An Introduction to Physics-based Animation

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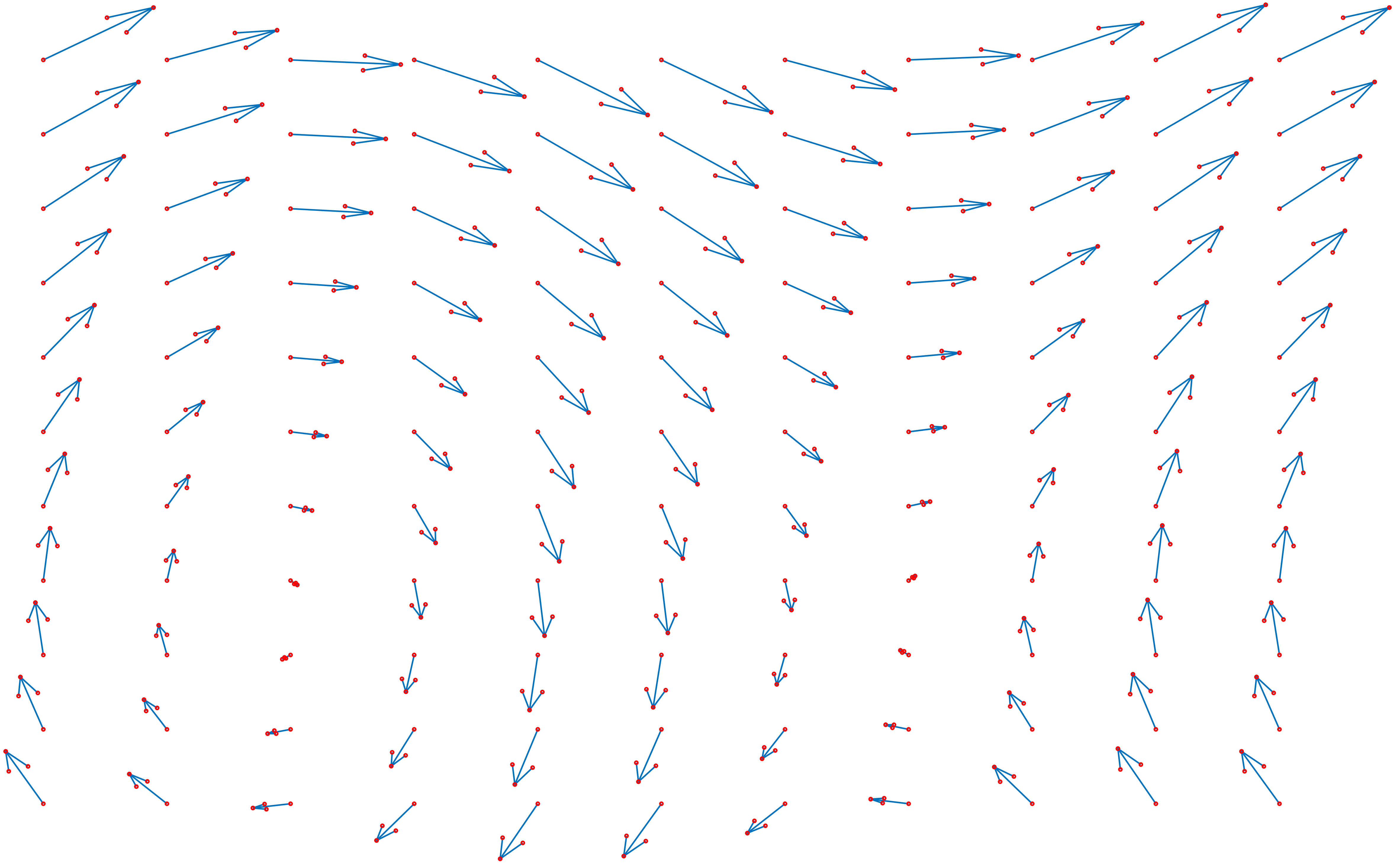
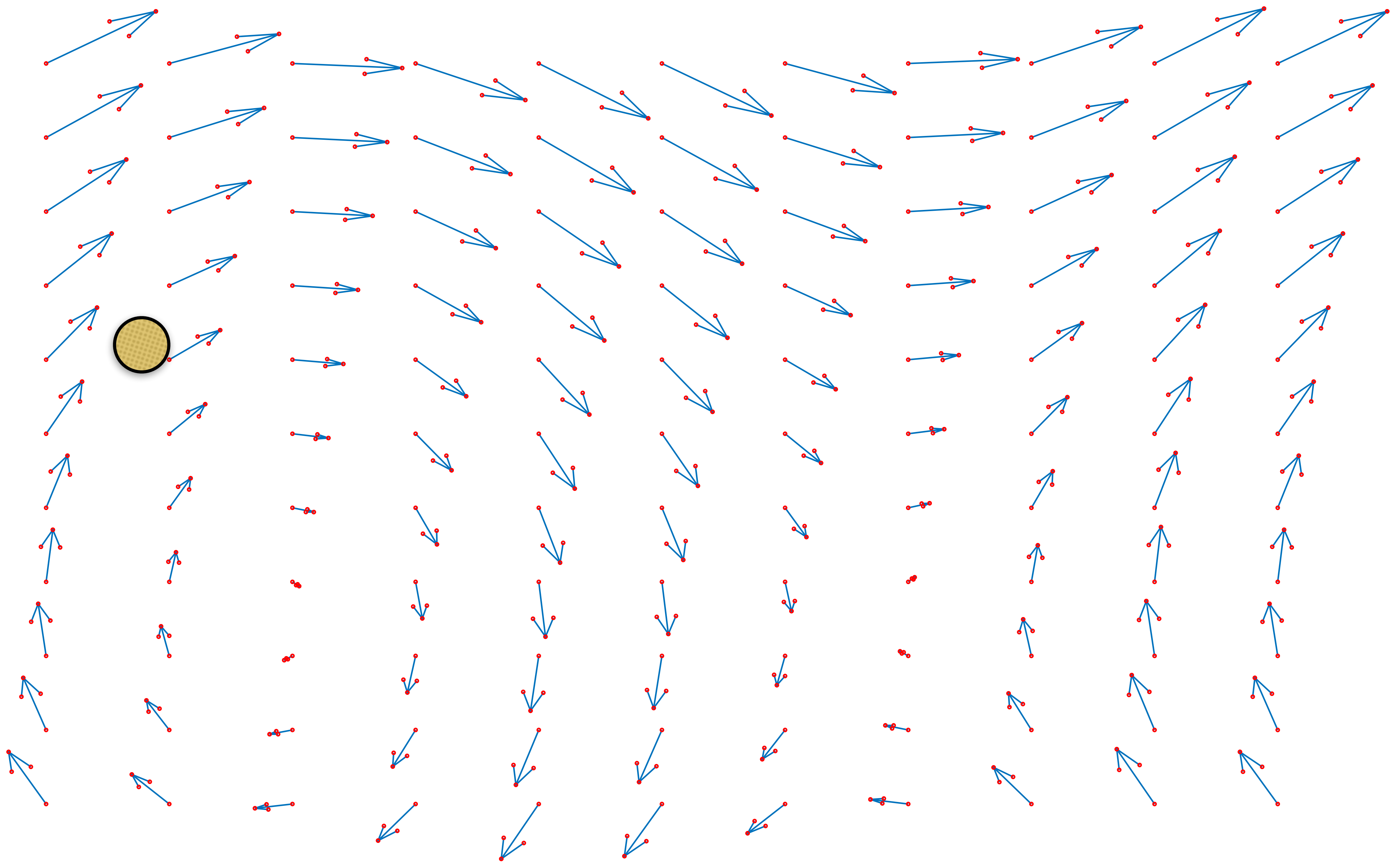
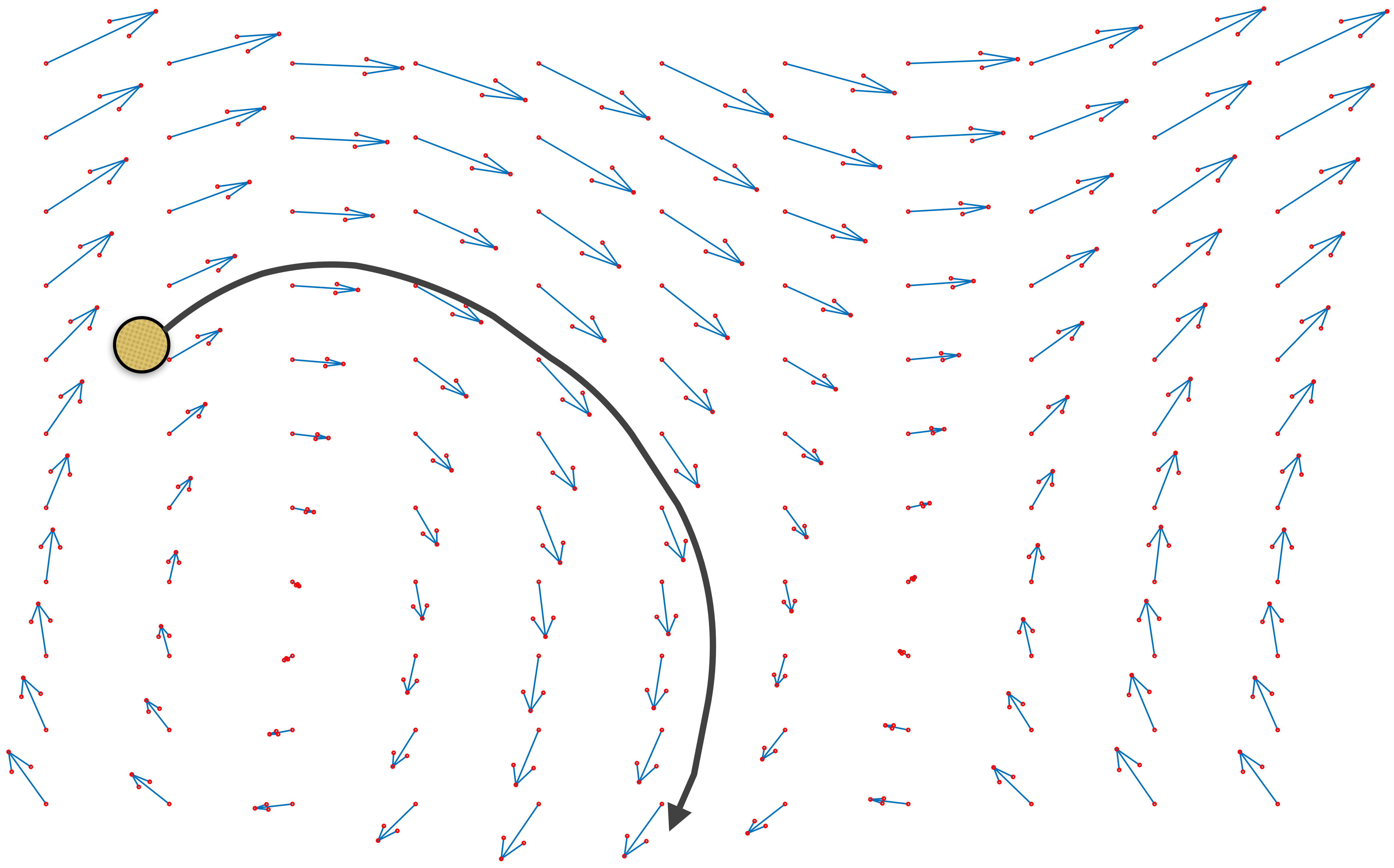
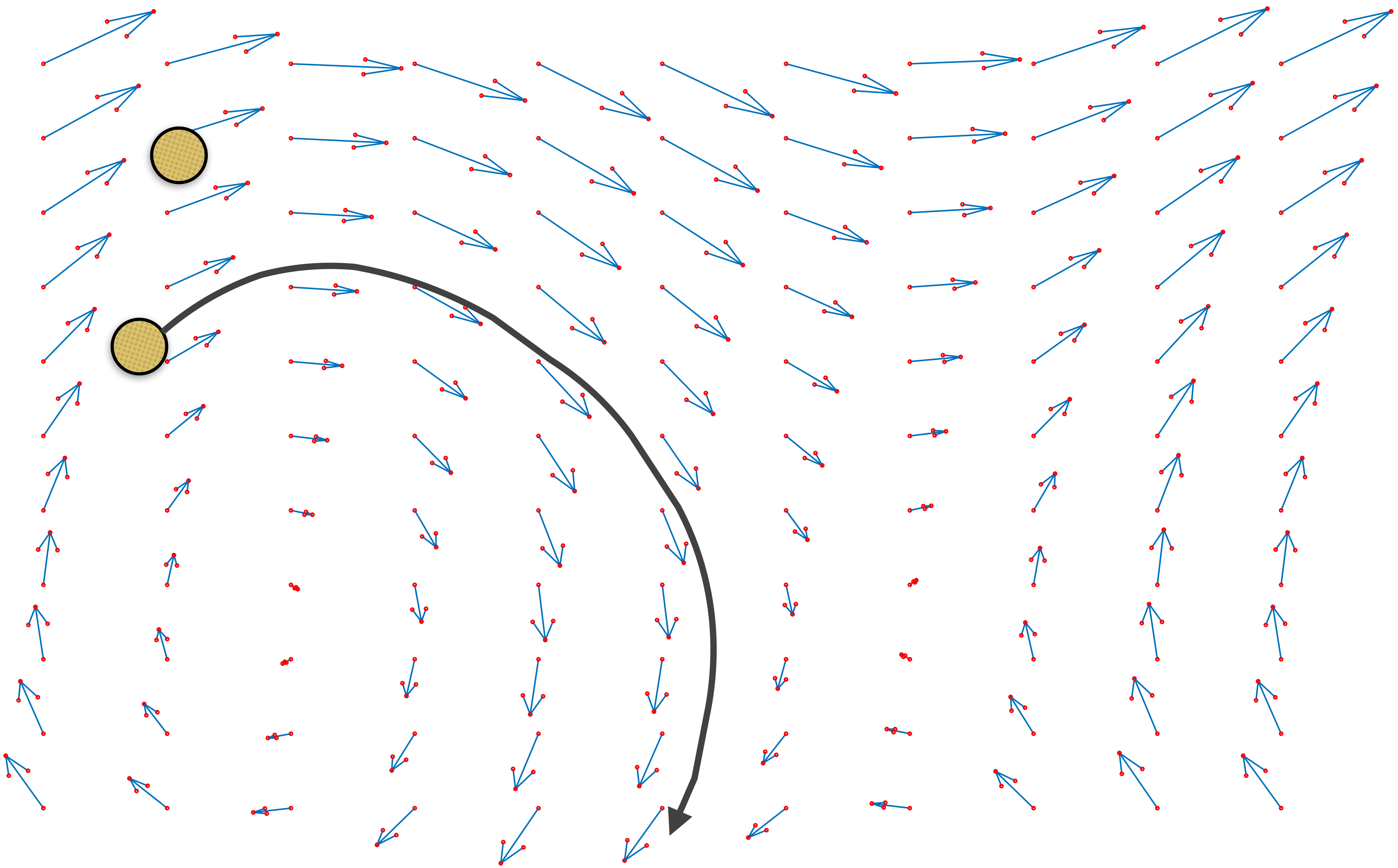
I. A Simple Start: Particle Dynamics

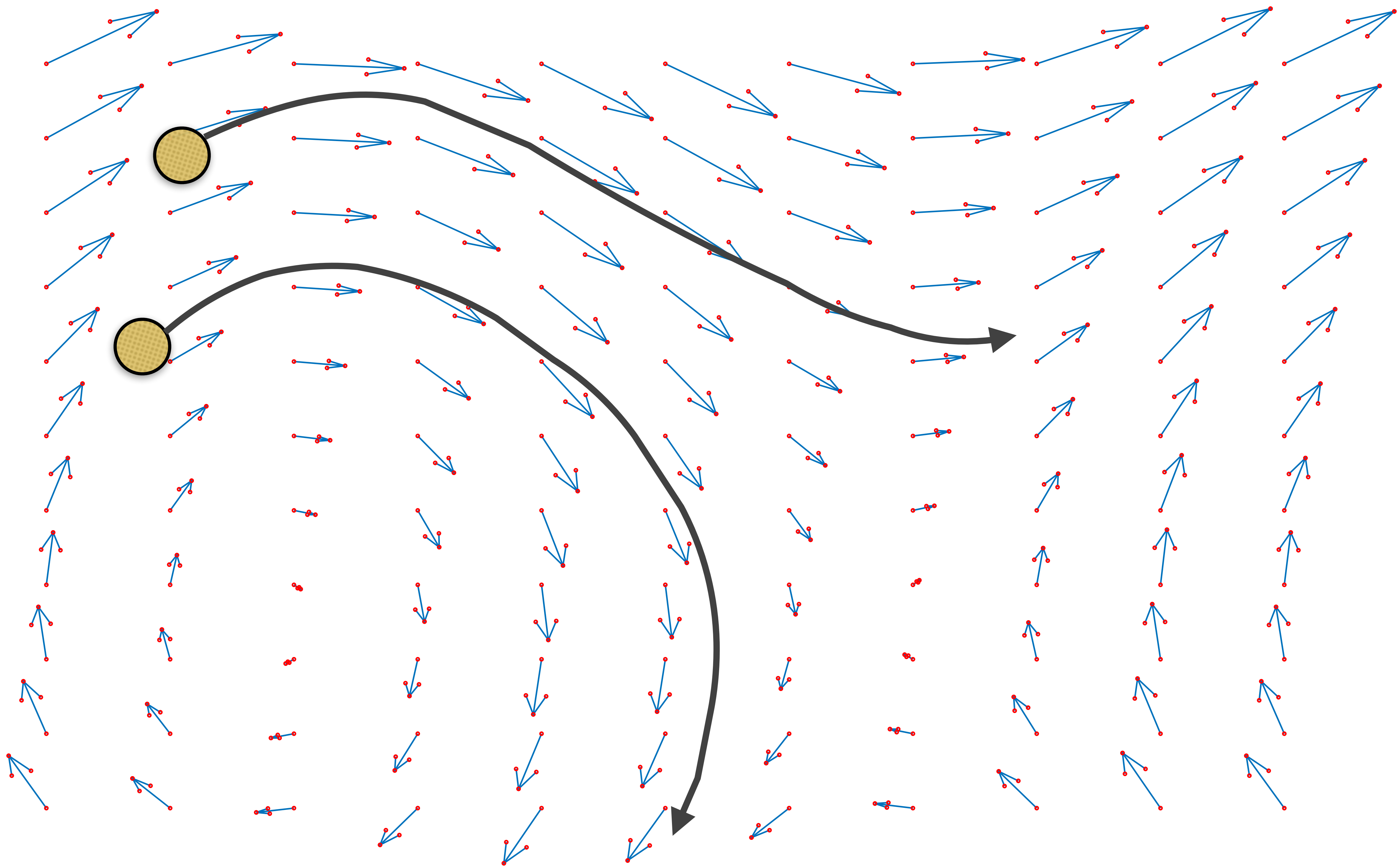
Let’s jump right in and consider the problem of tracing a particle through a velocity field











Initial Value Problem

$$\mathbf{x}_p(0) = \mathbf{x}_0$$

$$\frac{d\mathbf{x}_p(t)}{dt} = \mathbf{v}(\mathbf{x}_p, t)$$

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Change

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Change ⟶

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Change ⟶ Difference

Initial Value Problem

$$\mathbf{x}_p(0) = \mathbf{x}_0$$

$$\frac{d\mathbf{x}_p(t)}{dt} = \mathbf{v}(\mathbf{x}_p, t)$$

Change ⟶ Difference

Differential Equation

Initial Value Problem

$$\mathbf{x}_p(0) = \mathbf{x}_0$$

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Change ⟶ Difference

Ordinary Differential Equation

Initial Value Problem

$$\mathbf{x}_p(0) = \mathbf{x}_0$$

$$\frac{d\mathbf{x}_p(t)}{dt} = \mathbf{v}(\mathbf{x}_p, t)$$

Change $\longrightarrow$ Difference

First-order Ordinary Differential Equation

Initial Value Problem

$$\mathbf{x}_p(0) = \mathbf{x}_0$$

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Simple

Powerful

Initial Value Problem

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Simple

Powerful

Instructive

Euler’s Method

The Derivative

$$\frac{d\mathbf{x}_p(t)}{dt} = \lim_{\epsilon \to 0} \frac{\mathbf{x}_p(t+\epsilon) - \mathbf{x}_p(t)}{\epsilon}$$

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The Derivative

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$$\epsilon \longrightarrow \Delta t$$

$$\frac{d\mathbf{x}_p(t)}{dt} \approx \frac{\mathbf{x}_p(t+\Delta t) - \mathbf{x}_p(t)}{\Delta t}$$

Euler's Method

$$\frac{d\mathbf{x}_p(t)}{dt} \approx \frac{\mathbf{x}_p(t + \Delta t) - \mathbf{x}_p(t)}{\Delta t}$$

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$$+$$

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$$\mathbf{x}_p(t+\Delta t) = \mathbf{x}_p(t) + \Delta t \cdot \mathbf{v}(\mathbf{x}_p, t)$$

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The Great Tradeoff

$$\frac{d\mathbf{x}_p(t)}{dt} \approx \frac{\mathbf{x}_p(t+\Delta t) - \mathbf{x}_p(t)}{\Delta t}$$

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As Δt decreases

The Great Tradeoff

$$\frac{d\mathbf{x}_p(t)}{dt} \approx \frac{\mathbf{x}_p(t + \Delta t) - \mathbf{x}_p(t)}{\Delta t}$$

As Δt decreases

the approximation gets better

The Great Tradeoff

$$\frac{d\mathbf{x}_p(t)}{dt} \approx \frac{\mathbf{x}_p(t+\Delta t) - \mathbf{x}_p(t)}{\Delta t}$$

As Δt decreases

the approximation gets better

but

The Great Tradeoff

$$\frac{d\mathbf{x}_p(t)}{dt} \approx \frac{\mathbf{x}_p(t + \Delta t) - \mathbf{x}_p(t)}{\Delta t}$$

As Δt decreases

the approximation gets better

but

the computational cost increases

Let’s consider another problem

In the real world

$$\mathbf{f} = m\mathbf{a}$$

Another Initial Value Problem

$$\mathbf{x}_p(0) = \mathbf{x}_0$$

$$\frac{d^2\mathbf{x}_p(t)}{dt^2} = \frac{\mathbf{f}(\mathbf{x}_p, t)}{m_p}$$

Another Initial Value Problem

$$\mathbf{x}_p(0) = \mathbf{x}_0$$

$$\frac{d^2\mathbf{x}_p(t)}{dt^2} = \frac{\mathbf{f}(\mathbf{x}_p, t)}{m_p}$$

Second-order Ordinary Differential Equation

Another Initial Value Problem

$$\mathbf{x}_p(0) = \mathbf{x}_0$$
$$\mathbf{v}_p(0) = \mathbf{v}_0$$

$$\frac{d\mathbf{x}_p(t)}{dt} = \mathbf{v}(\mathbf{x}_p, t)$$

$$\frac{d\mathbf{v}_p(t)}{dt} = \frac{\mathbf{f}(\mathbf{x}_p, t)}{m_p}$$

Another Initial Value Problem

$$\mathbf{x}_p(0) = \mathbf{x}_0$$

$$\mathbf{v}_p(0) = \mathbf{v}_0$$

$$\frac{d\mathbf{x}_p(t)}{dt} = \mathbf{v}(\mathbf{x}_p, t)$$

$$\frac{d\mathbf{v}_p(t)}{dt} = \frac{\mathbf{f}(\mathbf{x}_p, t)}{m_p}$$

Coupled First-order Ordinary Differential Equations

Euler's Method (Again)

$$\mathbf{v}_p(t + \Delta t) = \mathbf{v}_p(t) + \Delta t \cdot \frac{\mathbf{f}(\mathbf{x}_p, t)}{m_p}$$

$$\mathbf{x}_p(t + \Delta t) = \mathbf{x}_p(t) + \Delta t \cdot \mathbf{v}_p(t + \Delta t)$$

Euler's Method (Again)

$$\mathbf{v}_p(t + \Delta t) = \mathbf{v}_p(t) + \Delta t \cdot \frac{\mathbf{f}(\mathbf{x}_p, t)}{m_p}$$

$$\mathbf{x}_p(t + \Delta t) = \mathbf{x}_p(t) + \Delta t \cdot \mathbf{v}_p(t + \Delta t)$$

Symplectic Euler

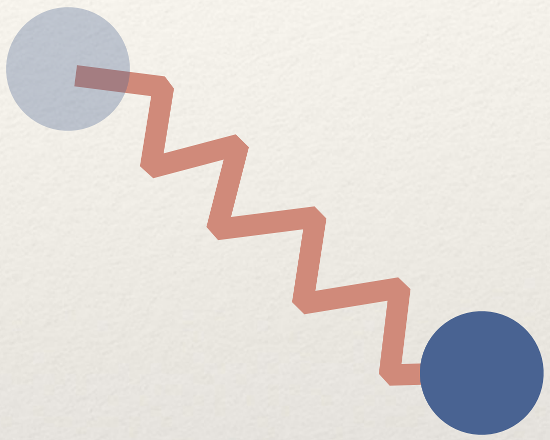
```
struct Particle {
  double mass;
  Eigen::Vector3d pos, vel, frc;
};


foreach (p : particles) {
  p.frc = 0.0;
}

foreach (f : forces) {
  foreach (p : forces.affectedParticles) {
    p.frc += f.computeForce(p);
  }
}

foreach (p : particle) {
  p.vel += dt * p.frc / p.mass;
  p.pos += dt * p.vel;
}
```

Check our Karl Sim’s *Particle Dreams*

Let’s Add Springs!

