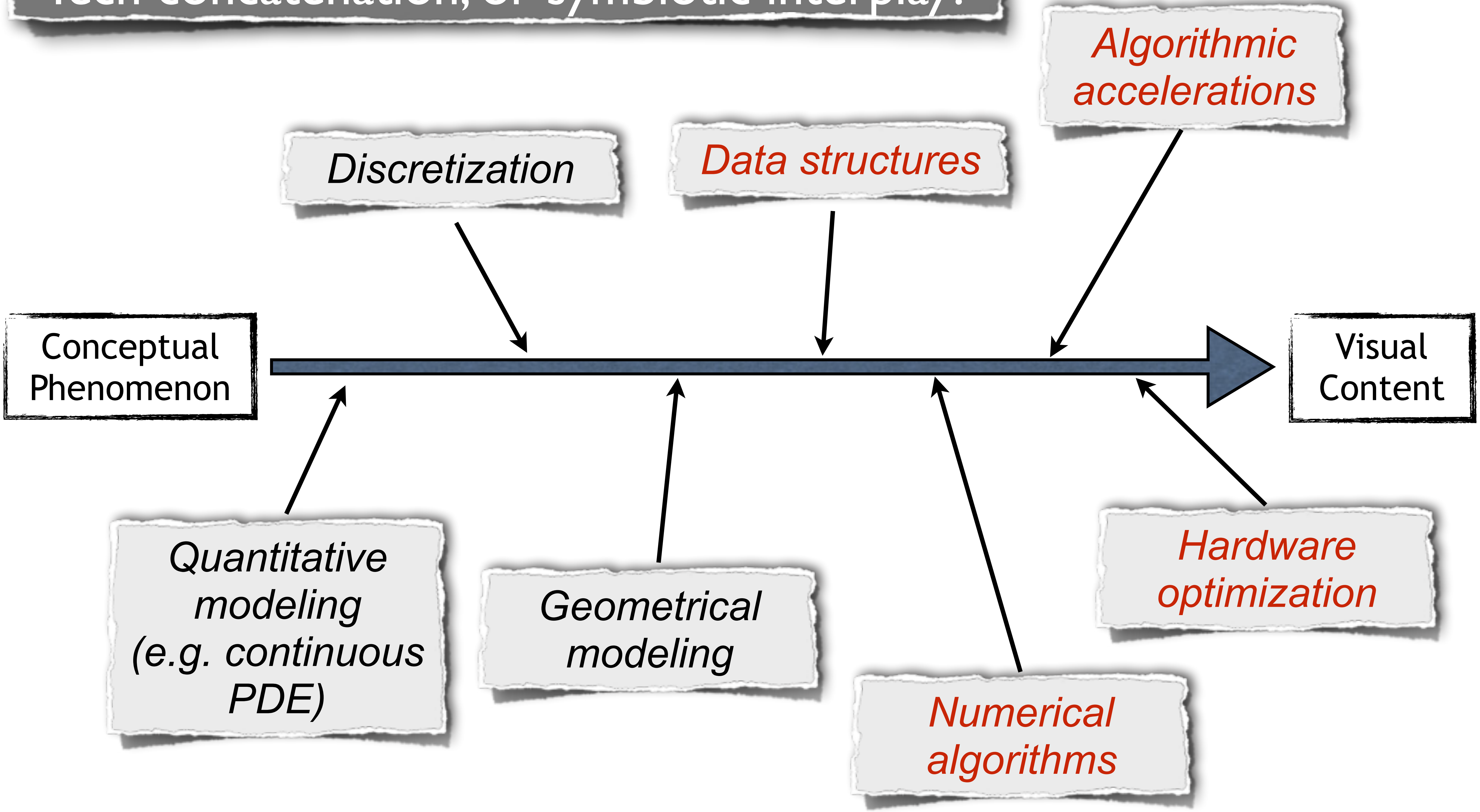
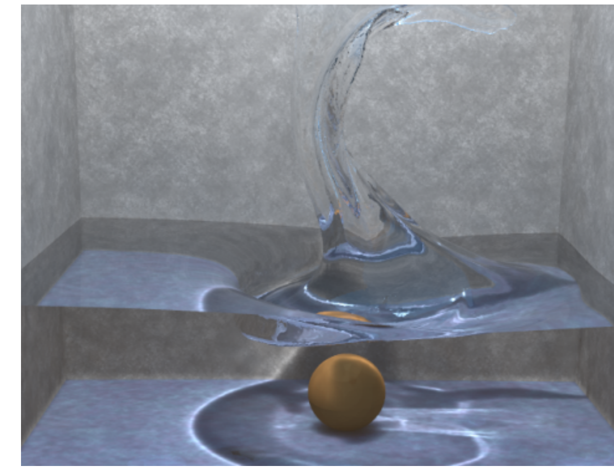


Performance potential: The rant begins ...