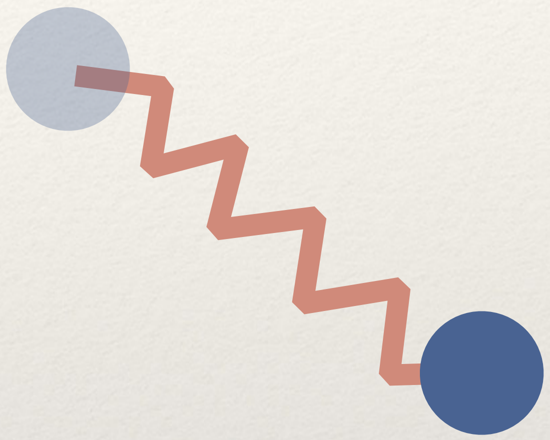
Springs

$$\mathbf{f} = -k\mathbf{d}$$



Springs

$$\mathbf{f}_p = -k\mathbf{x}_p$$



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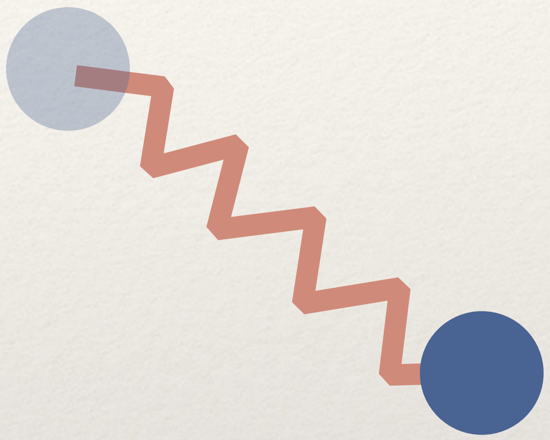
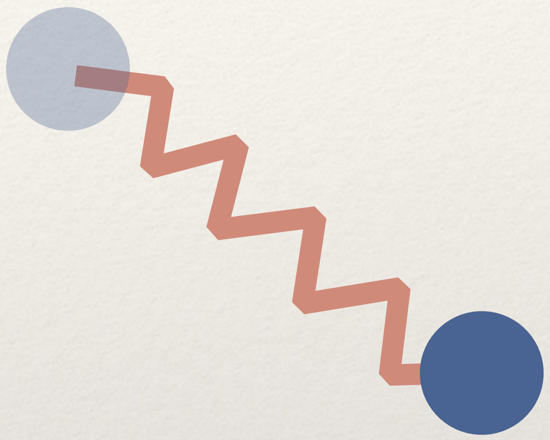


non-zero rest length?

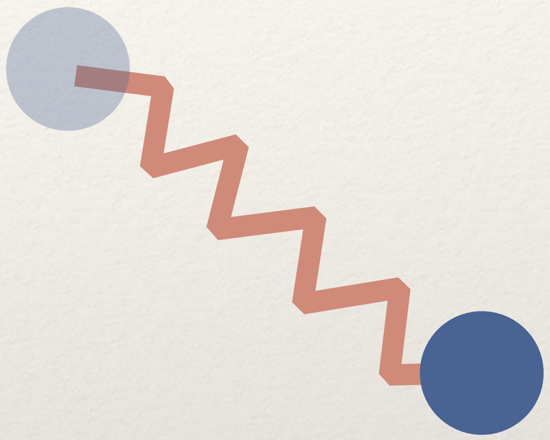
Springs

$$\mathbf{f}_p = -k\mathbf{x}_p$$

$$\mathbf{f}_p = -k\left(\|\mathbf{x}_p\|\right)\frac{\mathbf{x}_p}{\|\mathbf{x}_p\|}$$



Springs



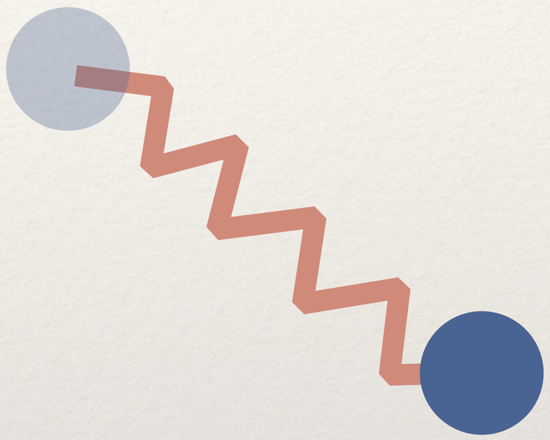
$$\mathbf{f}_p = -k\mathbf{x}_p$$

$$\mathbf{f}_p = -k\left(\|\mathbf{x}_p\|\right)\frac{\mathbf{x}_p}{\|\mathbf{x}_p\|}$$

$$\mathbf{f}_p = -k\left(\|\mathbf{x}_p\| - r\right)\frac{\mathbf{x}_p}{\|\mathbf{x}_p\|}$$

Springs

$$\mathbf{f}_p = -k\left(\|\mathbf{x}_p\| - r\right)\frac{\mathbf{x}_p}{\|\mathbf{x}_p\|}$$



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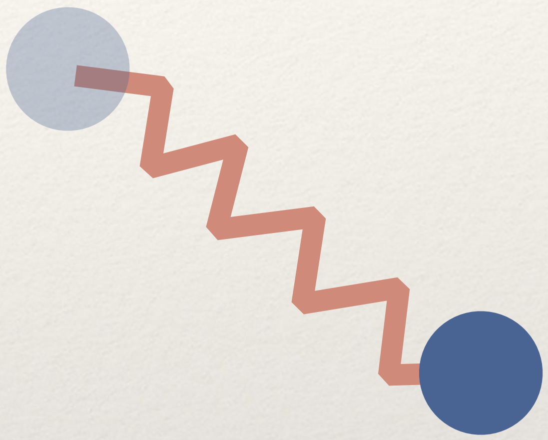
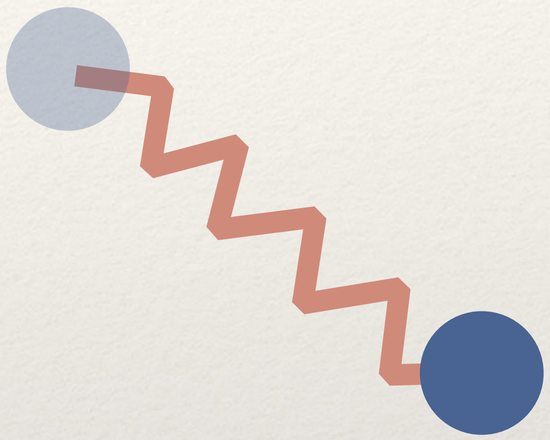


Strain $$\left(\frac{\|\mathbf{x}_p\|}{r} - 1\right)$$

Springs

$$\mathbf{f}_p = -k\left(\|\mathbf{x}_p\| - r\right)\frac{\mathbf{x}_p}{\|\mathbf{x}_p\|}$$



Strain $\left(\frac{\|\mathbf{x}_p\|}{r} - 1\right)$

$$\mathbf{f}_p = -k\left(\frac{\|\mathbf{x}_p\|}{r} - 1\right)\frac{\mathbf{x}_p}{\|\mathbf{x}_p\|}$$

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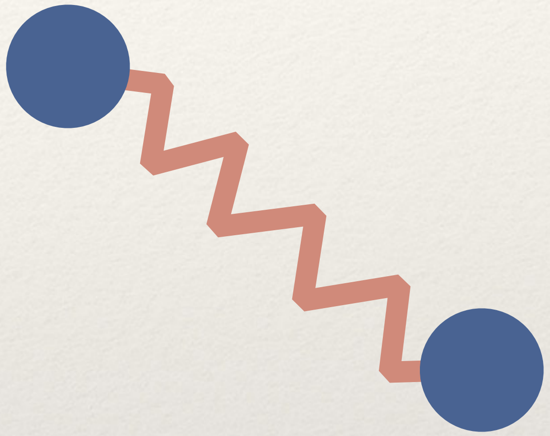

Springs

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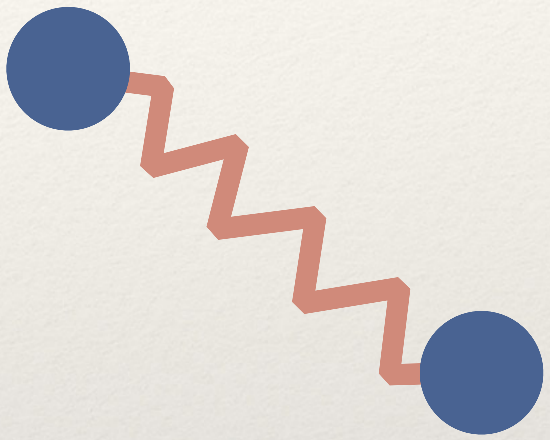
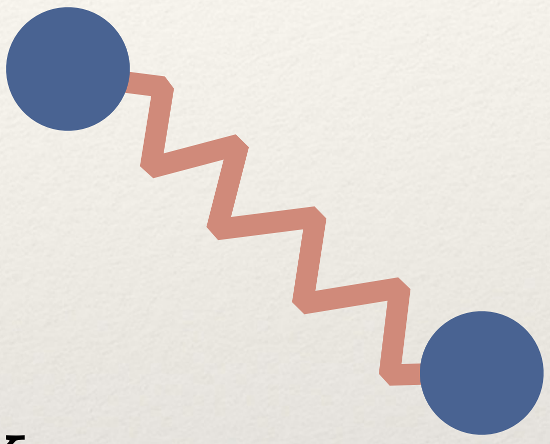


arbitrary connection?

Springs

$$\mathbf{f}_p = -k\left(\frac{\|\mathbf{x}_p\|}{r} - 1\right)\frac{\mathbf{x}_p}{\|\mathbf{x}_p\|}$$



$$\mathbf{f}_p = k\left(\frac{\|\mathbf{x}_q - \mathbf{x}_p\|}{r} - 1\right)\frac{\mathbf{x}_q - \mathbf{x}_p}{\|\mathbf{x}_q - \mathbf{x}_p\|}$$

Springs

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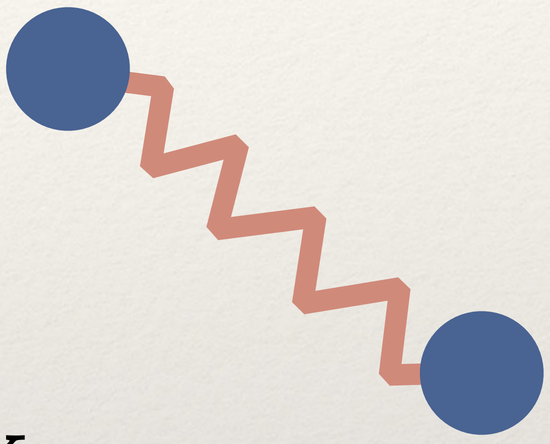

$$\mathbf{f}_p = k\left(\frac{\|\mathbf{x}_q - \mathbf{x}_p\|}{r} - 1\right)\frac{\mathbf{x}_q - \mathbf{x}_p}{\|\mathbf{x}_q - \mathbf{x}_p\|}$$

$$\mathbf{f}_q = -\mathbf{f}_p$$

Damping

$$\mathbf{f}_p = k \left(\frac{\|\mathbf{x}_q - \mathbf{x}_p\|}{r} - 1 \right) \frac{\mathbf{x}_q - \mathbf{x}_p}{\|\mathbf{x}_q - \mathbf{x}_p\|}$$

Damping

$$\mathbf{f}_p = k\left(\frac{\|\mathbf{x}_q - \mathbf{x}_p\|}{r} - 1\right)\frac{\mathbf{x}_q - \mathbf{x}_p}{\|\mathbf{x}_q - \mathbf{x}_p\|}$$

$$\mathbf{f}_p = k_d\left(\frac{\mathbf{v}_q - \mathbf{v}_p}{r} \cdot \frac{\mathbf{x}_q - \mathbf{x}_p}{\|\mathbf{x}_q - \mathbf{x}_p\|}\right)\frac{\mathbf{x}_q - \mathbf{x}_p}{\|\mathbf{x}_q - \mathbf{x}_p\|}$$

Damping

$$\mathbf{f}_p = k\left(\frac{\|\mathbf{x}_q - \mathbf{x}_p\|}{r} - 1\right)\frac{\mathbf{x}_q - \mathbf{x}_p}{\|\mathbf{x}_q - \mathbf{x}_p\|}$$

$$\mathbf{f}_p = k_d\left(\underbrace{\frac{\mathbf{v}_q - \mathbf{v}_p}{r}}_{\text{relative velocity}} \cdot \frac{\mathbf{x}_q - \mathbf{x}_p}{\|\mathbf{x}_q - \mathbf{x}_p\|}\right)\frac{\mathbf{x}_q - \mathbf{x}_p}{\|\mathbf{x}_q - \mathbf{x}_p\|}$$

Damping

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$$\mathbf{f}_p = \left[k_s\left(\frac{\|\mathbf{x}_q - \mathbf{x}_p\|}{r} - 1\right) + k_d\left(\frac{(\mathbf{v}_q - \mathbf{v}_p)\cdot(\mathbf{x}_q - \mathbf{x}_p)}{r\|\mathbf{x}_q - \mathbf{x}_p\|}\right)\right]\frac{\mathbf{x}_q - \mathbf{x}_p}{\|\mathbf{x}_q - \mathbf{x}_p\|}$$

```
foreach (p : particles) {
  p.frc = 0.0;
}

foreach (s : springs) {
  Eigen::Vector3d d = particles[s->j].pos - particles[s->i].pos;
  double l = d.norm();
  Eigen::Vector3d v = particles[s->j].vel - particles[s->i].vel;
  Eigen::Vector3d frc = (params.k_s*((l / s->r) - 1.0) +
     params.k_d*(v.dot(d)/(l*s->r))) * (d/l);
  particles[s.i].frc += frc
  particles[s.j].frc -= frc
}

foreach (p : particle) {
  p.vel += dt * p.frc / p.mass;
  p.pos += dt * p.vel;
}
```

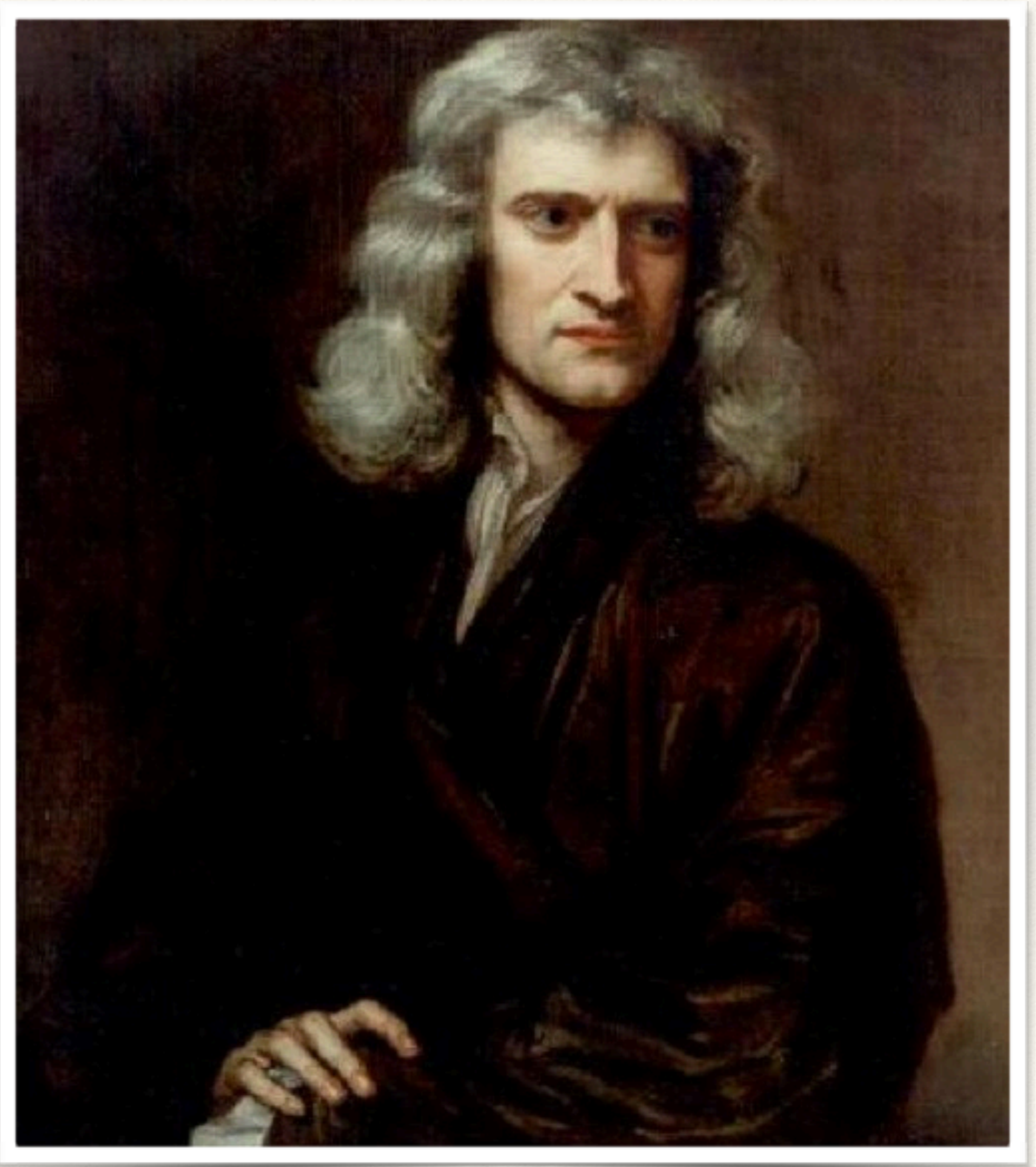
Live Demo

II. Mathematical Models

Newton’s Laws

Newtonian Mechanics

- Published in *Principia,* 1687
- Includes three laws of motion:
  - inertia
  - f = ma
  - action / reaction
- Idealized particle or point mass



Newton's First Law

A body persists at rest or in uniform motion in a straight line unless acted upon by a force

- Law of Inertia
  - Defines an inertial frame of reference

Newton's Second Law (f = ma)

The rate of change of momentum of a body is directly proportional to the force applied to the body

$$\frac{d}{dt} m\mathbf{v}(t) = m\mathbf{a} = \mathbf{f}(t)$$

- The basis for evolving a system of interacting particles

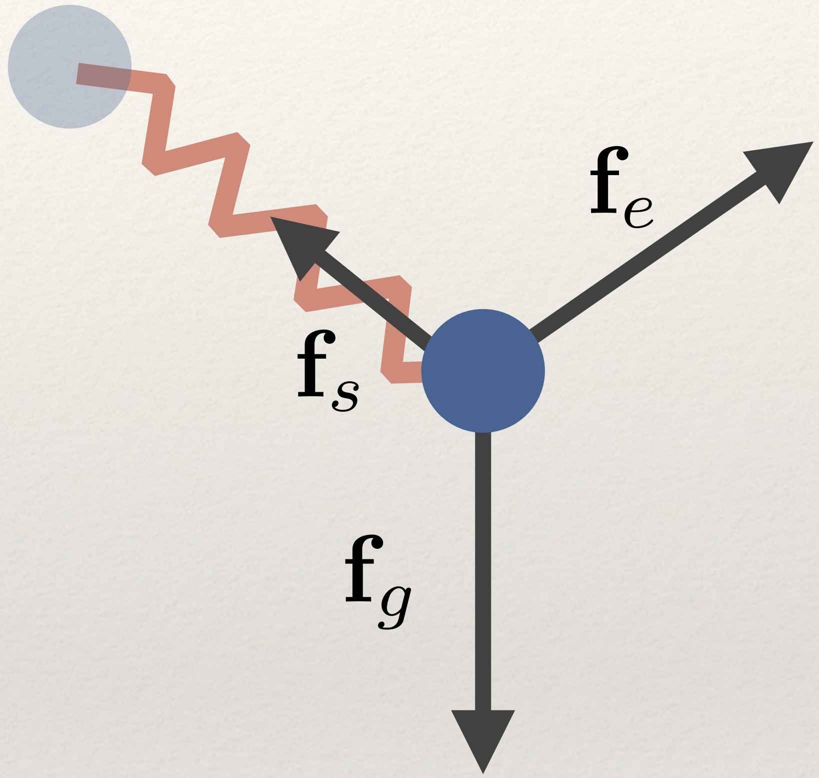
Newton's Second Law (f = ma)

- leads to a system of ODEs

$$\dot{\mathbf{x}}(t) = \mathbf{v}(t)$$

$$\dot{\mathbf{v}}(t) = \mathbf{a}(t) = \frac{1}{m}\mathbf{f}(t)$$

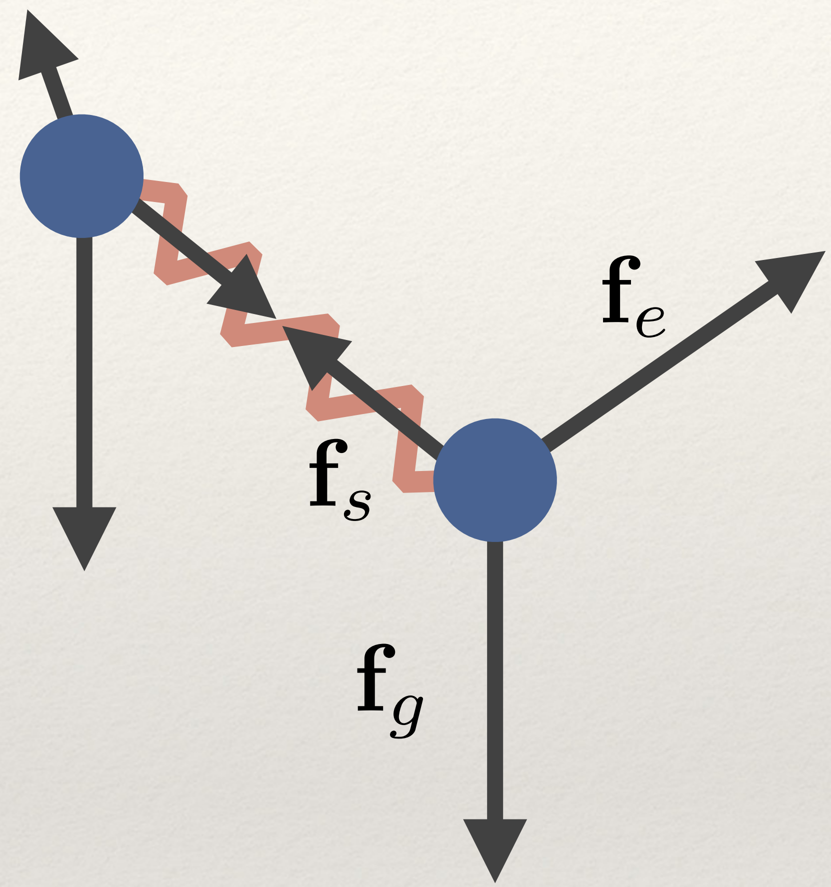
$$\mathbf{f}(t) = \mathbf{f}_e(t) + \mathbf{f}_g(t) + \mathbf{f}_s(t)$$



$$m\mathbf{a} = \mathbf{f}_e + \mathbf{f}_g + \mathbf{f}_s$$

Newton's Second Law (f = ma)

- To model a system of particles,
  - characterize all the forces on each particle
  - Start with some initial conditions and apply f = ma to evolve in time



$$m\mathbf{a} = \mathbf{f}_e + \mathbf{f}_g + \mathbf{f}_s$$

Newton’s Third Law (Action/Reaction)

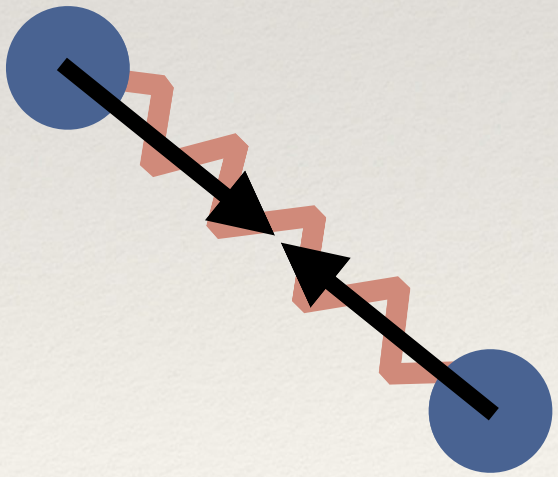
For every action, there is an equal and opposite reaction

- If body 1 applies force **f** to body 2, then body 2 applies force **-f** to body 1

Newton's Third Law (Action/Reaction)

For every action, there is an equal and opposite reaction

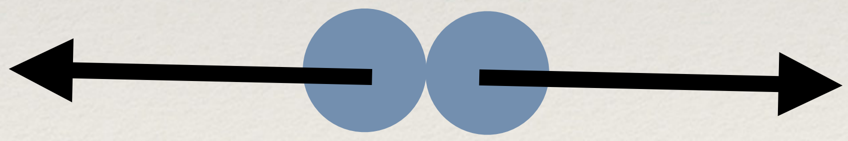
- If body 1 applies force **f** to body 2, then body 2 applies force **-f** to body 1
- Example: Two particles connected by a spring force, equal/opposite pair of forces



Newton's Third Law (Action/Reaction)

For every action, there is an equal and opposite reaction

- If body 1 applies force **f** to body 2, then body 2 applies force **-f** to body 1
- Example: In the collision of two particles, equal/opposite pair of forces prevents interpenetration



Newton's Third Law (Action/Reaction)

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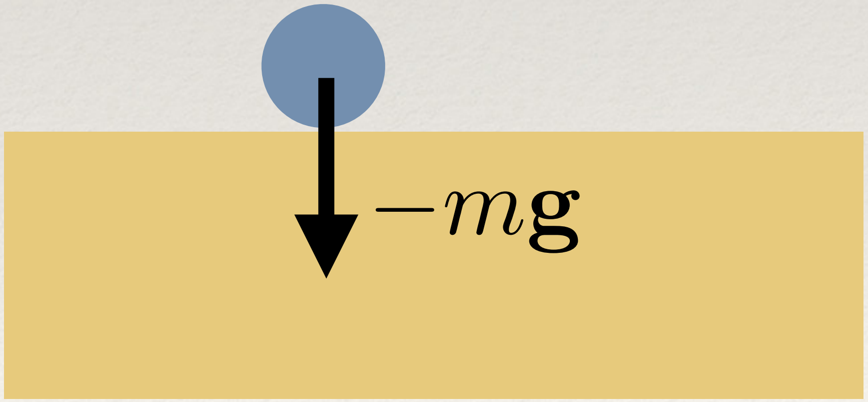
- If body 1 applies force **f** to body 2, then body 2 applies force **-f** to body 1
- Example: Particle resting on a surface, equal/opposite pair of forces prevents interpenetration



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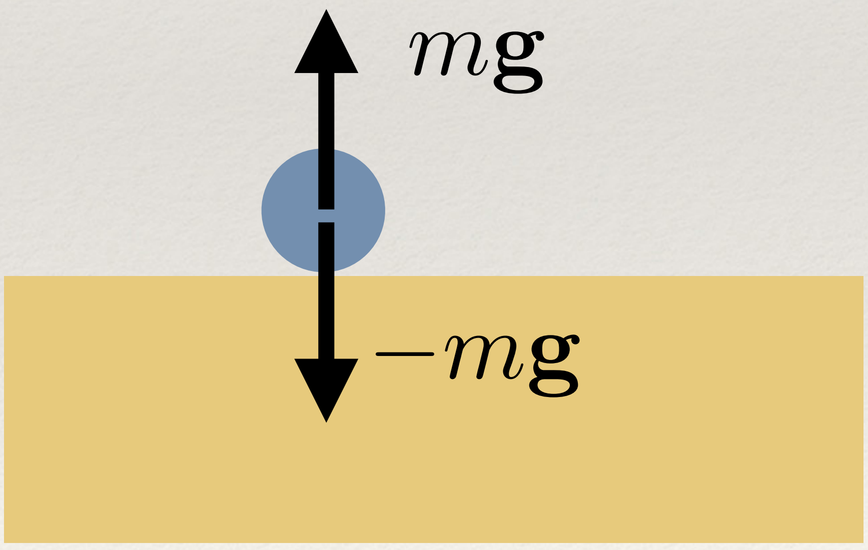


Alternative: Variational Mechanics

- Newtonian Mechanics is one formulation of classical mechanics
  - Based on vectors in Cartesian space
- Another set of approaches is called "variational" and is based on a principle of least action
  - variational approaches let you use any set of coordinates

Conservation Laws

Conserved Quantities

- Cannot be created or destroyed!
- Includes mass, linear momentum, angular momentum, and energy

Conservation Laws

- Used in deriving evolution equations
- Inform choice of discrete approximation to continuous equations
- Implications for visual quality, numerical accuracy, and stability

Conservation of Mass

- Mass not created or destroyed (inexact)
- Mass naturally conserved in particle-based methods
  - Particles carry mass with them as they move
- Grid-based methods sometimes have issues with proper mass conservation

Conservation of Momentum

- By Newton's second law, if there is no net force on a body, i.e., $\mathbf{f} = \mathbf{0}$

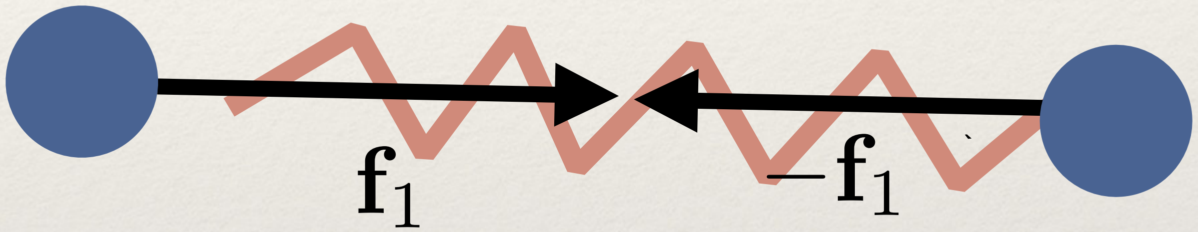
$$\frac{d}{dt} m\mathbf{v} = \mathbf{0}$$

$$\Rightarrow m\mathbf{v}(t) = \text{constant}$$

- So the momentum of the particle is conserved
- Similarly, if there is no net torque on a body, angular momentum is constant

Conservation of Momentum

- Newton's third law equal/opposite also implies conservation of linear and angular momentum



$$\frac{d}{dt}\mathbf{P}(t) = \mathbf{f}_1 + (-\mathbf{f}_1) = \mathbf{0}$$

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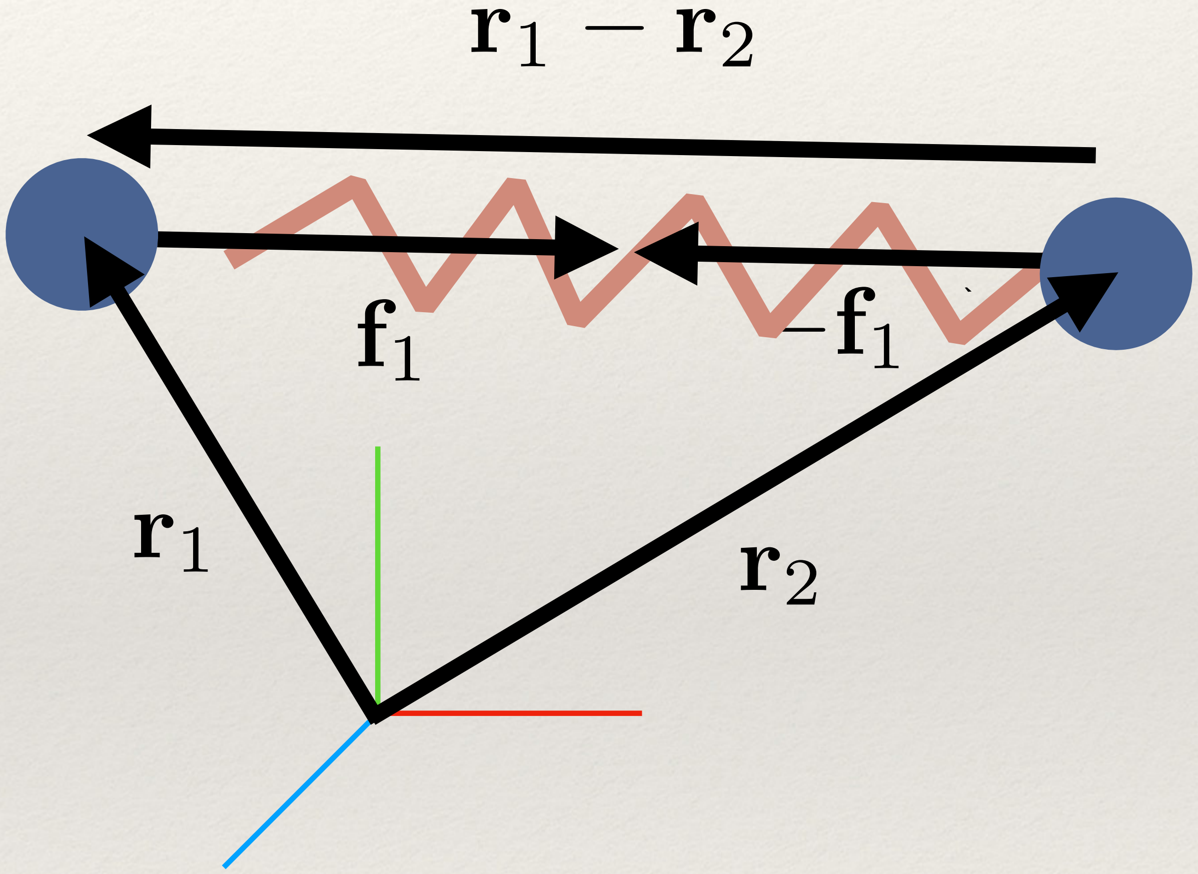
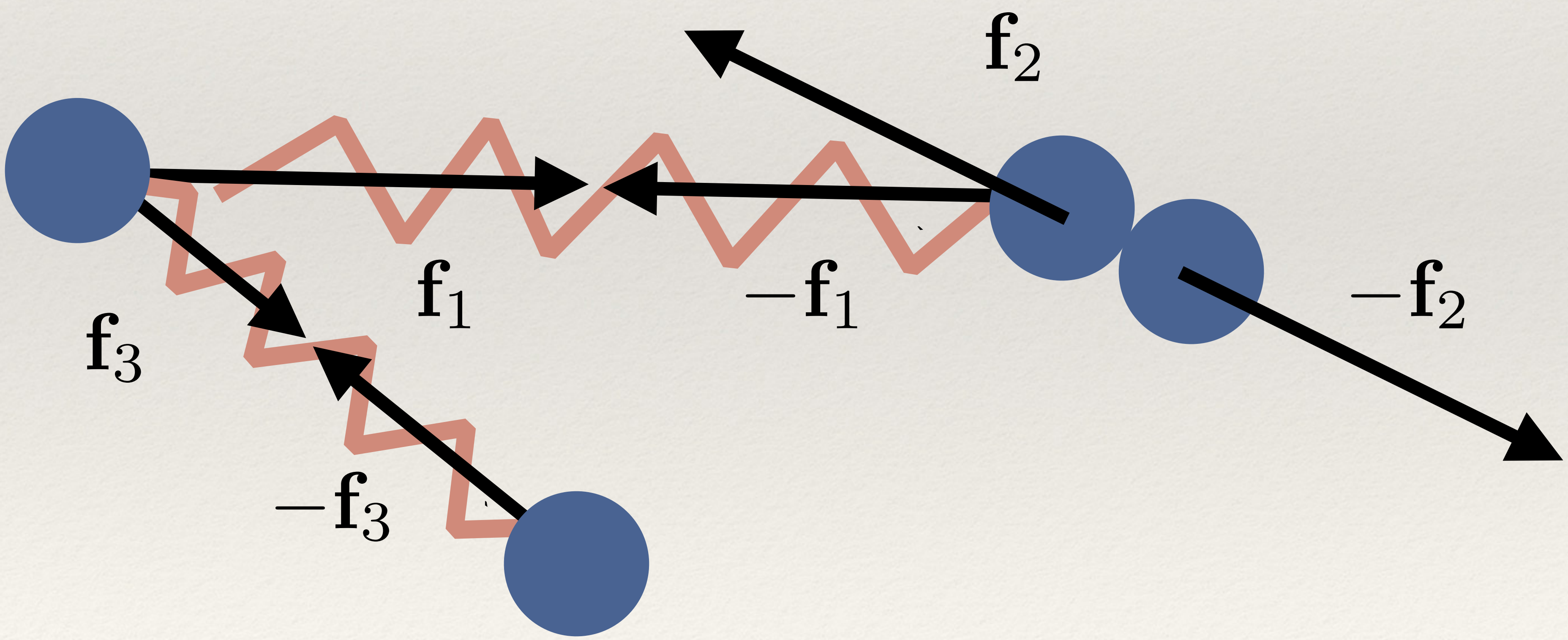


$$\frac{d}{dt}\mathbf{L}(t) = \mathbf{r}_1 \times \mathbf{f}_1 + \mathbf{r}_2 \times (-\mathbf{f}_1) = (\mathbf{r}_1 - \mathbf{r}_2) \times \mathbf{f}_1 = \mathbf{0}$$

Conservation of Momentum

- Same holds for a collection of interacting particles!



Conservation of Energy

- Initial energy (potential)

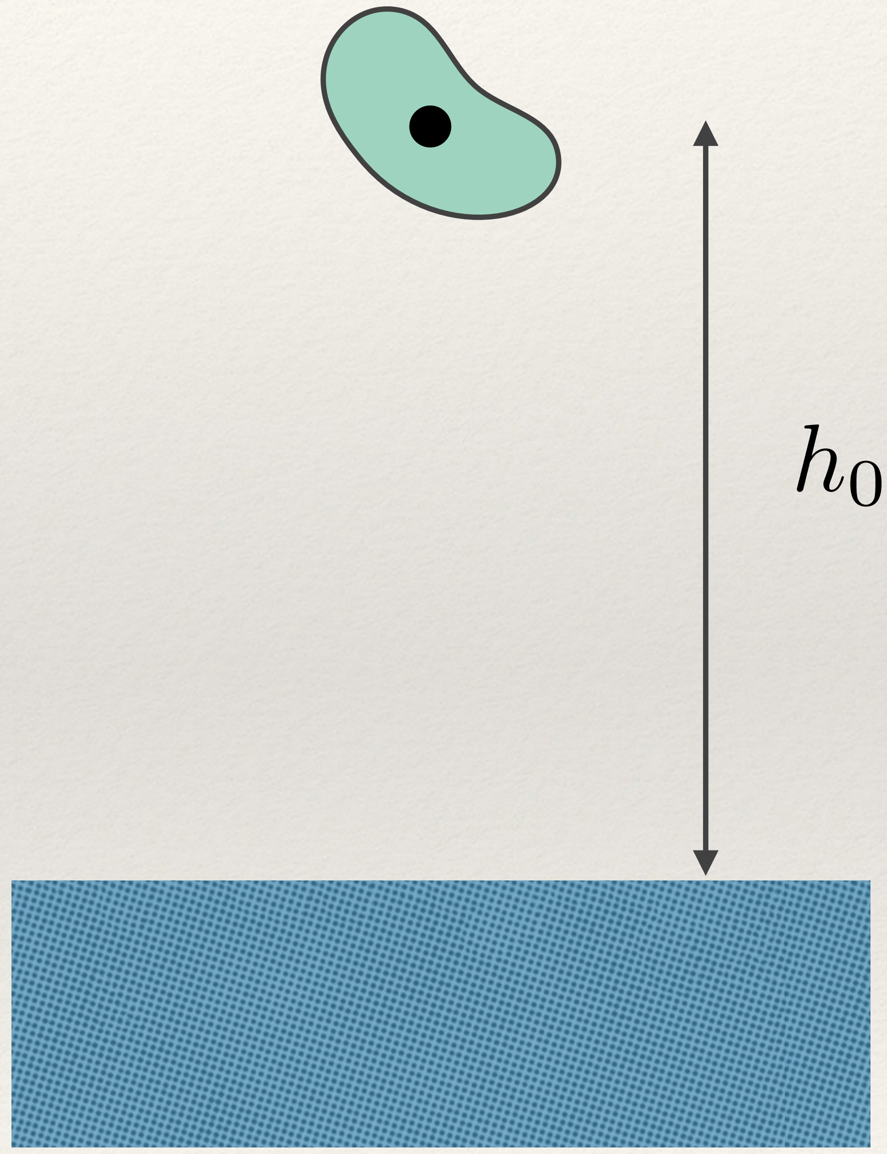
$$mgh_0$$

- Conservation of energy

$$\frac{1}{2}mv(t)^2 + mgh(t) = mgh_0$$

- Speed when hits

$$v(t) = \sqrt{2gh_0}$$



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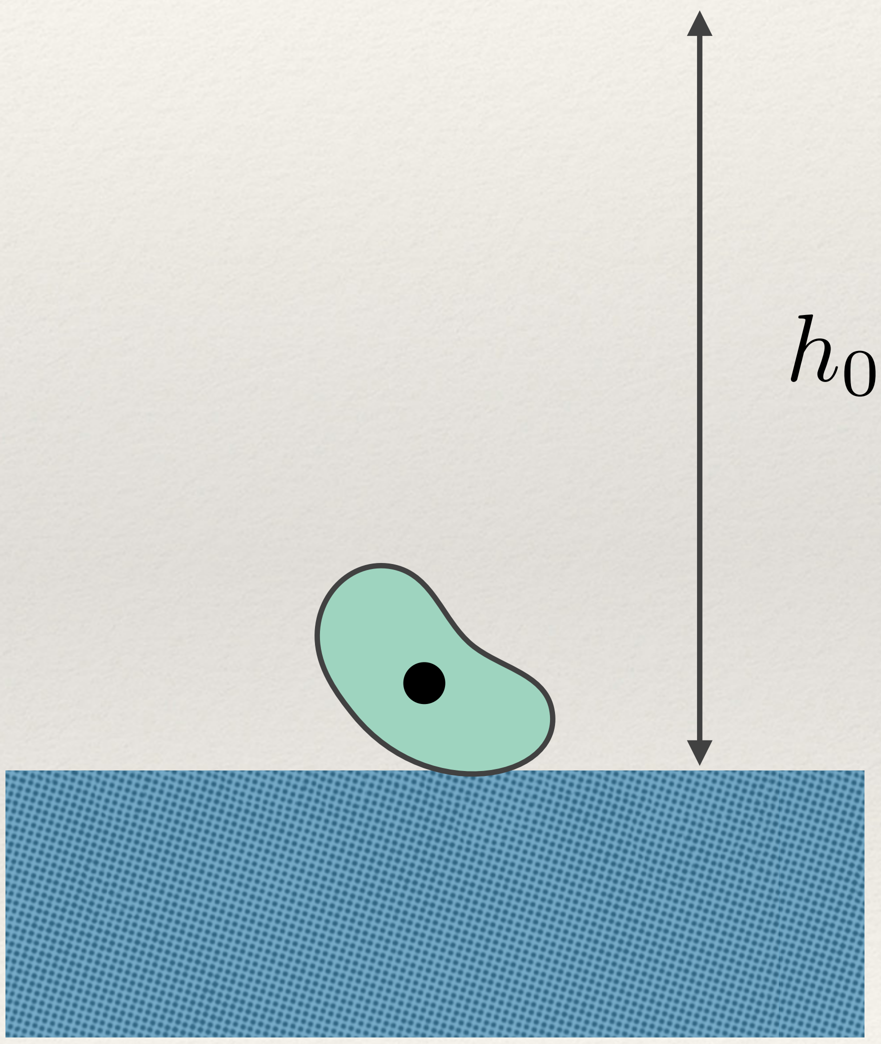
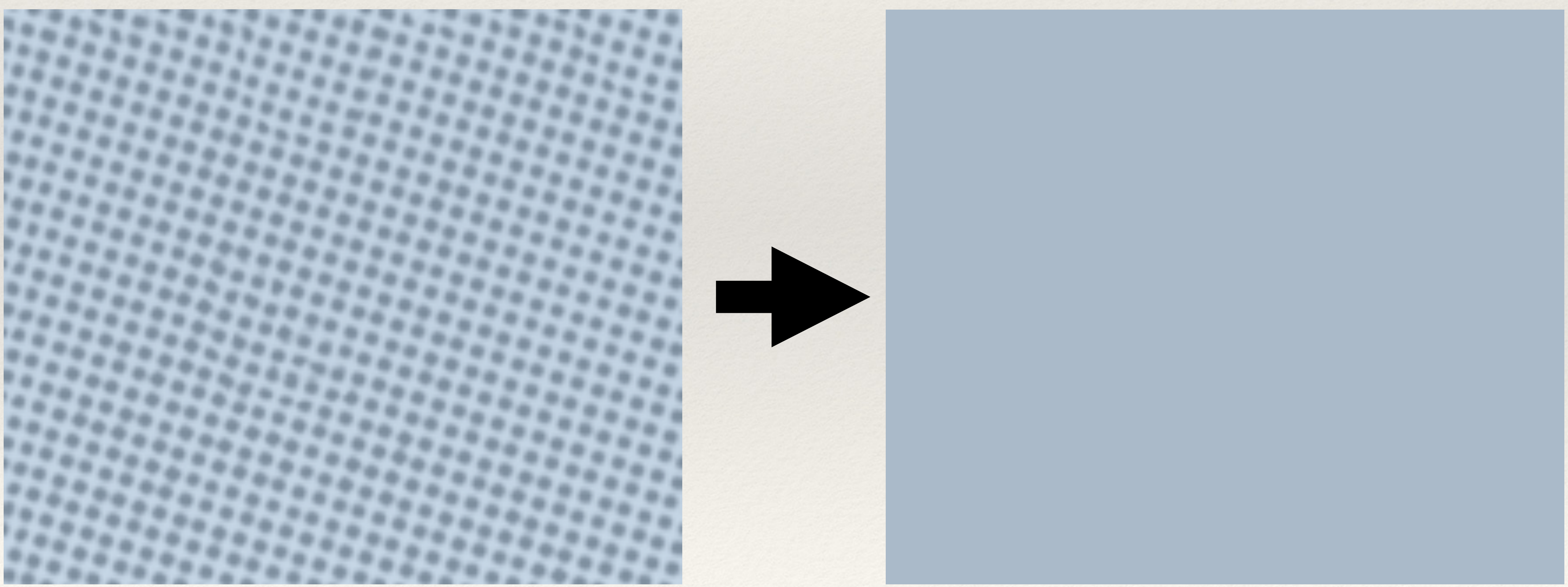


Conservation of Energy

- Different numerical schemes have different ent energy conservation properties
- In many schemes, energy grows or decays nonphysically
  - instability (blow up), or
  - motion too damped