The best serial algorithm does not always lead to the best parallel algorithm. While the initial implementation of a key module in fluid simulation used one algorithm, our best parallelization of the module uses an alternative algorithm. The alternative is 57% slower when serial, but has significantly more thread-level paral-

Some modules have high on-die and off-die bandwidth usage. Many of the streaming modules also perform relatively little computation per element per invocation or iteration. This results in high bandwidth usage. Five modules have on-die communication-to-computation ratios of at least one byte per ALU operation, and three have off-die ratios exceeding 0.5 bytes per ALU operation. Since CMPs have a large number of threads sharing both the on-

The off-die bandwidth usage of some of the modules is so high, especially for PCG, that it is likely to limit parallel scalability on most current and near-future systems. On our simulated system, assuming a 3GHz clock, PCG uses an average of 64GB/s of main memory bandwidth for 64 threads. The average bandwidth usage for each of the applications is significantly lower than the peak



Are we pursuing the right efficiency?

RANT ALERT!

Well-intended evaluation practices ...

> *"My serial implementation of algorithm X on machine Y ran in Z seconds. When I parallelized my code, I got a speedup of 15x on 16 cores ..."*

... are sometimes abused like this:

> *"... when I ported my implementation to CUDA, this numerical solver ran 200 times faster than my original MATLAB code ..."*

(frequent culprit: flawed understanding of how the computing platform works @ low level)

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Watch for warning signs:

- Speedup across platforms grossly exceeding specification ratios
  - e.g. NVIDIA Titan RTX vs. Intel Cascade Lake Xeon

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    - GPU has about 6x higher (peak) compute capacity
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    - Different implementations on the 2 platforms
    - Baseline code was not optimal/parallel enough

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- "Standard" parallelization yields linear speedups on **many** *cores*
  - [Reasonable scenario] Implementation is CPU-bound
  - [Problematic scenario] Implementation is CPU-wasteful

Are we pursuing the right efficiency?

RANT ALERT!

A different perspective ...

> *" ... after optimizing my code, the runtime is about 5x slower than **the best possible performance** that I could expect from this machine ..."*

*... i.e. 20% of maximum theoretical **efficiency!***

***Challenge** : How can we tell how fast the <u>best</u> implementation could have been?*
(without implementing it ...)

Are we pursuing the right efficiency?

RANT ALERT!

Example : Solving the quadratic equation

$$ax^2 + bx + c = 0$$

What is the *minimum* amount of time needed to solve this?

Data access cost bound

"We cannot solve this faster than the time needed to read ***a,b,c*** *and write* ***x****"*

"We cannot solve this faster than the time needed evaluate the polynomial, for given values of a,b,c and x"
(i.e. 2 ADDs, 2 MULTs plus data access)

Solution verification bound

Equivalent operation bound

"We cannot solve this faster than the time it takes to compute a square root"

Are we pursuing the right efficiency?

RANT ALERT!

What about linear systems of equations?

$$\mathbf{Ax} = \mathbf{b}$$

"Textbook Efficiency" (for certain types of problems)

*It is **theoretically possible** to compute the solution to a linear system (with certain properties) with a cost comparable to **10x the cost of verifying** that a given value **x** is an actual solution*

… or …

*It is **theoretically possible** to compute the solution to a linear system at **10x the cost of computing*** the ***r=b-Ax*** and verifying that ***r=0***

Scope of Class

- Narrower platform/API focus for this semester
  - Single-chassis multiprocessors
    (but substantial similarity to GPU programming)
  - Will not focus on distributed or highly heterogeneous programming (e.g. MPI)

Scope of Class

- Technical topics
  - Multithreaded programming; Synchronization; Using the OpenMP API
  - Instruction Level Parallelism; Vectorization and challenges; SIMD intrinsics
  - Memory hierarchy and its implications; Caches; Virtual Memory
  - Assessing efficiency, predicting parallel potential, and benchmarking performance
  - Understanding the role of compute and/or memory throughput as a limiting factor of performance
  - Optimizing data structures for target architecture; Memory allocation and management

Scope of Class

- Application focus
  - Sparse linear algebra; Matrix representations; Iterative solvers for sparse systems
  - Dense linear algebra; Matrix/Vector operations; Matrix Factorizations; Using the MKL library
  - Grid and stencil computations; Convolutions and their use in neural networks
  - Fourier transforms; Eigenvalue problems; PCA and Singular Value Decomposition
  - Optimization methods; Least-squares and approximation; Descent methods

Course logistics

- Location : Grainger Hall 2080
- 3 credits
- Class meets : TTh 2:30pm - 3:45pm
  - Office hours (by instructor) - CS6387
    Mondays 11:00am - 11:45am
    Wednesdays 1:15pm - 2:00pm (starting Jan 29th)
    Fridays : 4:15pm - 5:00pm (starting Jan 24th)
  - Friday slot will likely transform into an in-class review/help session within a couple weeks (location to be announced - in CS building)

Course information

- Piazza
  - Signup link : http://piazza.com/wisc/spring2020/cs639
  - Class link : piazza.com/wisc/spring2020/cs639/home
  - Email the instructor if you are have issues enrolling
- Email : sifakis@cs.wisc.edu
  - Please add "[CS639]" in the beginning of the subject line!
  - Email policy : Feel free to email as frequently as you need. Typically you will receive a response within 24hrs. However, be prepared to wait until next office hours (worst case) to get a comprehensive answer. If urgent, ask for an appointment.