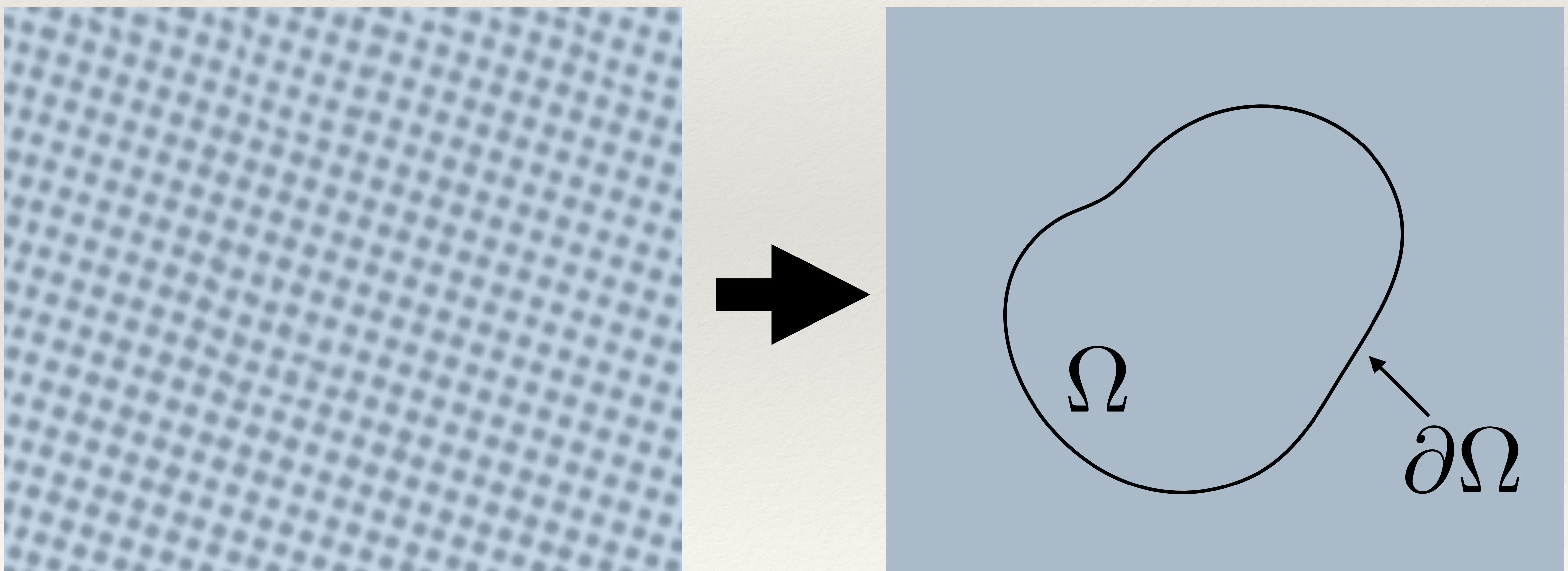
Conservation Laws for Continua

- At large enough length scales, model matter as a continuum rather than set of discrete particles



Conservation Laws for Continua

- To derive evolution equations for continua, consider arbitrary control volume Ω



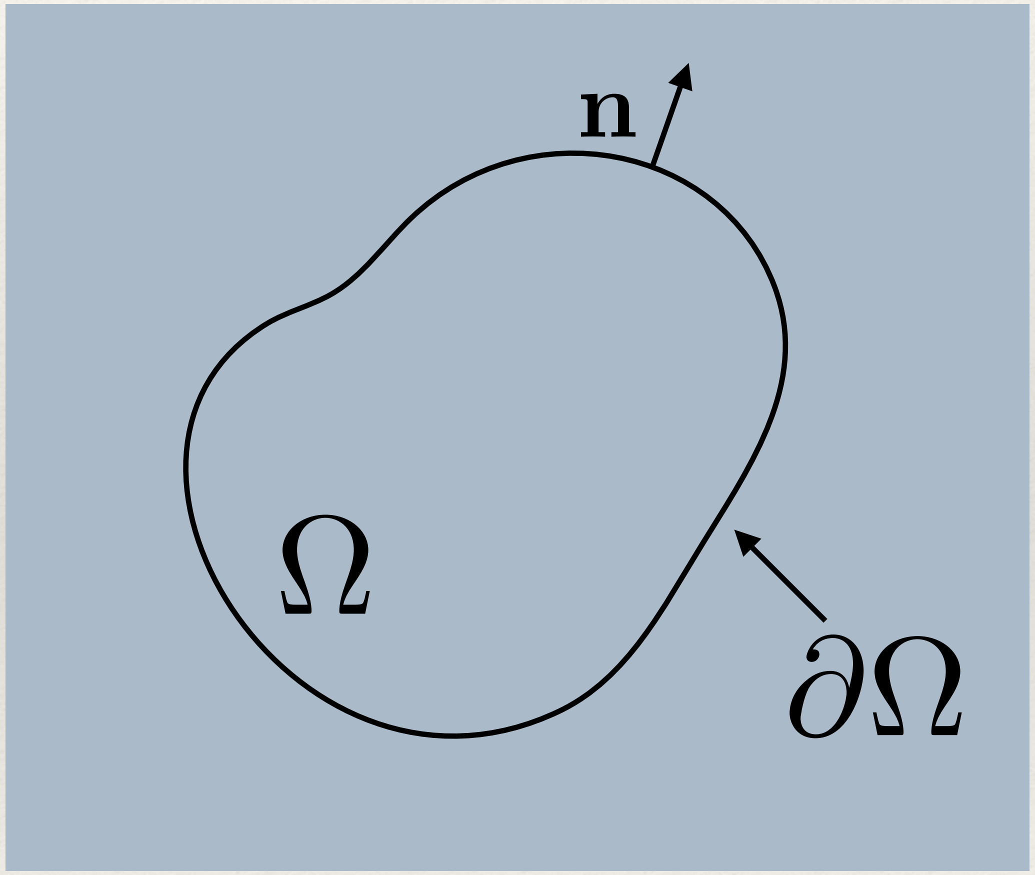
Conservation Laws for Continua

- Conservation of Mass

$$\frac{d}{dt}\int_{\Omega}\rho dV = -\oint_{\partial\Omega}\rho\mathbf{v}\cdot\mathbf{n}dS$$

- Continuity Equation

$$\Rightarrow \frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0$$

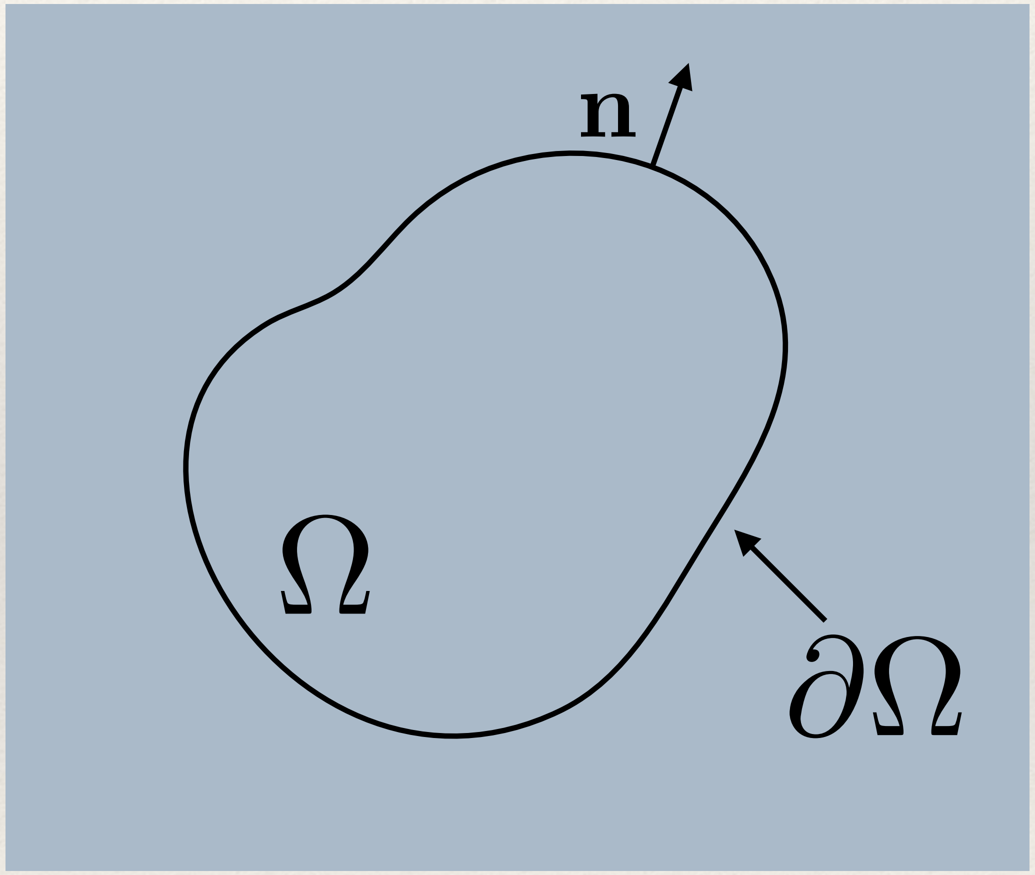


Conservation Laws for Continua

- Local conservation law

$$\frac{\partial u}{\partial t} + \nabla \cdot \mathbf{f}(u) = 0$$

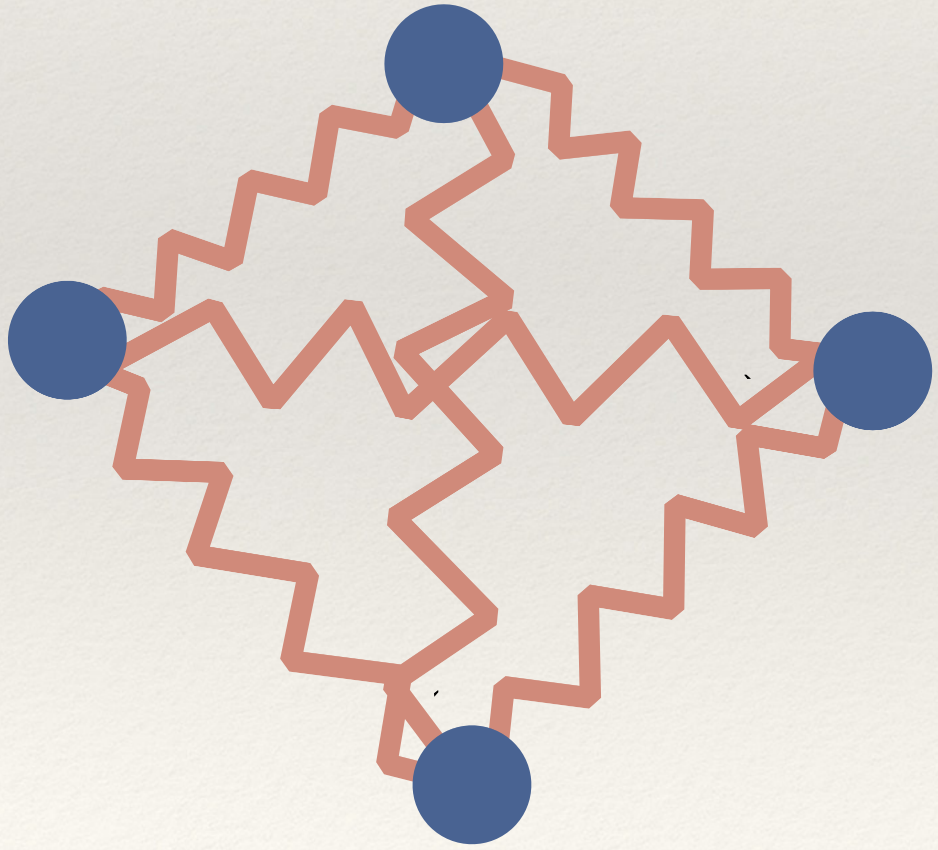
flux



Rigid Bodies

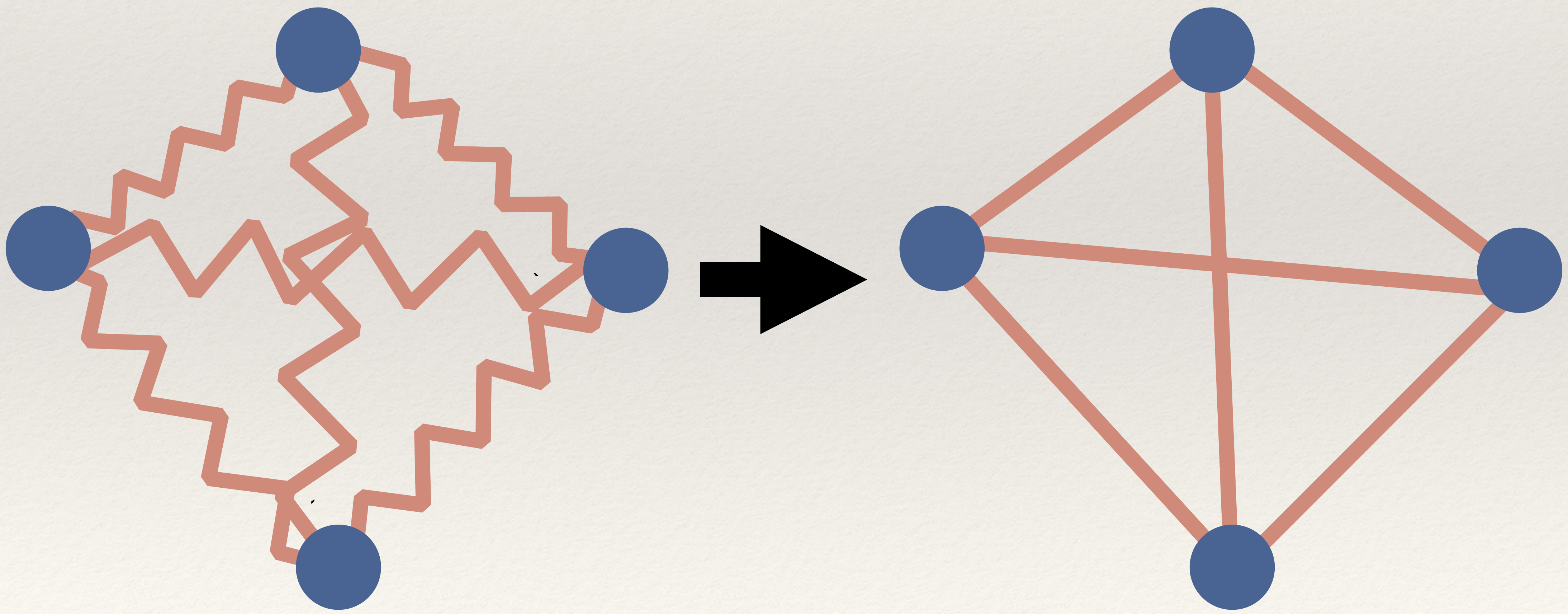
Rigid Body Idealization

- If deformation is negligible, a rigid body approximation is more efficient than a soft body model



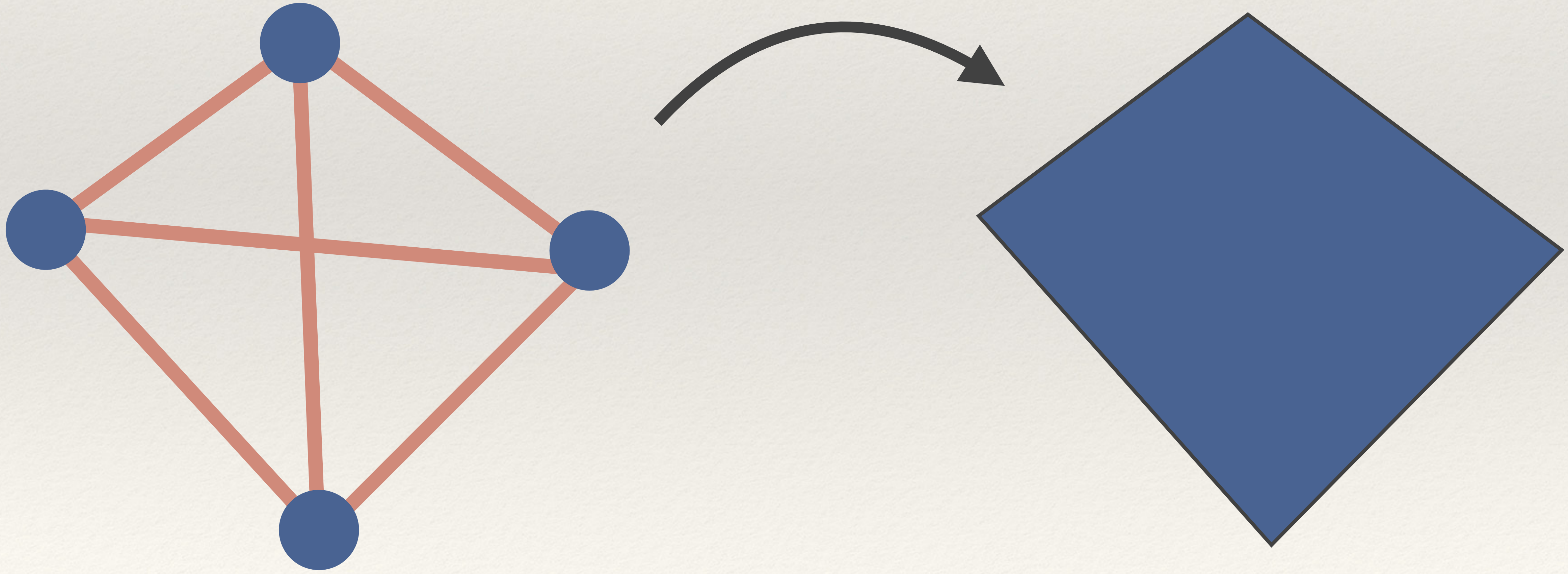
Rigid Body Idealization

- Elastic forces are replaced with constraints that particles in the body remain a fixed distance apart



Rigid Body Idealization

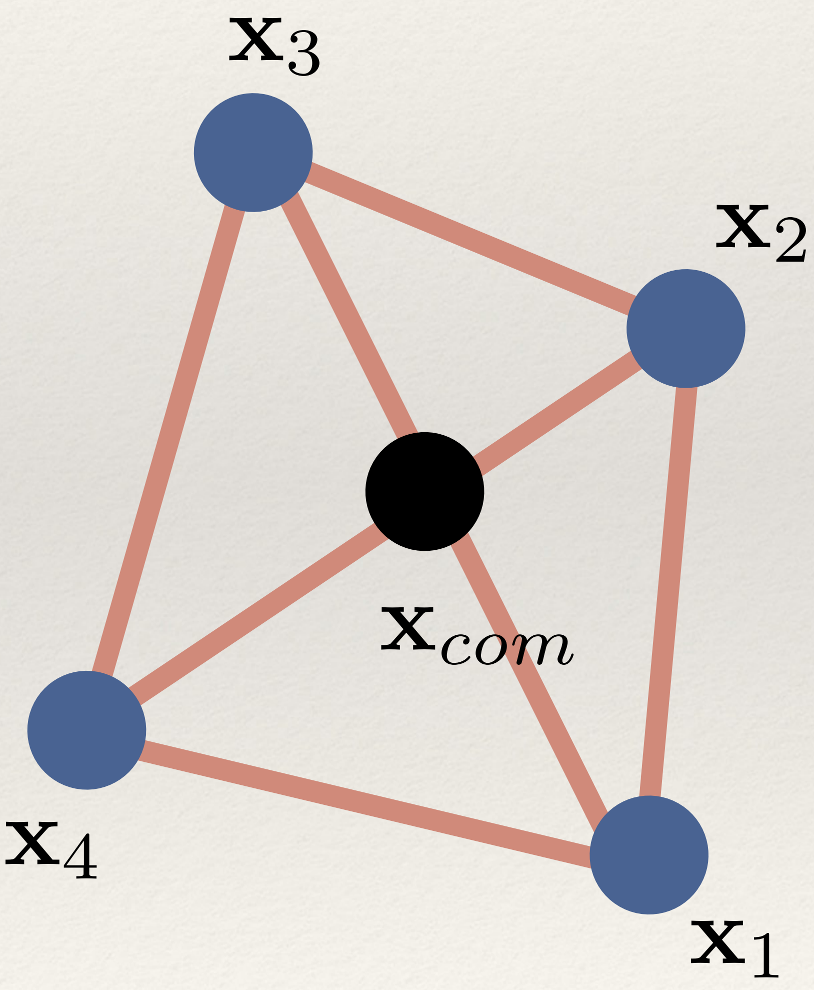
- 3n DoF are replaced with 6 DoF! position and orientation $\mathbf{x}(t), \mathbf{R}(t)$



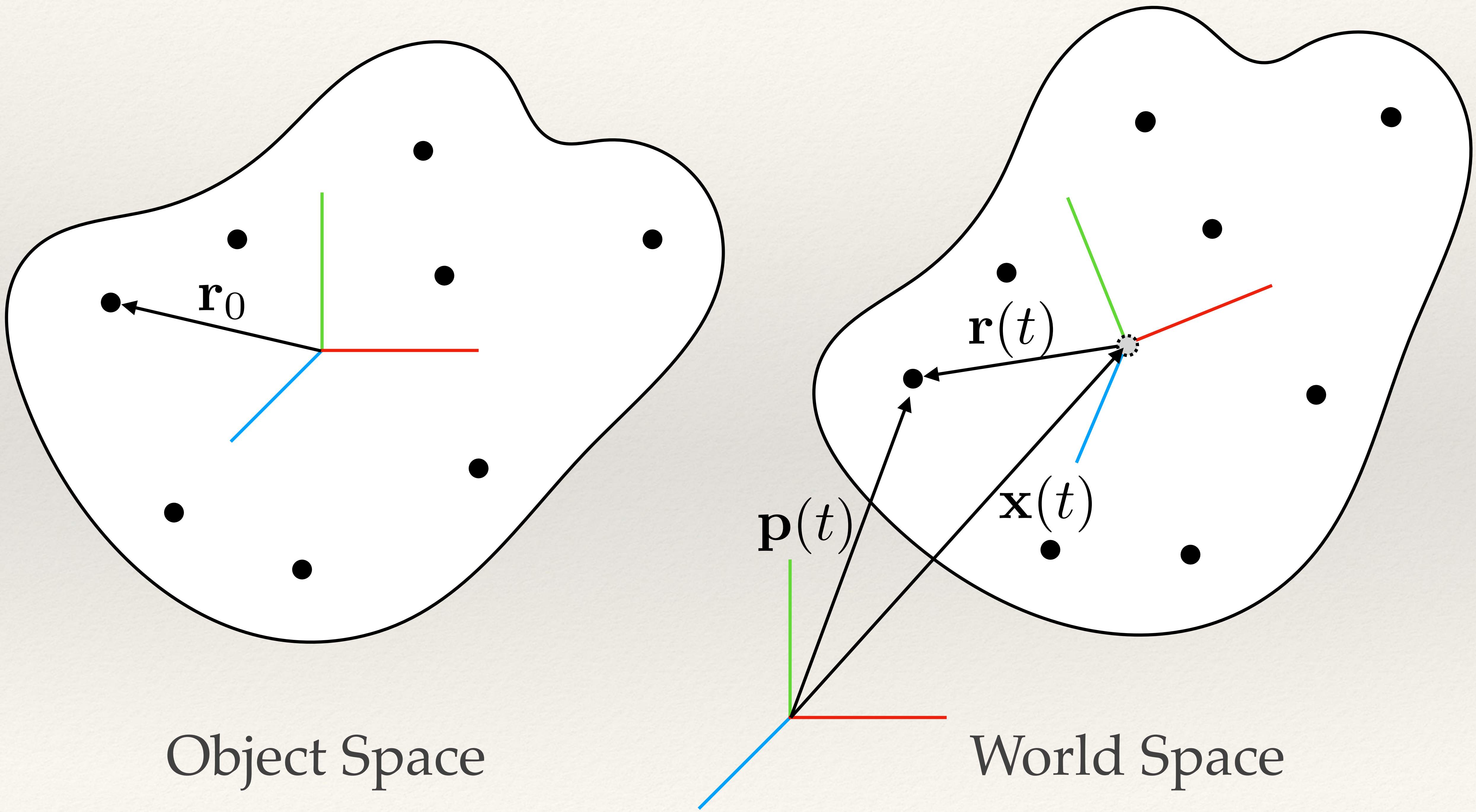
Rigid Body Kinematics

- Center of mass

$$\mathbf{x}_{com} = \frac{\sum_{i=1}^{N} m_i \mathbf{x}_i}{\sum_{i=1}^{N} m_i}.$$



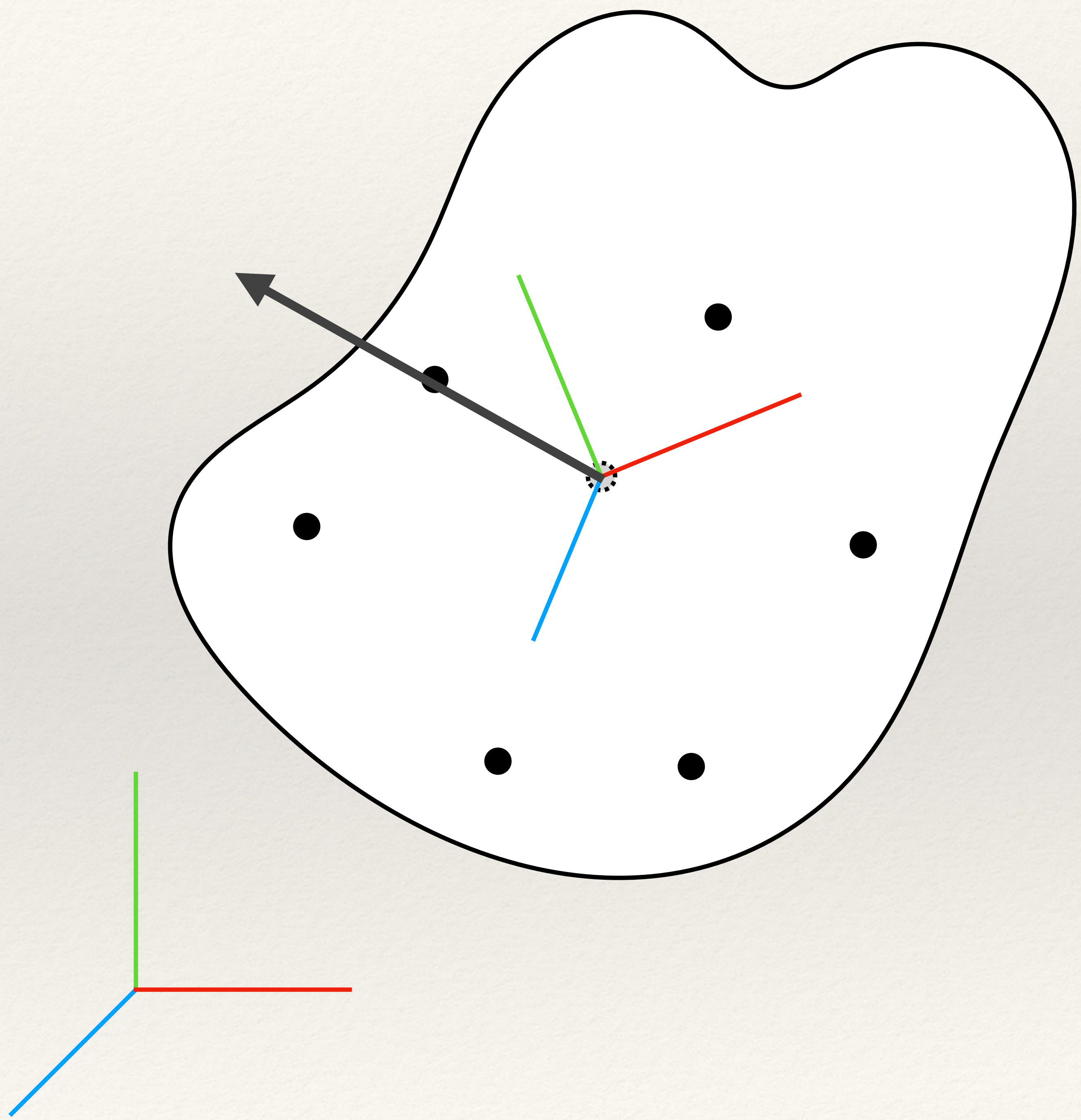
Rigid Body Coordinates



Linear and Angular Velocity

- Linear velocity

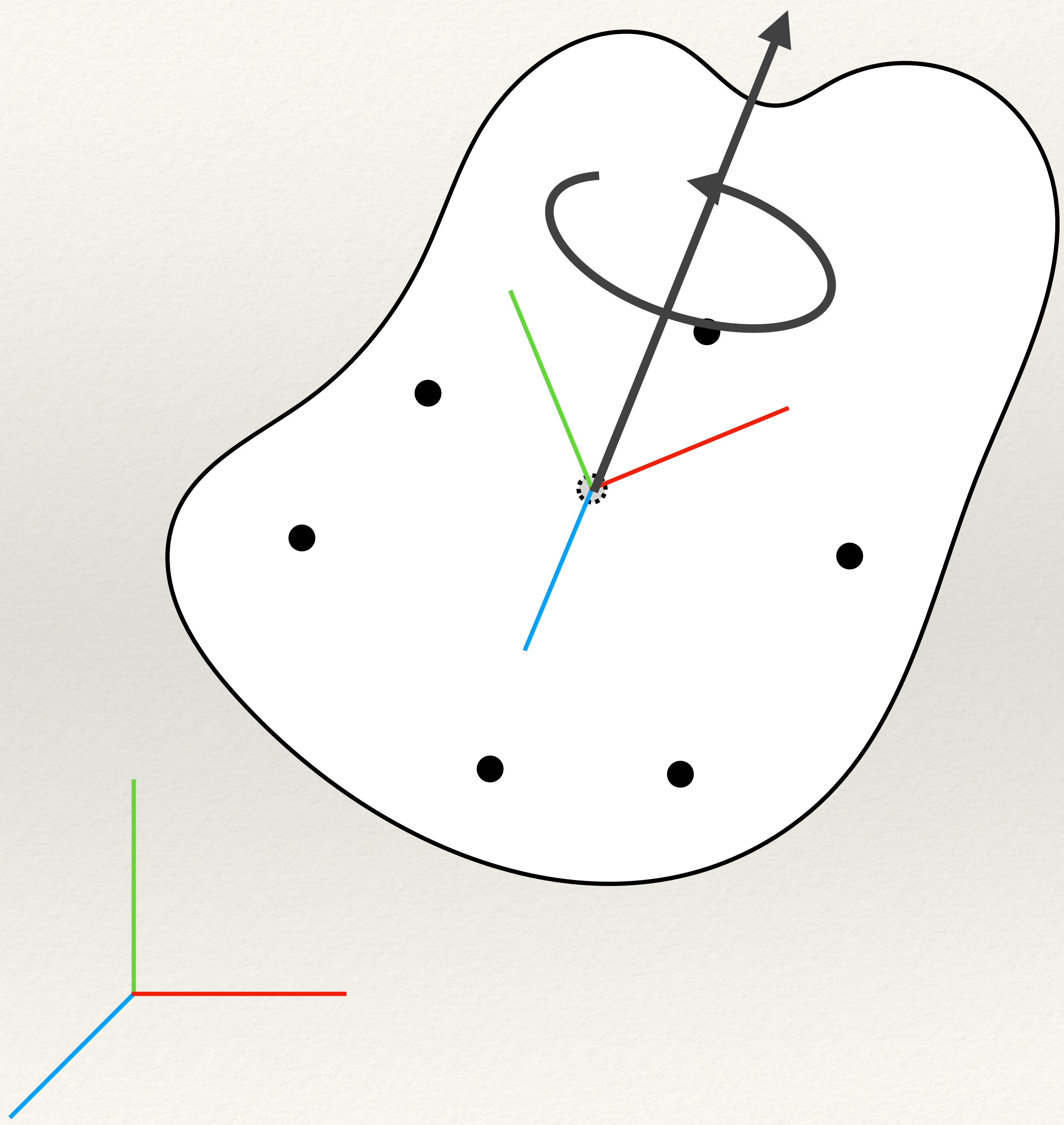
$$\mathbf{v}(t) = \dot{\mathbf{x}}(t)$$



Linear and Angular Velocity

- Angular velocity

$$\omega(t)$$



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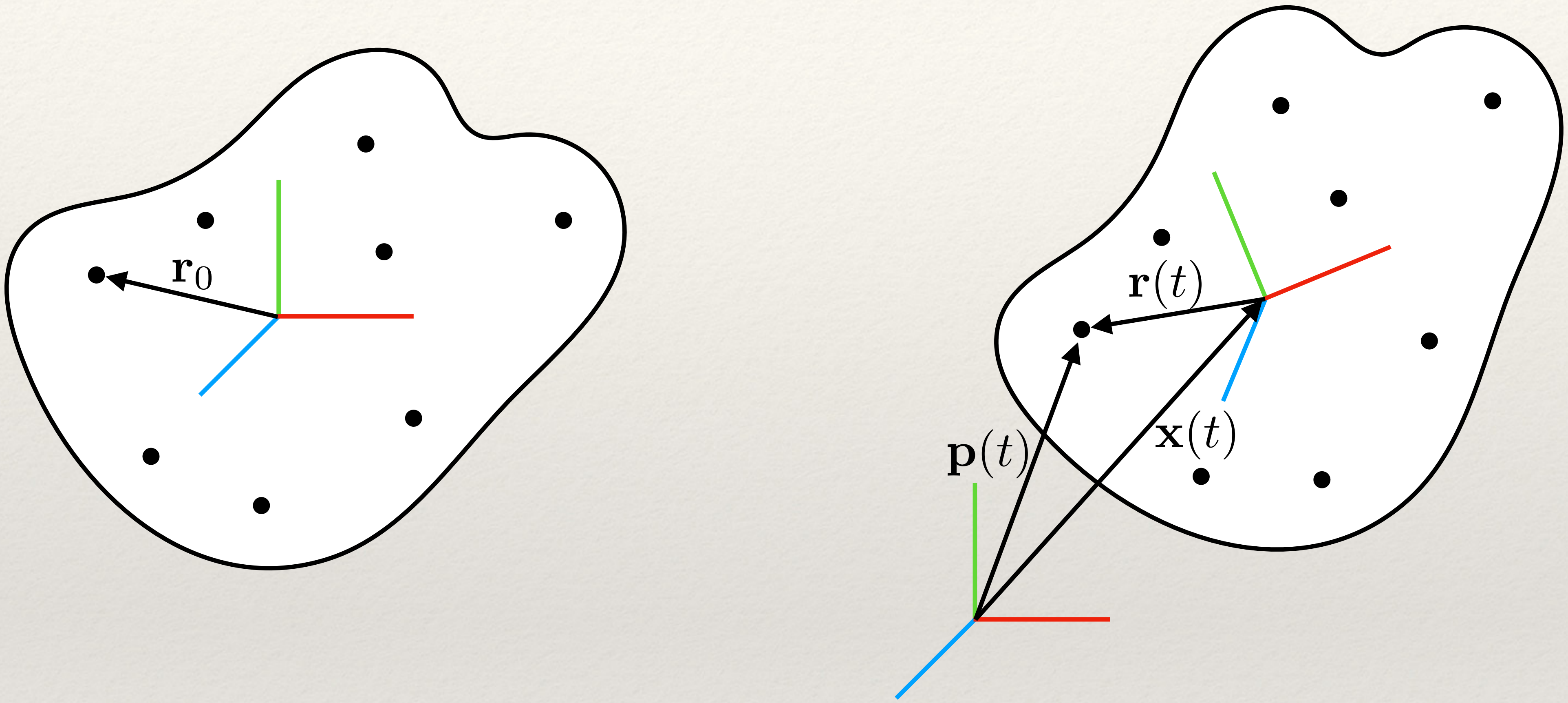


particle position $\mathbf{p}(t) = \mathbf{x}(t) + \underbrace{\mathbf{R}(t)\mathbf{r}_0}_{\mathbf{r}(t)}$

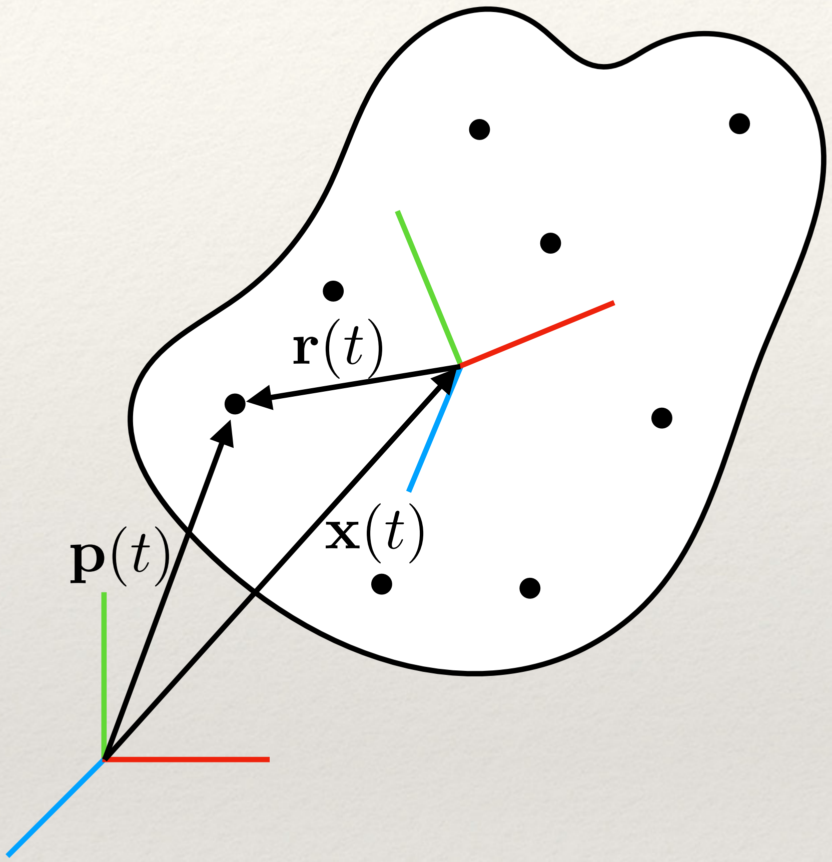
particle velocity $\dot{\mathbf{p}}(t) = \mathbf{v}(t) + \omega(t) \times \mathbf{r}(t)$

Linear and Angular Momentum

- Linear Momentum

$$\mathbf{P}(t) = \sum_{i=1}^{N} m_i \mathbf{v}_i(t)$$

(c.o.m. origin) $\Rightarrow \mathbf{P}(t) = m\mathbf{v}(t)$



- Angular Momentum

$$\mathbf{L}(t) = \sum_{i=1}^{N} \mathbf{r}_i(t) \times m_i \mathbf{v}_i(t)$$

(c.o.m. origin) $\Rightarrow \mathbf{L}(t) = \mathbf{I}(t)\omega(t)$

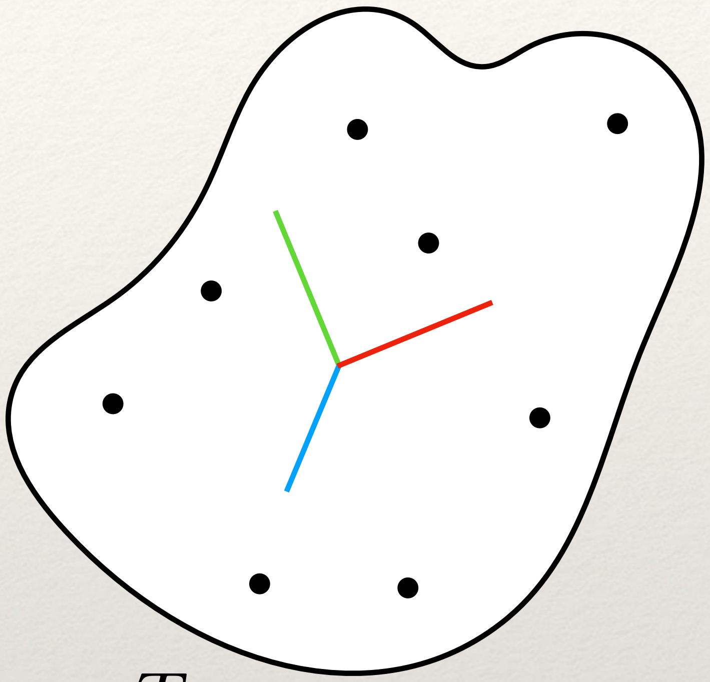
$\mathbf{I}(t)$: **inertia tensor**

Rigid Body Inertia Tensor

$$\mathbf{I}(t) = \sum_{i=1}^{N} m_i \left(\mathbf{r}_i^T \mathbf{r}_i \delta - \mathbf{r}_i \mathbf{r}_i^T\right)$$

$$= \mathbf{R}(t) \underbrace{\sum_{i=1}^{N} m_i \left(\mathbf{r}_{0i}^T \mathbf{r}_{0i} \delta - \mathbf{r}_{0i} \mathbf{r}_{0i}^T\right) \mathbf{R}(t)^T}_{\mathbf{I}_0}$$

$$= \mathbf{R}(t) \mathbf{I}_0 \mathbf{R}(t)^T.$$



Linear and Angular Momentum

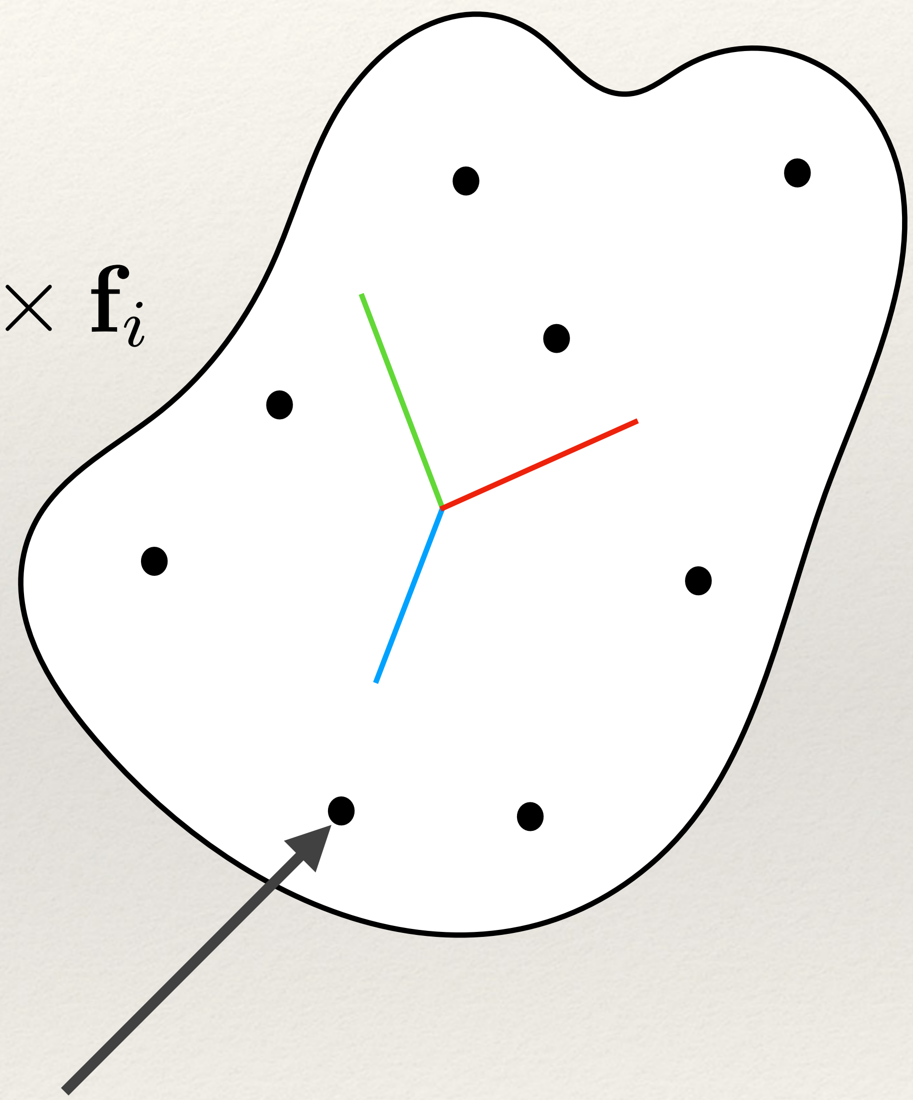
- No net force =>
  - linear momentum and velocity constant
- No net torque =>
  - angular momentum constant
  - angular velocity not necessarily constant

$$\mathbf{P}(t) = m\mathbf{v}(t)$$

$$\mathbf{L}(t) = \mathbf{I}(t)\omega(t)$$

Newton's Second Law for Rigid Bodies

$$\frac{d}{dt}\begin{pmatrix}\mathbf{P}(t)\\ \mathbf{L}(t)\end{pmatrix} = \begin{pmatrix}\mathbf{f}(t)\\ \tau(t)\end{pmatrix}, \qquad \begin{aligned}\mathbf{f}(t) &= \sum \mathbf{f}_i\\ \tau(t) &= \sum \mathbf{r}_i \times \mathbf{f}_i\end{aligned}$$



- Summary

$$\frac{d}{dt}\begin{pmatrix}\mathbf{x}(t)\\ R(t)\\ \mathbf{P}(t)\\ \mathbf{L}(t)\end{pmatrix} = \begin{pmatrix}\mathbf{v}(t)\\ \omega^{\star}(t)R(t)\\ \mathbf{f}(t)\\ \tau(t)\end{pmatrix}$$

Soft Bodies

Adding Elasticity and Damping

$$\mathbf{f} = m\mathbf{a}$$

$$\mathbf{K}(\mathbf{x} - \mathbf{u}) + \mathbf{D}(\mathbf{v}) + \mathbf{M}\mathbf{a} = \mathbf{f}_{ext}$$

in terms of displacements $\mathbf{d}$

$$\mathbf{K}(\mathbf{d}) + \mathbf{D}(\dot{\mathbf{d}}) + \mathbf{M}\ddot{\mathbf{d}} = \mathbf{f}_{ext}$$

Adding Elasticity and Damping

$$m\mathbf{a} = \mathbf{f}$$

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K

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- Generalization of spring stiffness, called *stiffness* matrix

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- Sparse, Symmetric, Diagonally Dominant, Row/Col sums 0

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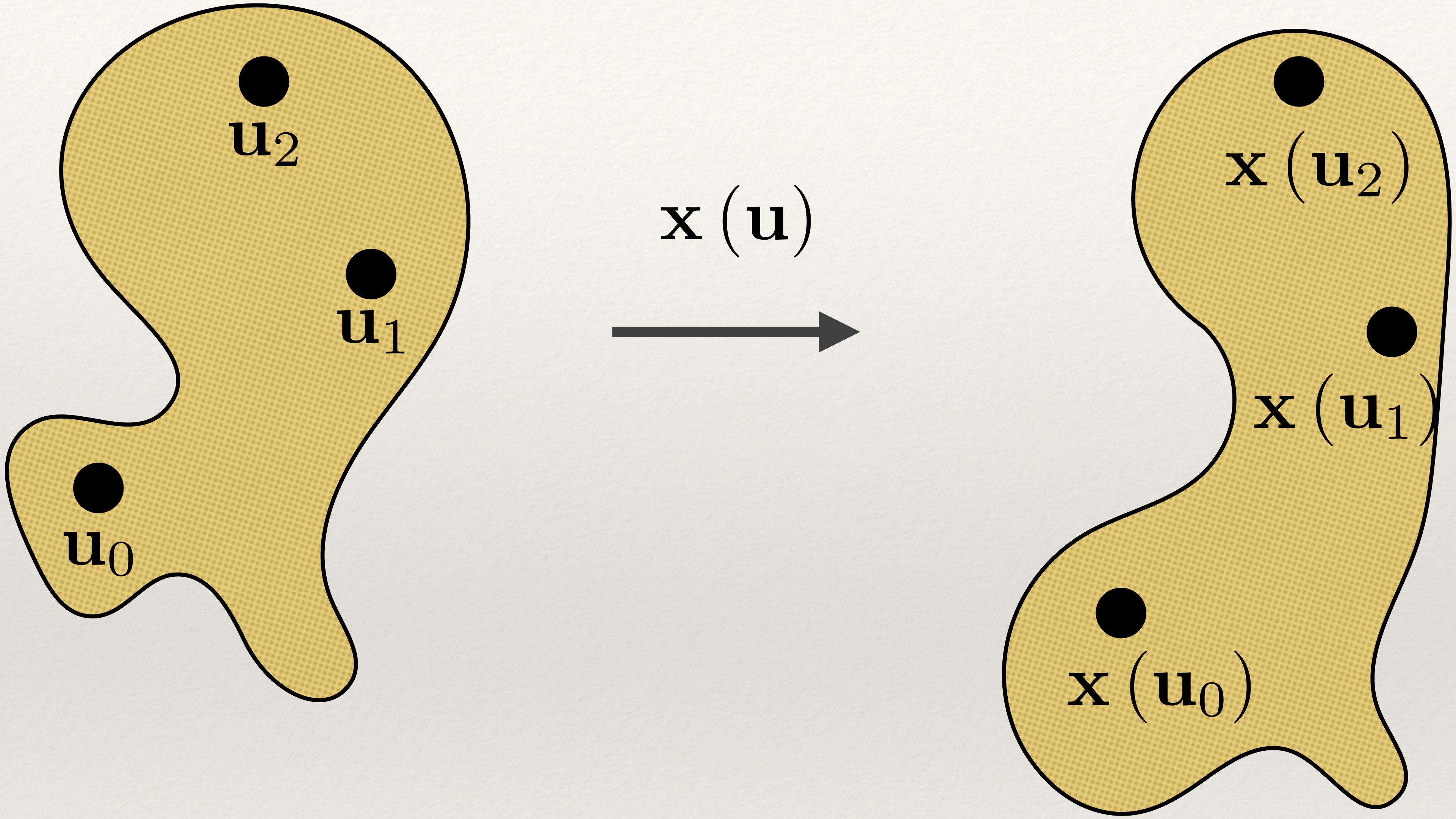
$$\mathbf{K} = \frac{-\partial \mathbf{f}_i}{\partial \mathbf{x}_j} = \frac{-\partial \eta}{\partial \mathbf{x}_i \partial \mathbf{x}_j}$$

So how do we calculate elastic forces?