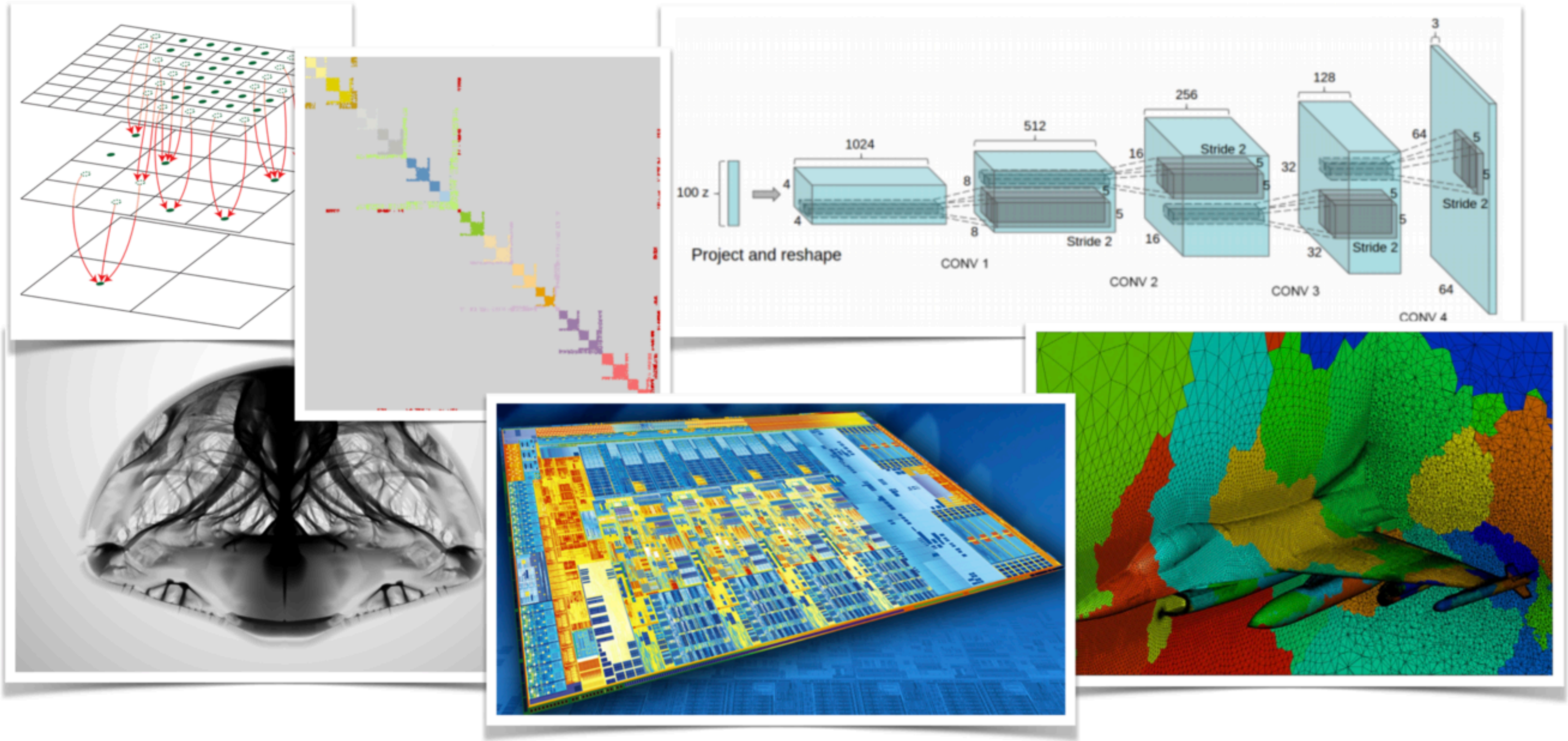
Evaluation

- Grading
  - 60% - Regular Programming Assignments
  - 15% - Optional Midterm - Friday March 6th, 7:15-9:15pm
  - 25% - Final Exam
  - Midterm grade will only count if greater than final exam. Otherwise the final exam will count for 40%
- There may be opportunities for bonus credit, for example:
  - Assistance with class infrastructure
  - Scribing lecture notes
  - Strong and helpful presence on Piazza

Prerequisites

Prerequisites not <u>strictly</u> enforced in this first offering, but ...

- You should be comfortable with programming in the C language
  - CS354, or equivalent, is strongly encouraged. Talk to the instructor if you're not sure of your background/preparation in C programming.
  - You should be comfortable with debugging applications in C, using version control systems (e.g. Git, Mercurial, SVN), and simple build systems (e.g. Make/CMake). Some resources will be provided to help.
  - We will review relevant APIs (e.g. OpenMP) in class.
- Case studies and application topics will be mostly from scientific computing
  - Familiarity with basic linear algebra will be useful (but not essential)



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