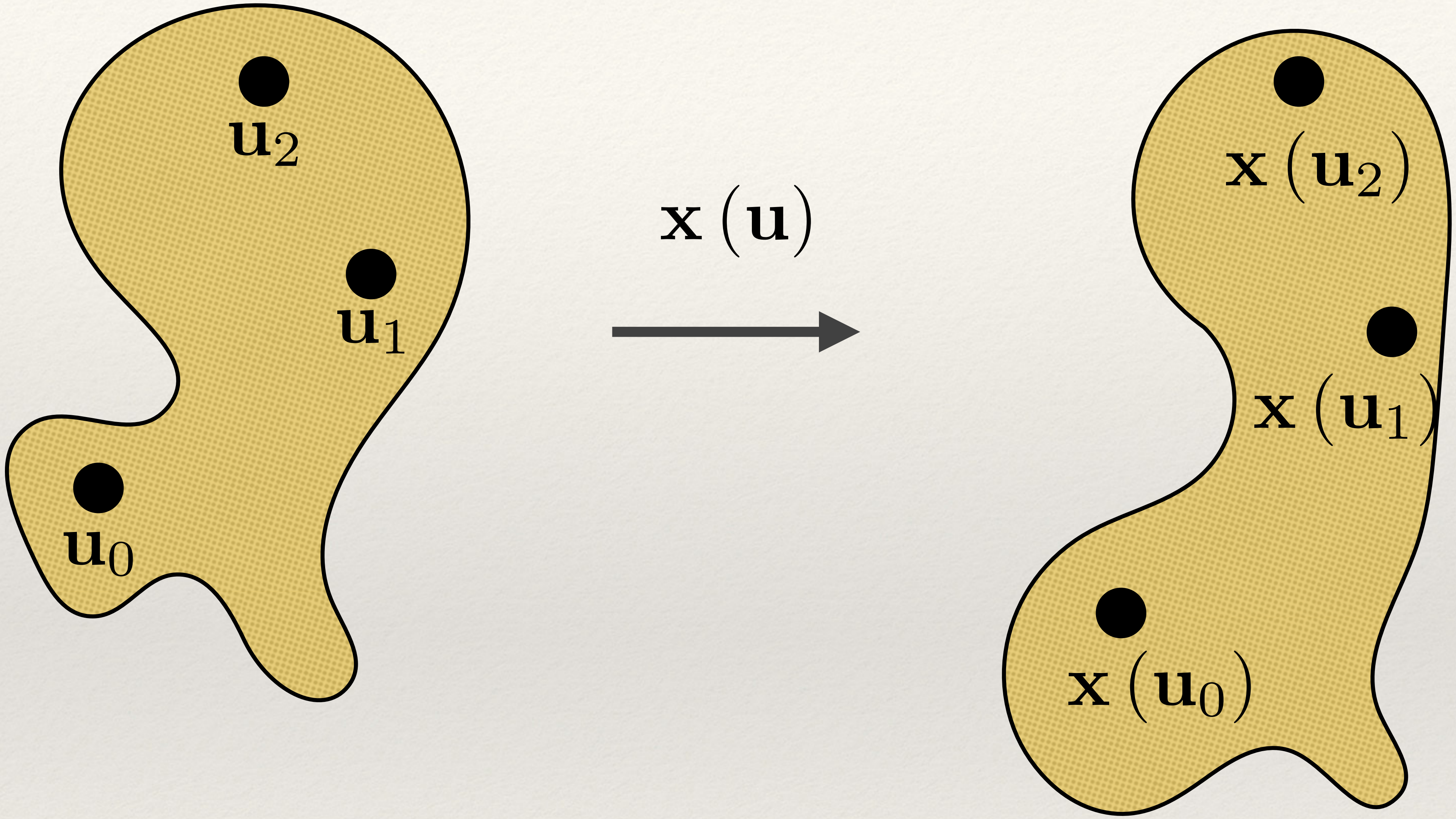
Elastic Forces Cookbook

- Deformation Function (world pos, rest position)
- Deformation Gradient (deformation function)
- Strain (deformation gradient)
- Stress (strain)
- Energy (stress, strain)
- Forces (energy)

Deformation and Its Gradient

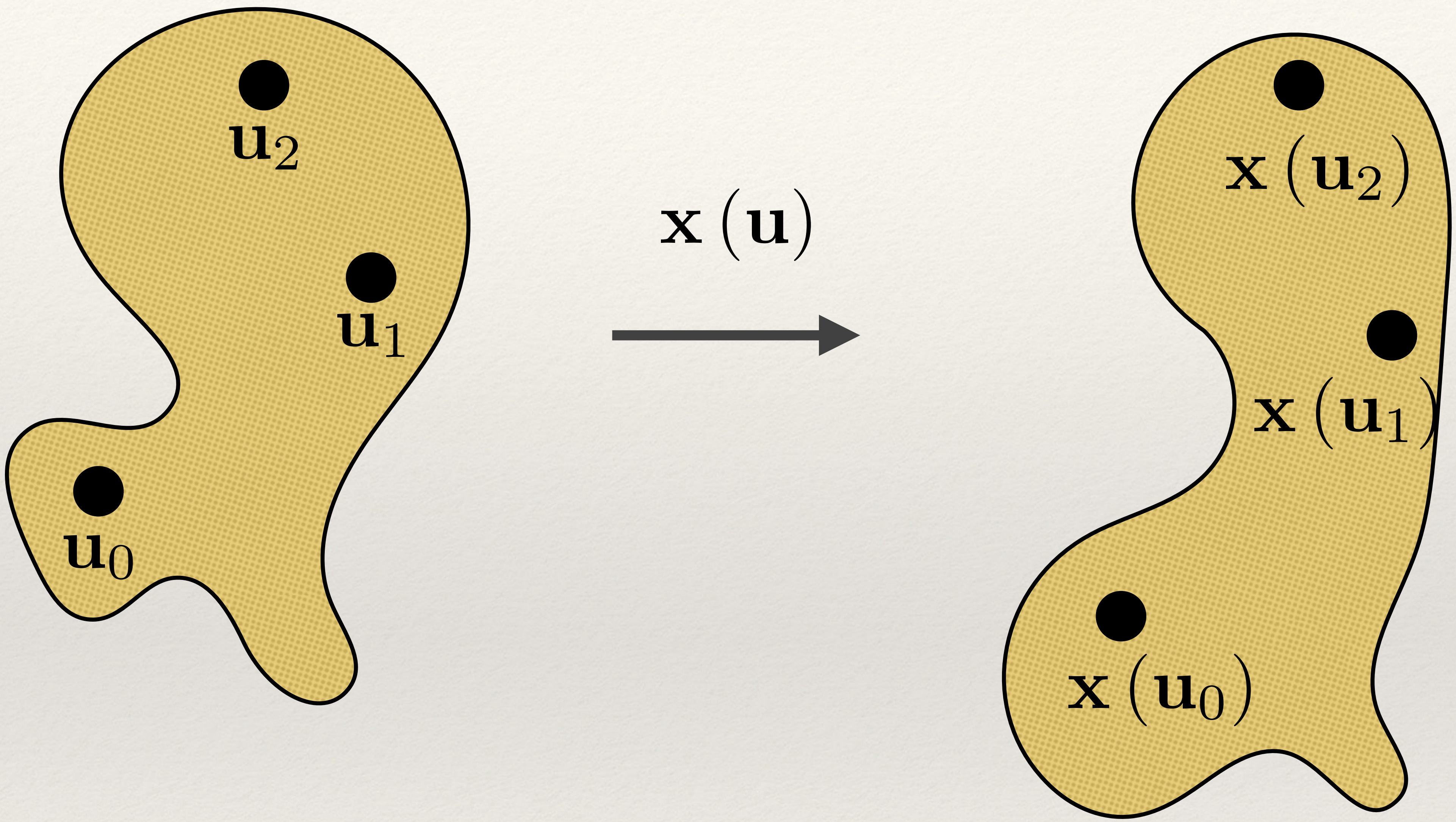


Deformation and Its Gradient



$$\mathbf{x}(\mathbf{u}) = \mathbf{x}(\mathbf{u}_0) + \mathbf{F}(\mathbf{u} - \mathbf{u}_0)$$

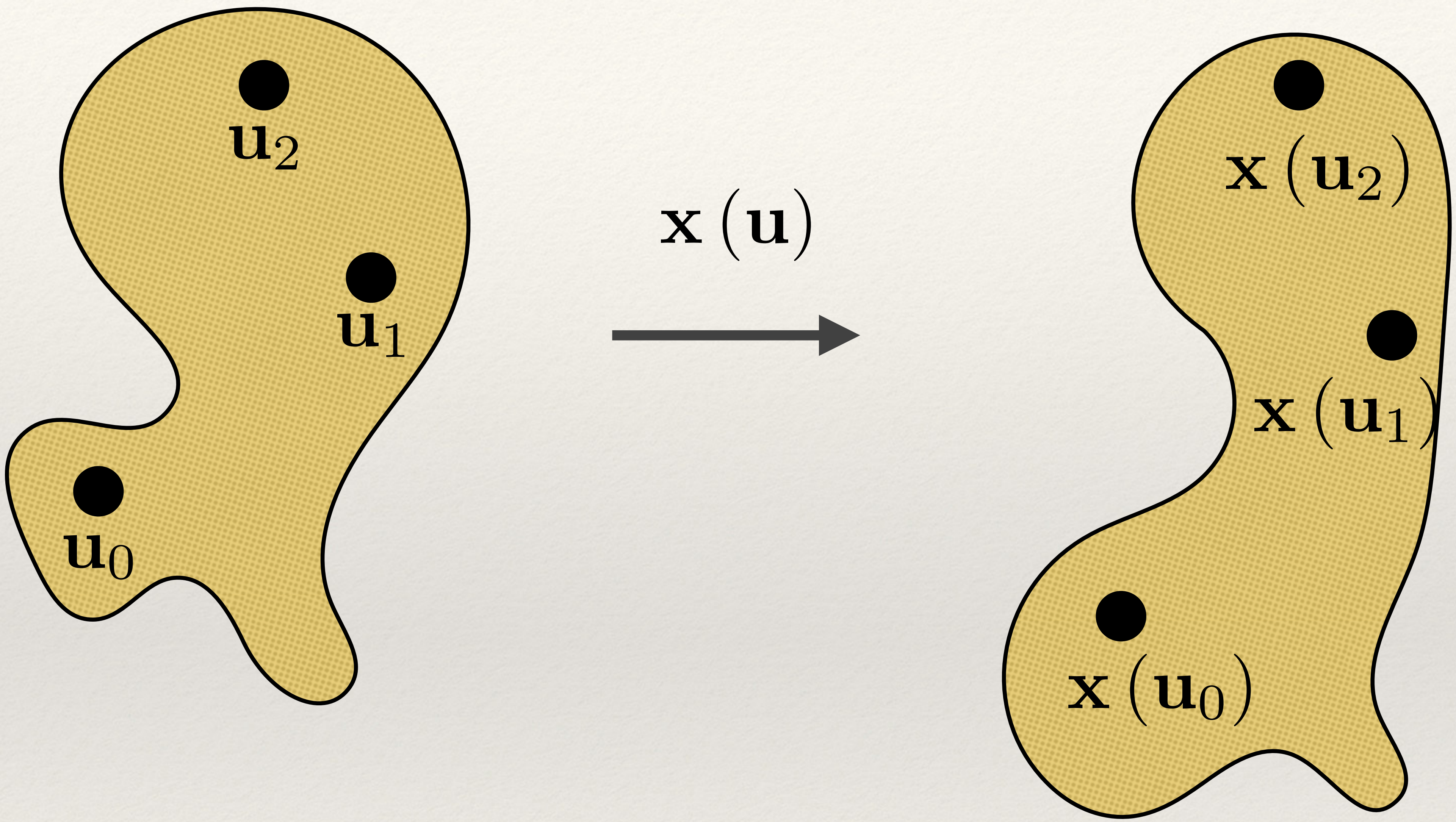
Deformation and Its Gradient



$$\mathbf{x}(\mathbf{u}) = \mathbf{x}(\mathbf{u}_0) + \mathbf{F}(\mathbf{u} - \mathbf{u}_0)$$

$$\frac{\partial \mathbf{x}}{\partial \mathbf{u}} = \mathbf{F}$$

Deformation and Its Gradient



$$\mathbf{x}(\mathbf{u}) = \mathbf{x}(\mathbf{u}_0) + \mathbf{F}(\mathbf{u} - \mathbf{u}_0)$$

$$\frac{\partial \mathbf{x}}{\partial \mathbf{u}} = \mathbf{F}$$

Strain is

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- a measure of deformation

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- dimensionless (i.e. has no units)

Strain is

- a measure of deformation
- dimensionless (i.e. has no units)
- a function of the deformation gradient

Strain Metrics

- Green's finite $\epsilon = \frac{1}{2}\left(\mathbf{F}^T\mathbf{F} - \mathbf{I}\right)$

- Cauchy's infinitesimal $\epsilon = \frac{1}{2}\left(\mathbf{F}^T + \mathbf{F}\right) - \mathbf{I}$

- Co-rotated $\epsilon = \frac{1}{2}\left(\tilde{\mathbf{F}}^T + \tilde{\mathbf{F}}\right) - \mathbf{I}$

  where $\mathbf{F} = \mathbf{Q}\tilde{\mathbf{F}}$

Stress

Stress

- stress is a function of strain

Stress

- stress is a function of strain
- stress has units of (Newton / meter^2)

Stress

- stress is a function of strain
- stress has units of (Newton / meter^2)
- models of stress-strain relationships can be highly complex, especially with organic materials

Linear Stress-strain Relationships

General, linear

$$\sigma = \mathbf{C}\epsilon$$

Linear Stress-strain Relationships

General, linear

$$\sigma = \mathbf{C}\epsilon$$

isotropic material

$$\sigma = \lambda \mathrm{Tr}\left(\epsilon\right)\mathbf{I} + 2\mu\epsilon$$

Elastic Potential, Traction, Force

$$\eta = \frac{1}{2}\sigma : \epsilon = \frac{1}{2}\sum_{i,j}\sigma_{ij}\epsilon_{ij}$$

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Elastic Potential, Traction, Force

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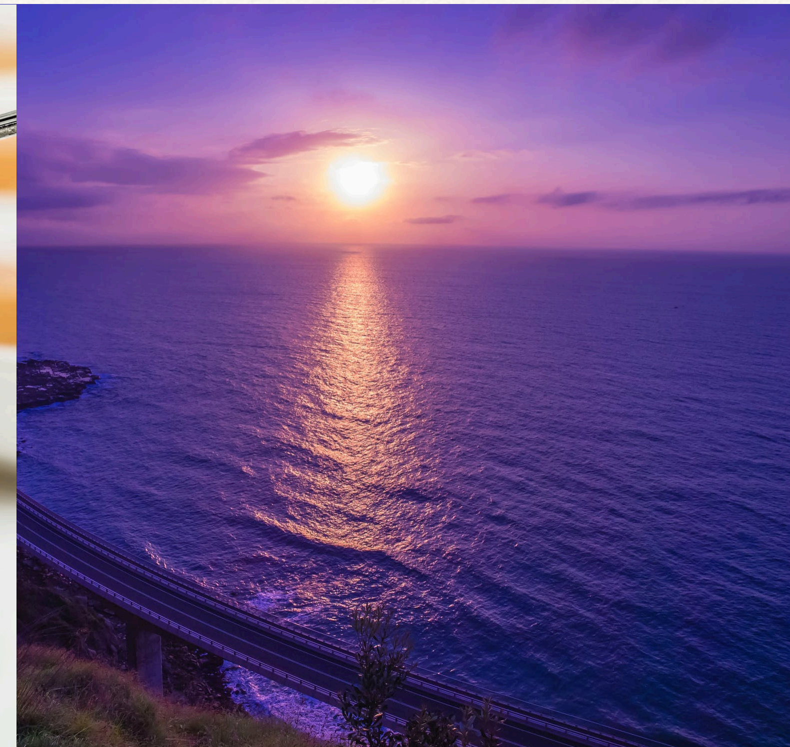
$$\mathbf{f} = \oint_{\partial R} \sigma\mathbf{n}\, dS$$

Plasticity

$$\mathbf{F} = \mathbf{F}_e \mathbf{F}_p$$

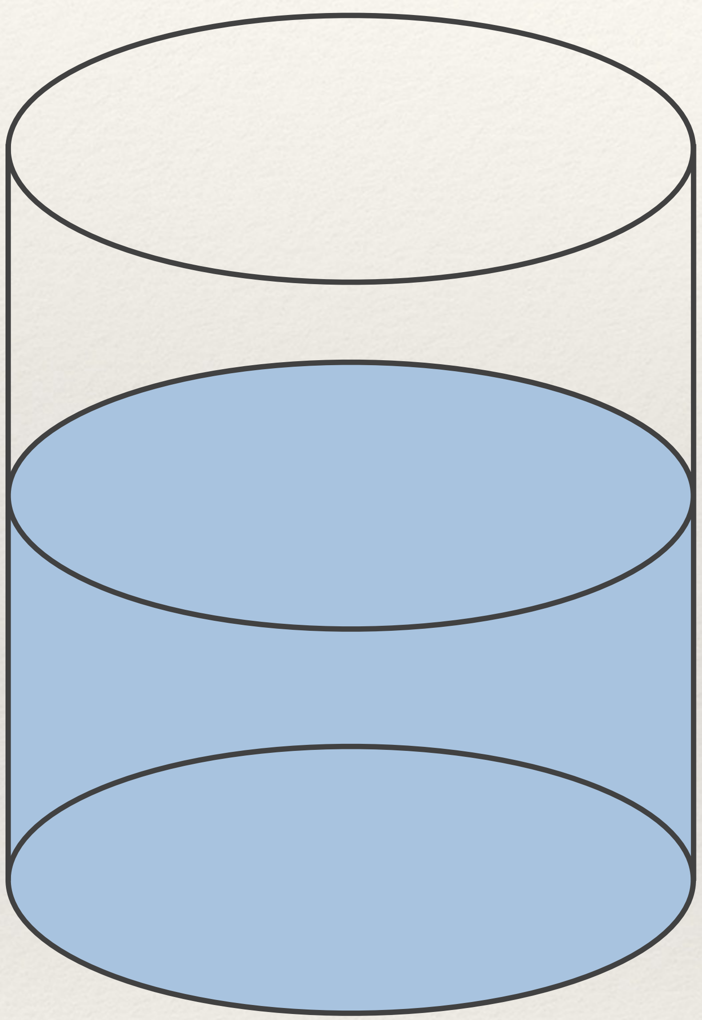
Fluids

Fluids

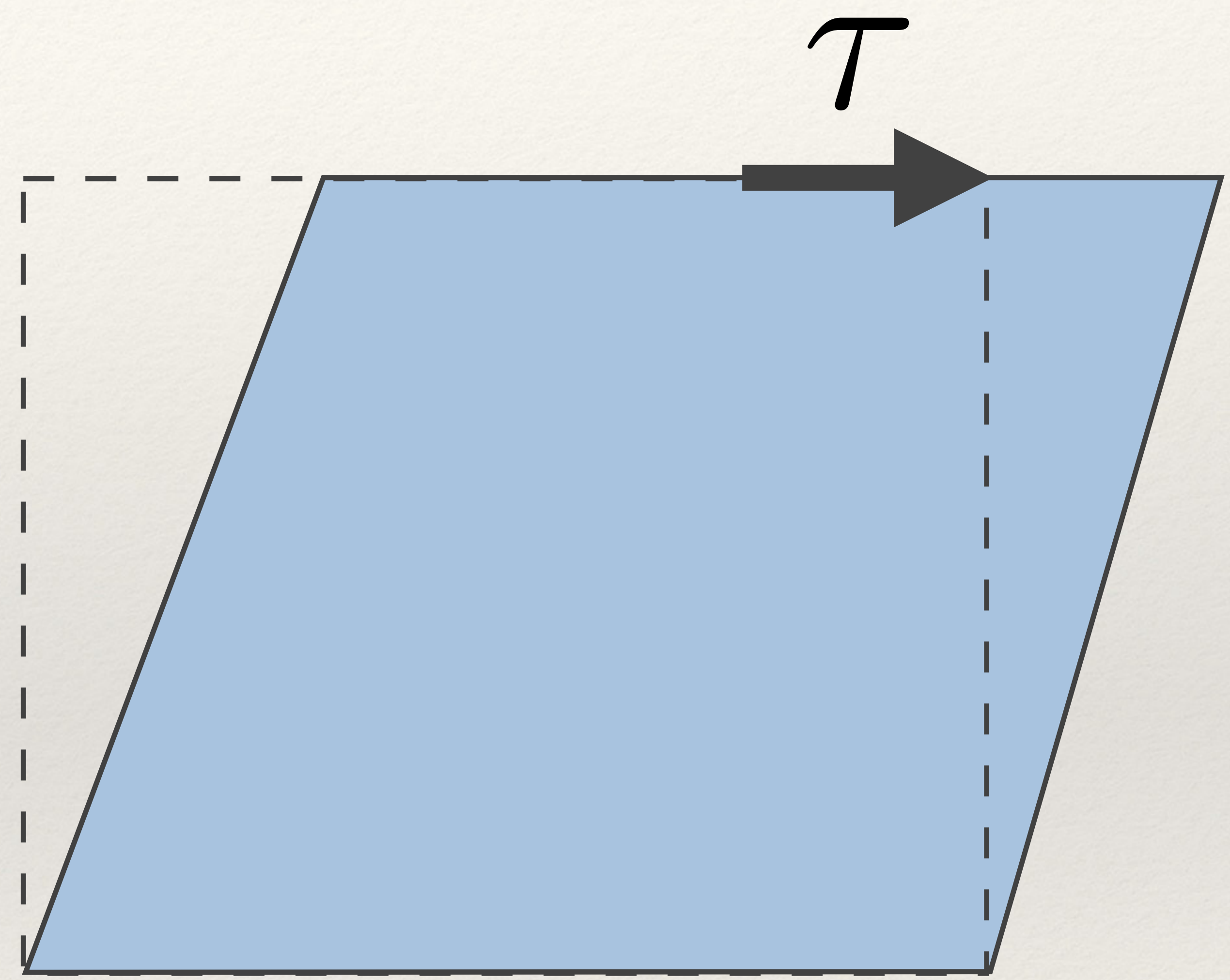





Fluids

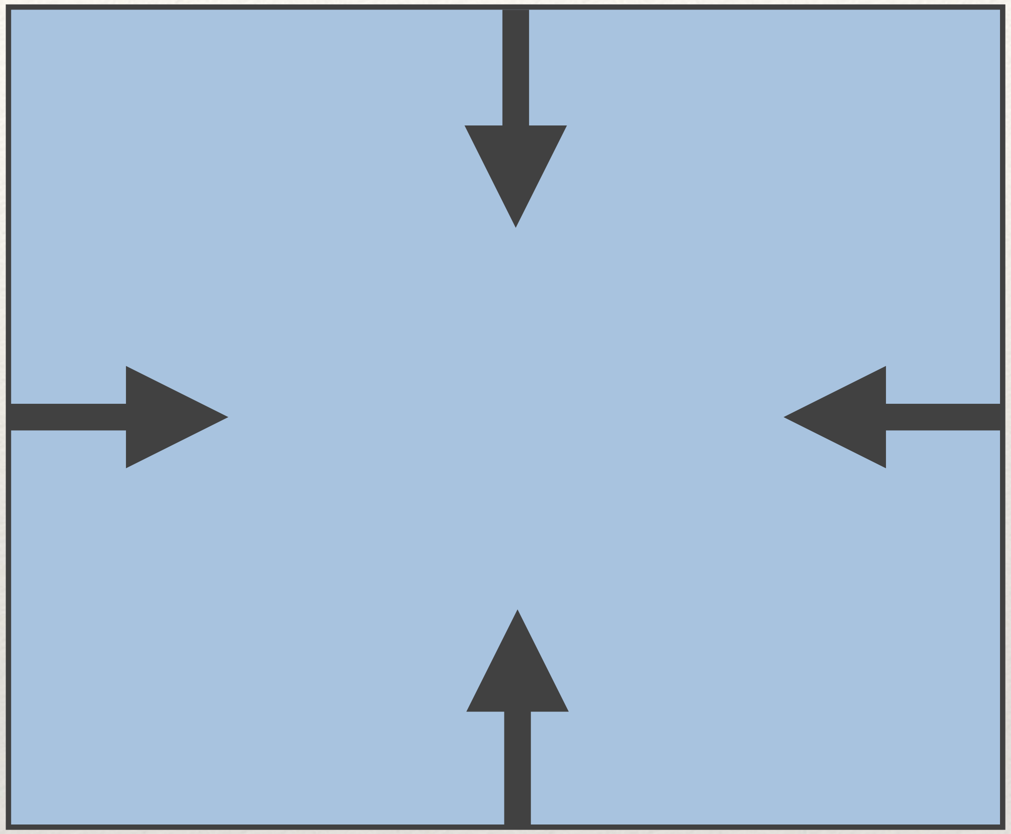


take shape
of container



can't support
shear stress

Fluids



can support
normal stress

Navier-Stokes Equations

$$\rho(\mathbf{u}_t + \mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla p + \mu \Delta \mathbf{u} + \mathbf{f}$$

$$\nabla \cdot \mathbf{u} = 0$$

ρ : density

p : pressure

$\mathbf{f}$: forces

$\mathbf{u}$: velocity

μ : viscosity

Navier-Stokes Equations

$$\overset{\text{m}}{\rho}\overbrace{(\mathbf{u}_t + \mathbf{u}\cdot\nabla\mathbf{u})}^{\mathbf{a}} = -\overbrace{\nabla p + \mu\Delta\mathbf{u} + \mathbf{f}}^{\mathbf{f}}$$

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Navier-Stokes Equations

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μ : viscosity

Navier-Stokes Equations

$$\overset{\text{m}}{\rho}\,\overbrace{\left(\mathbf{u}_t + \mathbf{u}\cdot\nabla\mathbf{u}\right)}^{\mathbf{a}} = -\overbrace{\nabla p + \mu\Delta\mathbf{u} + \mathbf{f}}^{\mathbf{f}}$$

$$\nabla\cdot\mathbf{u} = 0$$

ρ : density p : pressure $\mathbf{f}$: forces

$\mathbf{u}$: velocity μ : viscosity

Navier-Stokes Equations

$$\overset{\text{m}}{\rho}\,\overbrace{\left(\mathbf{u}_t + \mathbf{u}\cdot\nabla\mathbf{u}\right)}^{\mathbf{a}} = \overbrace{-\nabla p + \mu\Delta\mathbf{u} + \mathbf{f}}^{\mathbf{f}}$$

$$\nabla\cdot\mathbf{u} = 0$$

ρ : density $\quad$ p : pressure $\quad$ $\mathbf{f}$: forces

$\mathbf{u}$: velocity $\quad$ μ : viscosity

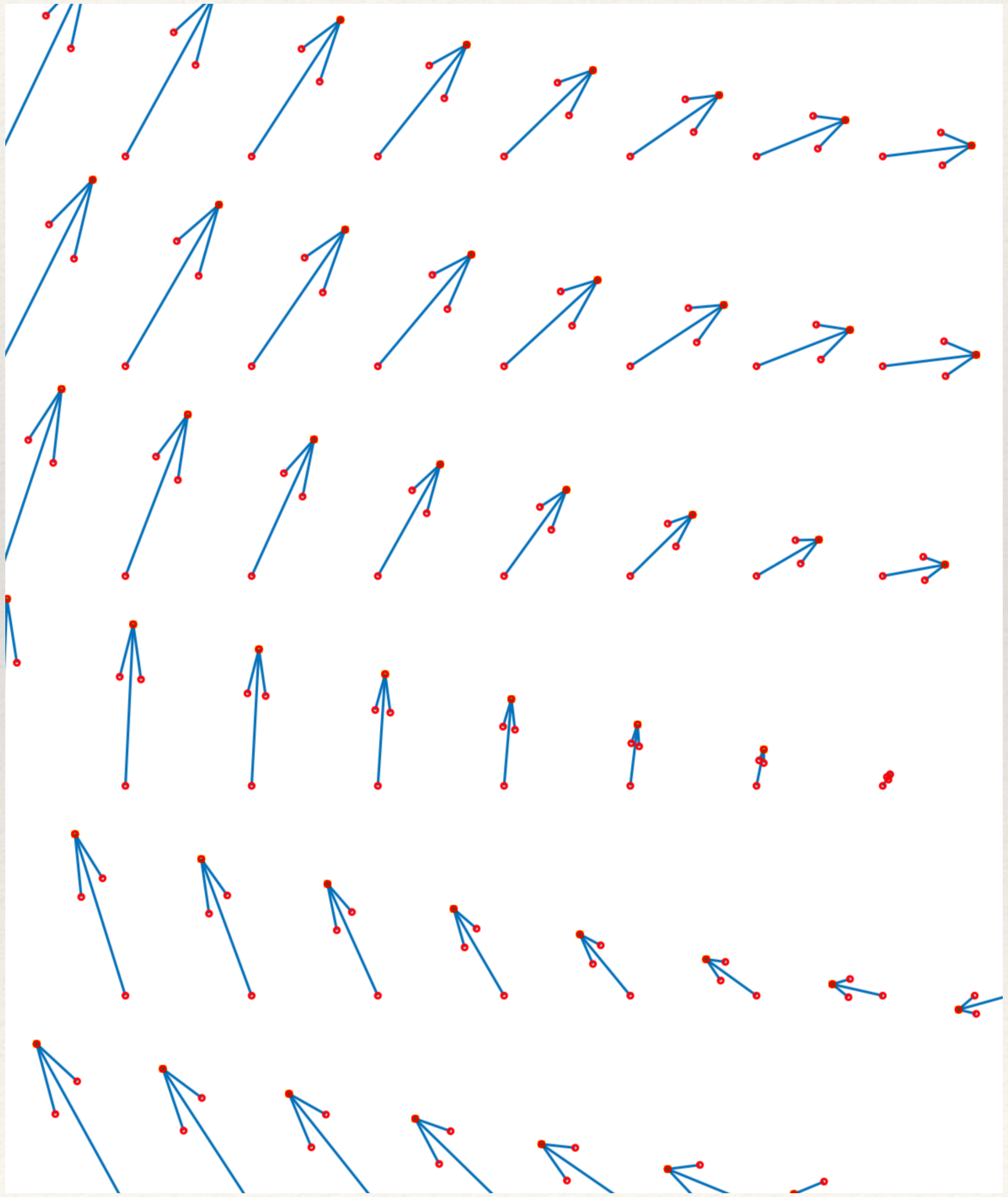
Material Derivative

$$\mathrm{m} \quad \rho \overbrace{\left(\mathbf{u}_t + \mathbf{u} \cdot \nabla \mathbf{u}\right)}^{\mathbf{a}} = -\overbrace{\nabla p + \mu \Delta \mathbf{u} + \mathbf{f}}^{\mathbf{f}}$$

$$\nabla \cdot \mathbf{u} = 0$$

Material Derivative

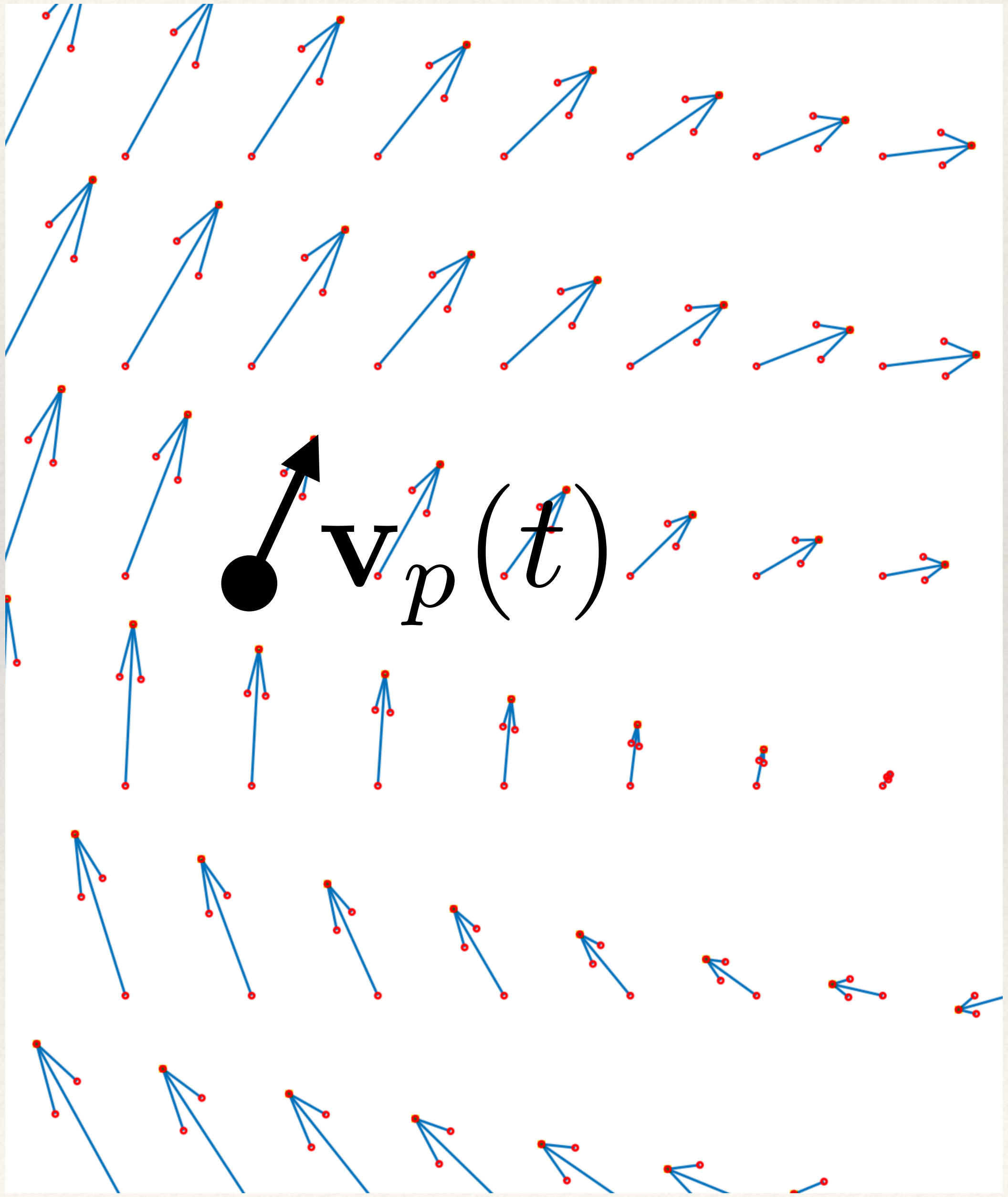
$$\mathbf{u}(\mathbf{x}, t)$$



Material Derivative

$$\mathbf{u}(\mathbf{x}, t)$$

$$\begin{aligned}\mathbf{a}_p(t) &= \frac{d}{dt}\mathbf{v}_p(t) \\ &= \frac{d}{dt}\mathbf{u}(\mathbf{x}_p(t), t) \\ &= \left(\frac{\partial \mathbf{u}}{\partial t} + \frac{\partial \mathbf{u}}{\partial \mathbf{x}}\frac{d\mathbf{x}_p}{dt}\right)\end{aligned}$$

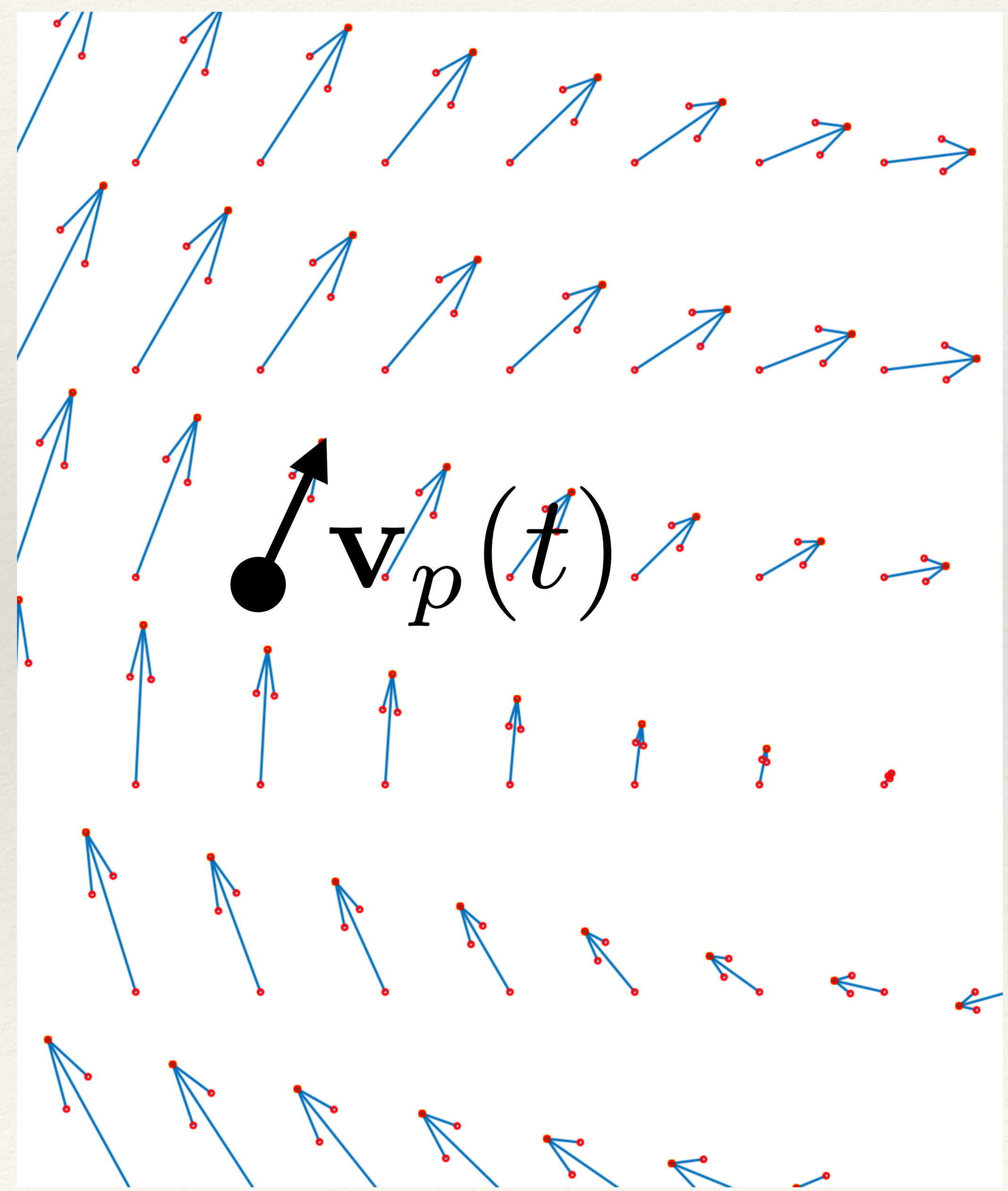


Material Derivative

$$
\begin{aligned}
\mathbf{a}_p(t) &= \frac{d}{dt}\mathbf{v}_p(t) \\
&= \frac{d}{dt}\mathbf{u}(\mathbf{x}_p(t), t) \\
&= \underbrace{\left(\frac{\partial \mathbf{u}}{\partial t} + \frac{\partial \mathbf{u}}{\partial \mathbf{x}}\frac{d\mathbf{x}_p}{dt}\right)}_{\mathbf{u}_t + \mathbf{u}\cdot\nabla\mathbf{u}}
\end{aligned}
$$

$$
\frac{D\mathbf{u}}{Dt} = \mathbf{u}_t + \mathbf{u}\cdot\nabla\mathbf{u}
$$

$\mathbf{u}(\mathbf{x}, t)$



Pressure Forces

$$\overset{\text{m}}{\rho}\overbrace{(\mathbf{u}_t + \mathbf{u}\cdot\nabla\mathbf{u})}^{\mathbf{a}} = -\overbrace{\nabla p + \mu\Delta\mathbf{u} + \mathbf{f}}^{\mathbf{f}}$$

$$\nabla\cdot\mathbf{u} = 0$$

- maintains fluid volume, resisting compression/expansion
- forces fluid from areas of high pressure to low pressure

Viscous Forces

$$\overbrace{\rho}^{\mathrm{m}}\overbrace{\left(\mathbf{u}_t + \mathbf{u}\cdot\nabla\mathbf{u}\right)}^{\mathbf{a}} = \overbrace{-\nabla p + \mu\Delta\mathbf{u} + \mathbf{f}}^{\mathbf{f}}$$

$$\nabla\cdot\mathbf{u} = 0$$

- internal friction
- Laplacian measures difference from neighbors

μ	$(\mathrm{mPa}\cdot\mathrm{s})$
μ_{air}	1.8×10^{-2}
μ_{water}	1
μ_{honey}	5×10^{3}

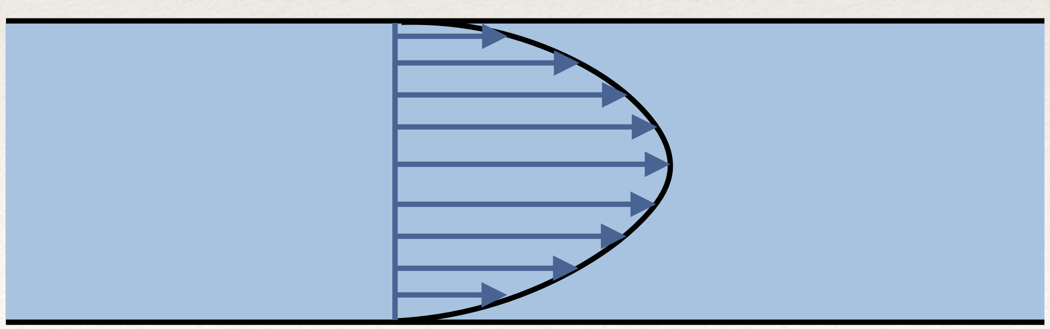
Viscous Forces: Solid Boundaries

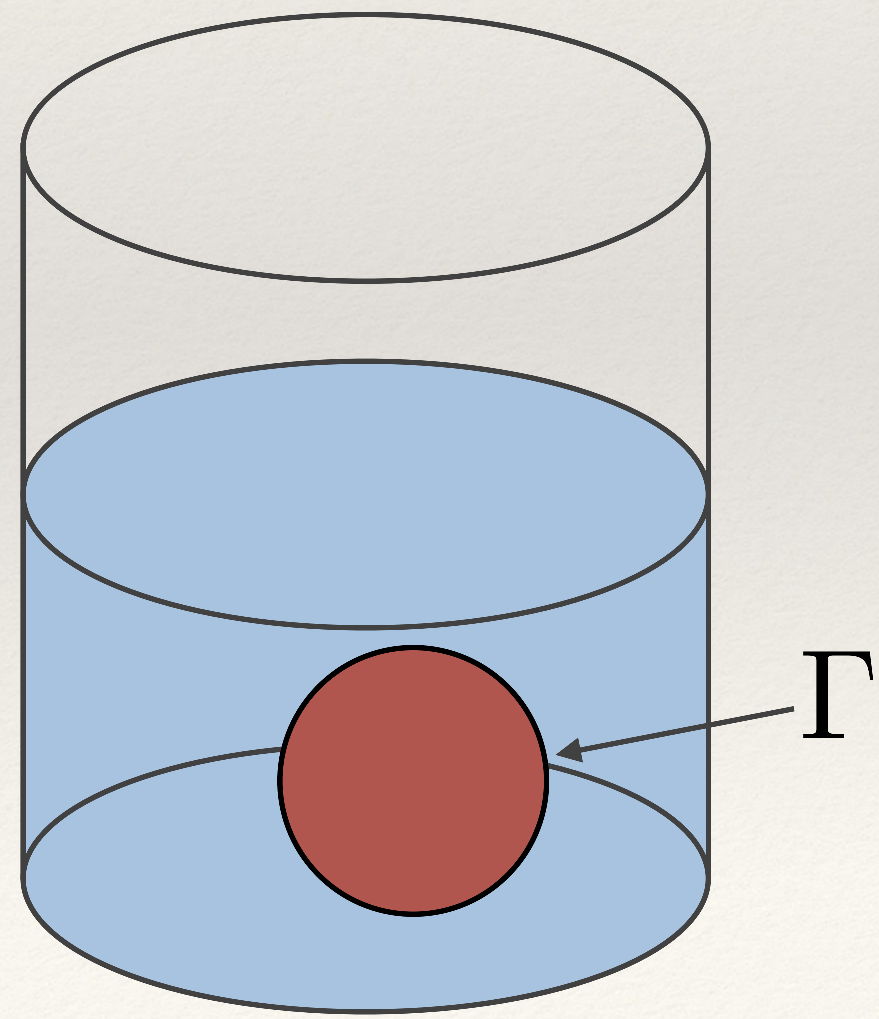
$$\overset{\mathrm{m}}{\rho}\,\overbrace{\left(\mathbf{u}_t + \mathbf{u}\cdot\nabla\mathbf{u}\right)}^{\mathbf{a}} = \overbrace{-\nabla p + \mu\Delta\mathbf{u} + \mathbf{f}}^{\mathbf{f}}$$

$$\nabla\cdot\mathbf{u} = 0$$

- no-slip boundary condition

$$\mathbf{u}(\mathbf{x}, t) = \mathbf{V}(\mathbf{x}, t), \quad \mathbf{x}\in\Gamma$$





External Forces

$$\rho\overbrace{(\mathbf{u}_t + \mathbf{u}\cdot\nabla\mathbf{u})}^{\mathbf{a}} = -\overbrace{\nabla p + \mu\Delta\mathbf{u} + \mathbf{f}}^{\mathbf{f}}$$

m

$$\nabla\cdot\mathbf{u} = 0$$

- Gravity, surface tension, interaction forces, control forces, embedded structures

Incompressibility

$$\overset{\text{m}}{\rho}\,\overbrace{\left(\mathbf{u}_t + \mathbf{u}\cdot\nabla\mathbf{u}\right)}^{\mathbf{a}} = -\overbrace{\nabla p + \mu\Delta\mathbf{u} + \mathbf{f}}^{\mathbf{f}}$$

$$\boxed{\nabla\cdot\mathbf{u} = 0}$$

- Conservation of mass $\qquad \dfrac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{u}) = 0$

- Constant density $\qquad \Rightarrow \nabla\cdot\mathbf{u} = 0$

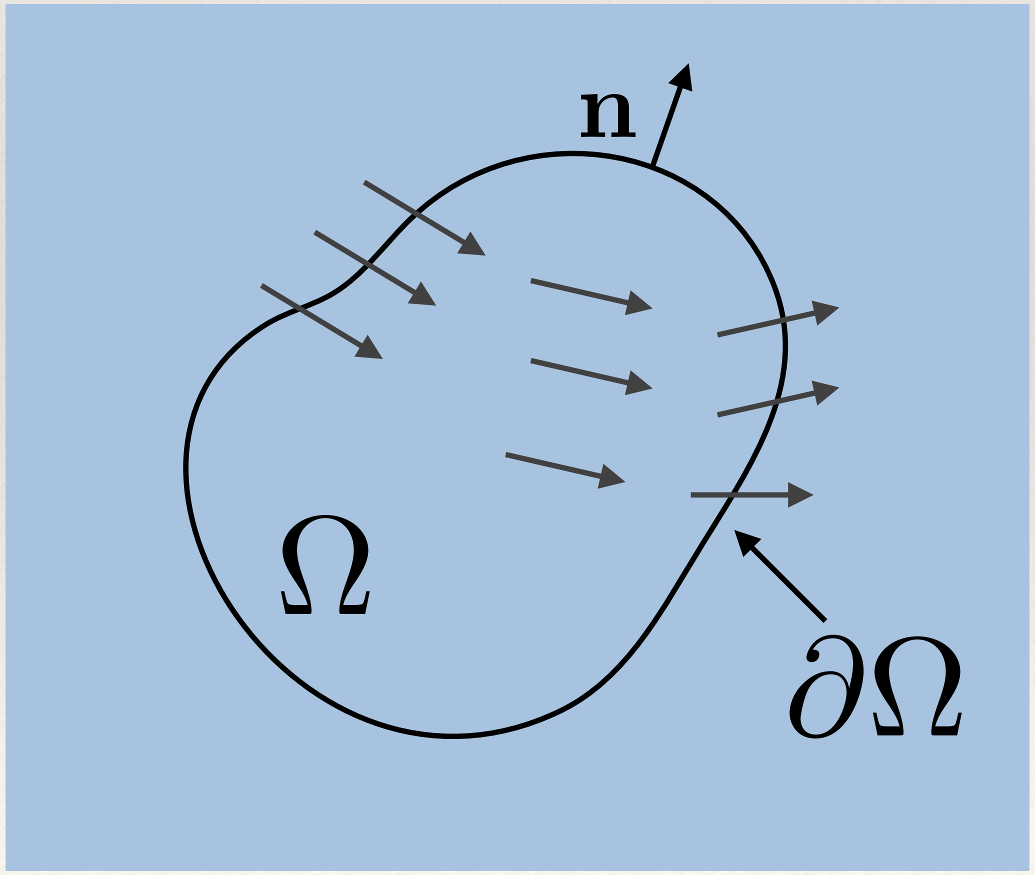
Incompressibility

$$\overset{\text{m}}{\rho}\,\overbrace{\left(\mathbf{u}_t + \mathbf{u}\cdot\nabla\mathbf{u}\right)}^{\mathbf{a}} = -\overbrace{\nabla p + \mu\Delta\mathbf{u} + \mathbf{f}}^{\mathbf{f}}$$

$$\nabla\cdot\mathbf{u} = 0$$

- Net flow through boundary must be zero

$$0 = \int_{\Omega}\nabla\cdot\mathbf{u} = \int_{\partial\Omega}\mathbf{u}\cdot\mathbf{n}$$



Incompressibility

$$\overset{\text{m}}{\rho}\,\overbrace{\left(\mathbf{u}_t + \mathbf{u}\cdot\nabla\mathbf{u}\right)}^{\mathbf{a}} = -\overbrace{\nabla p + \mu\Delta\mathbf{u} + \mathbf{f}}^{\mathbf{f}}$$

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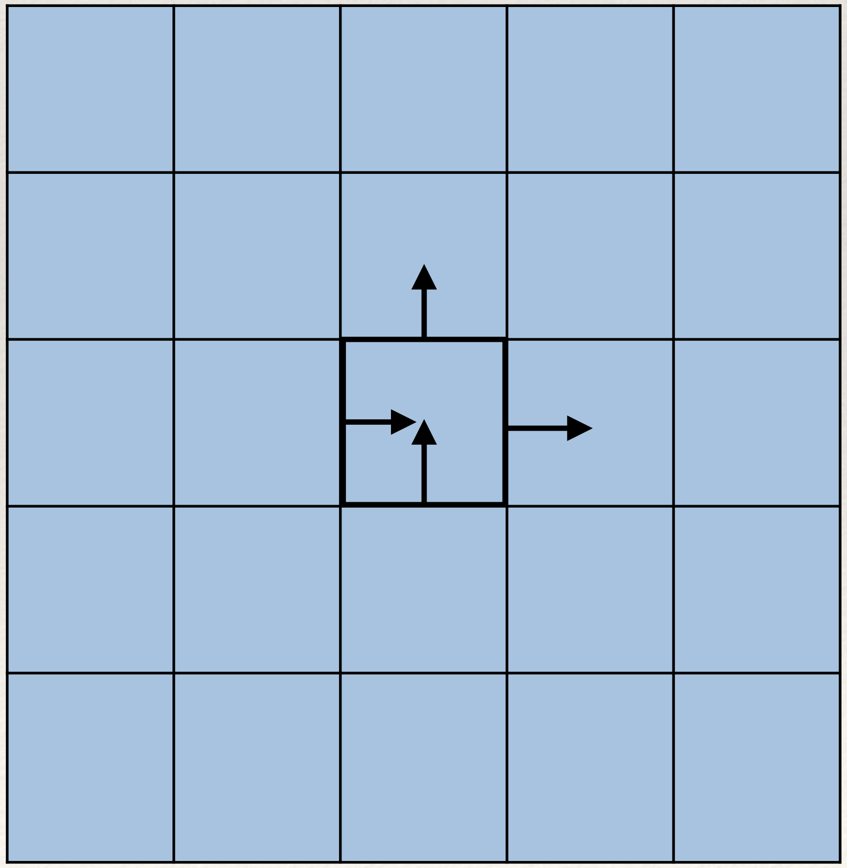


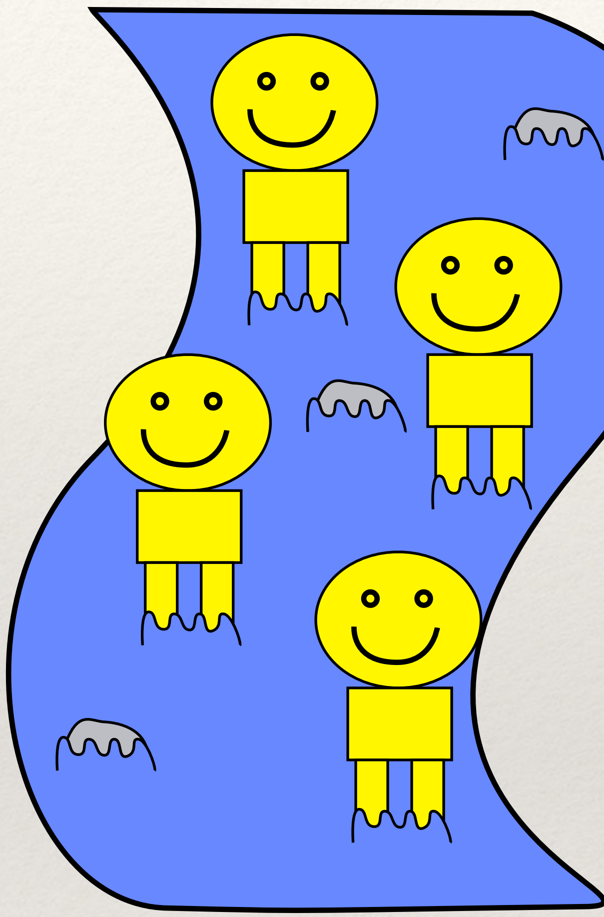
III. Spatial Discretization

Lagrangian vs. Eulerian

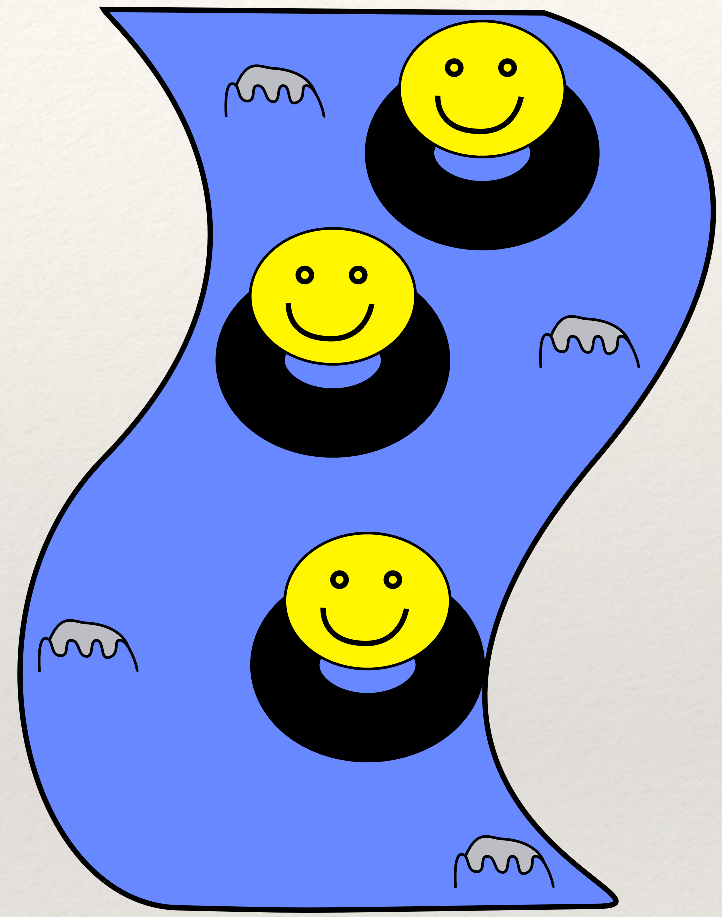
Reference Frames

- An Eulerian reference frame is fixed.
- A Lagrangian reference frame moves with the material.

Reference Frames

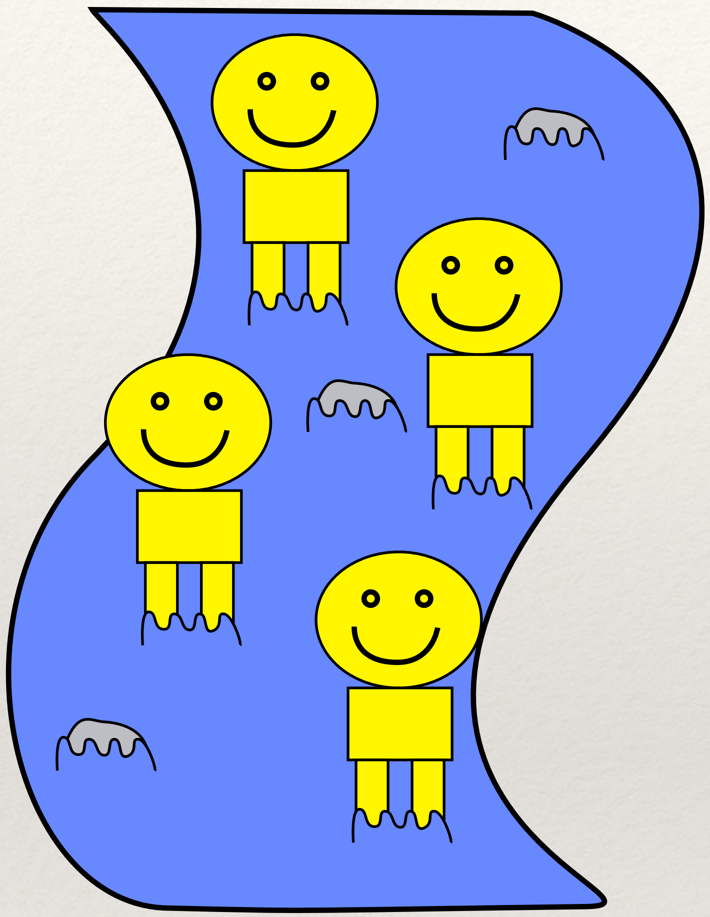


Eulerian

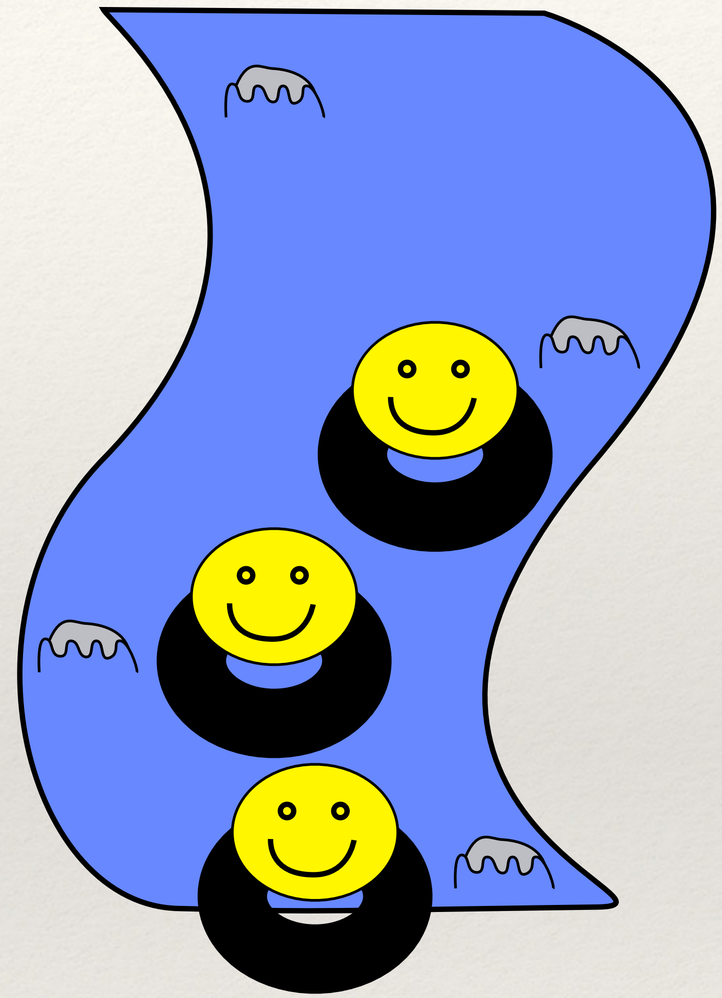


Lagrangian

Reference Frames

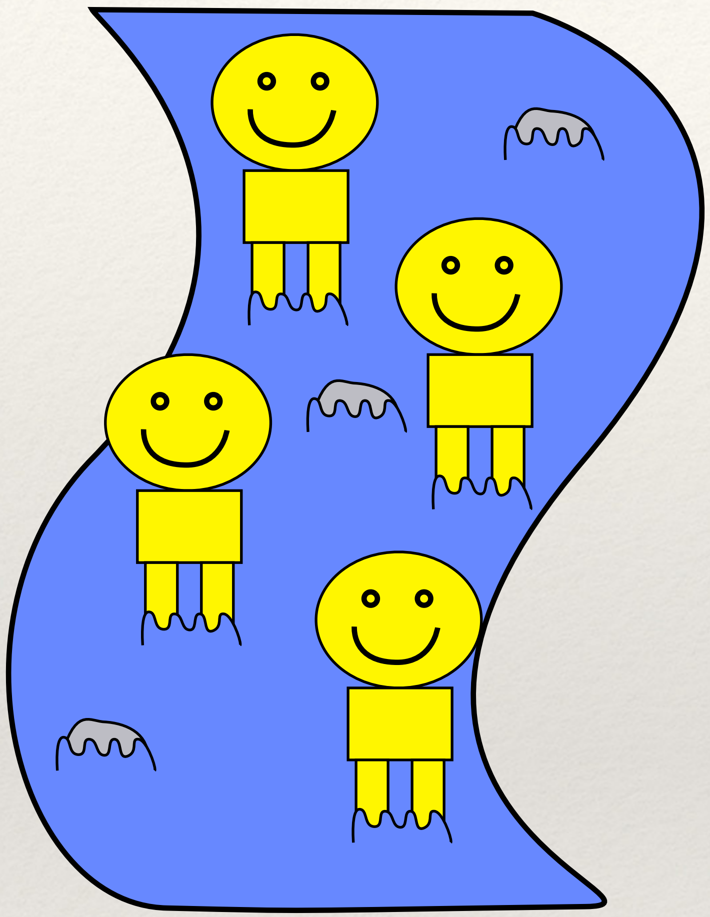


Eulerian



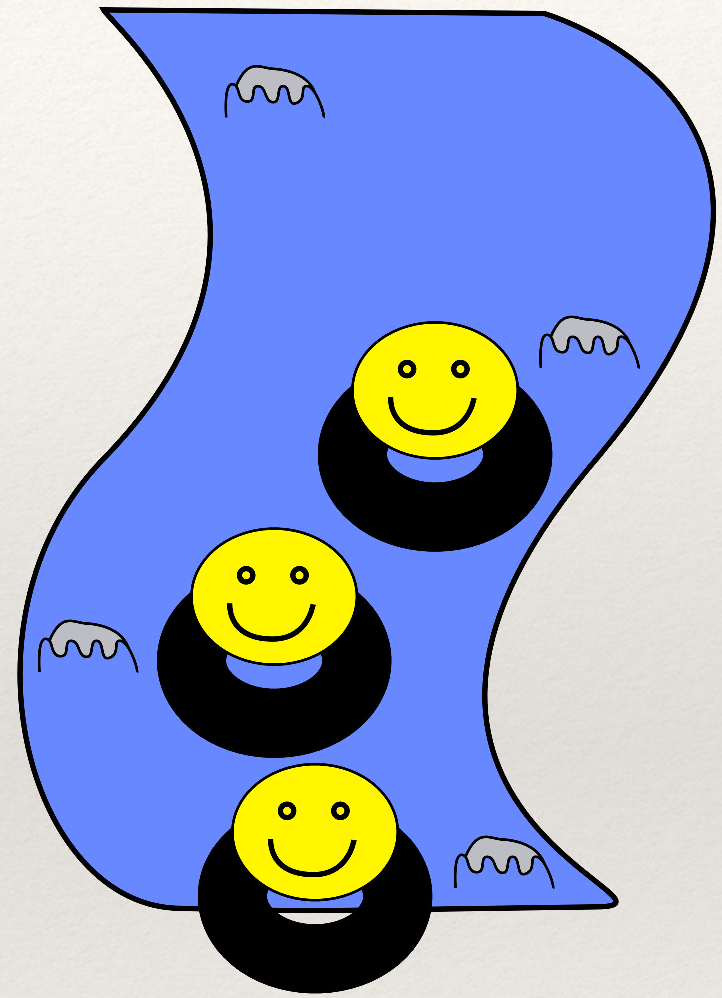
Lagrangian

Reference Frames



Eulerian

$$\frac{\partial y}{\partial t} + \mathbf{u} \cdot \nabla y$$



Lagrangian

$$\frac{dy}{dt}$$

Grids, Meshes, and Particles

Regular Grids

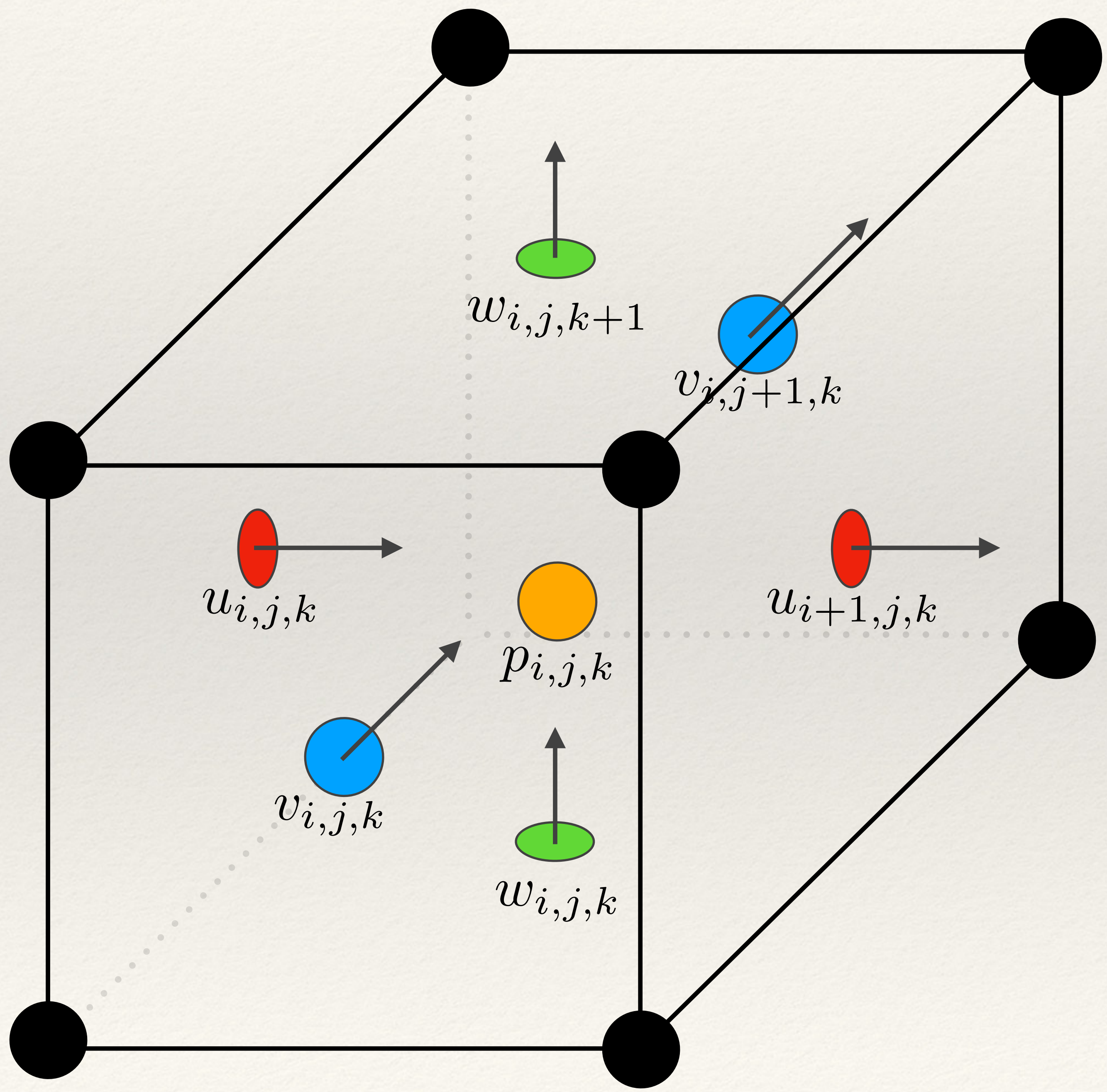
Advantages

- Simple
- Fast operations (e.g. point location)
- Can take advantage of structure for efficiency

Disadvantages

- Difficult to track shape over time
- Difficult to handle non-grid-aligned boundaries

Staggered Grid



Meshes (Simplicial Complexes)

Advantages

- Easy to map to previous points in time
- Can conform to boundaries

Disadvantages

- Difficult to generate meshes
- Difficult to perform some operations (e.g. point location)

Particles

Advantages

- Simple
- Easy to map to previous points in time

Disadvantages

- Difficult to perform integration because they don't partition space

Hybrid Structures

Advantages

- Advantages of underlying structures

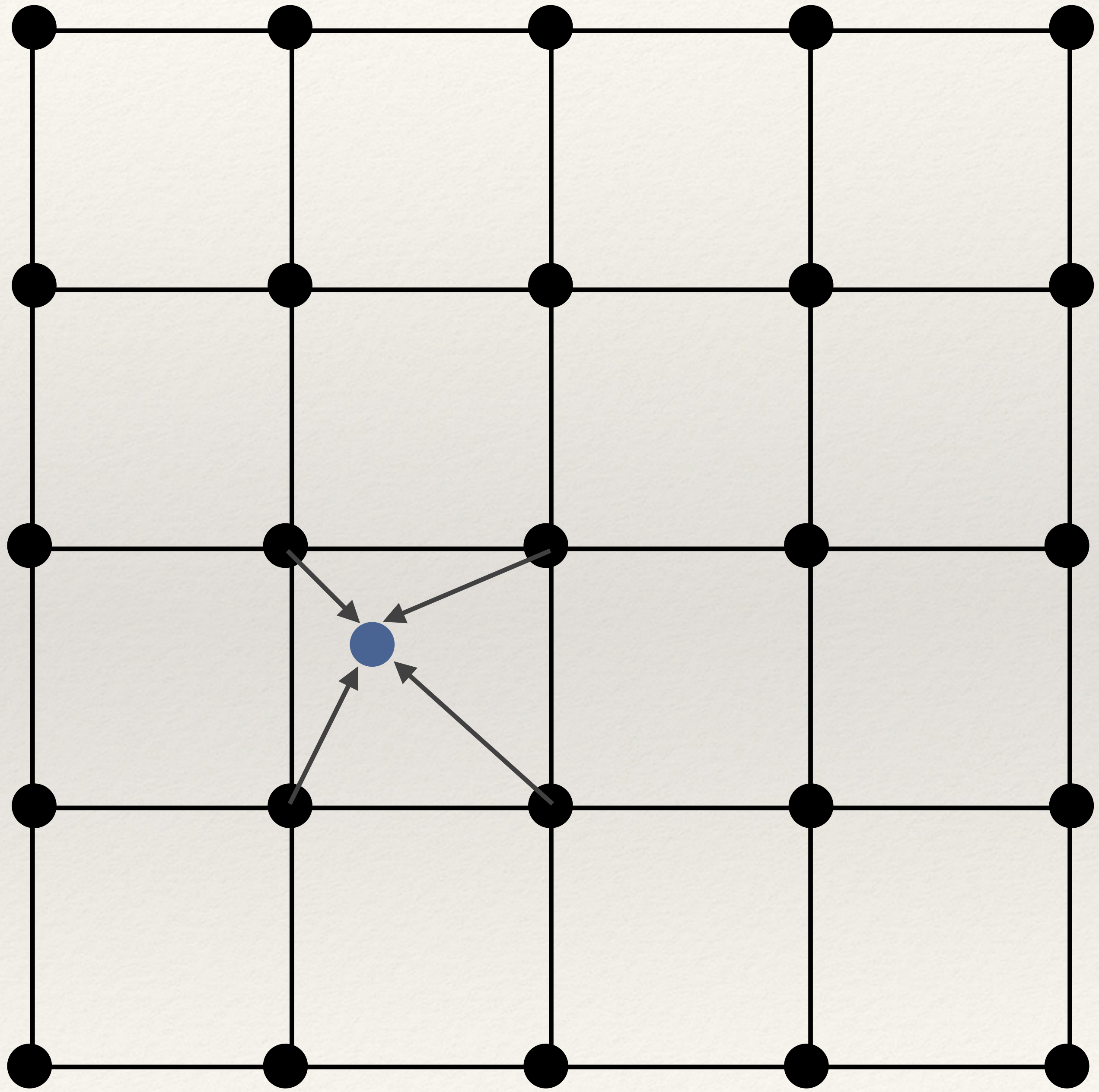
Disadvantages

- Complexity
- Computational and accuracy costs from mapping between structures

Interpolation

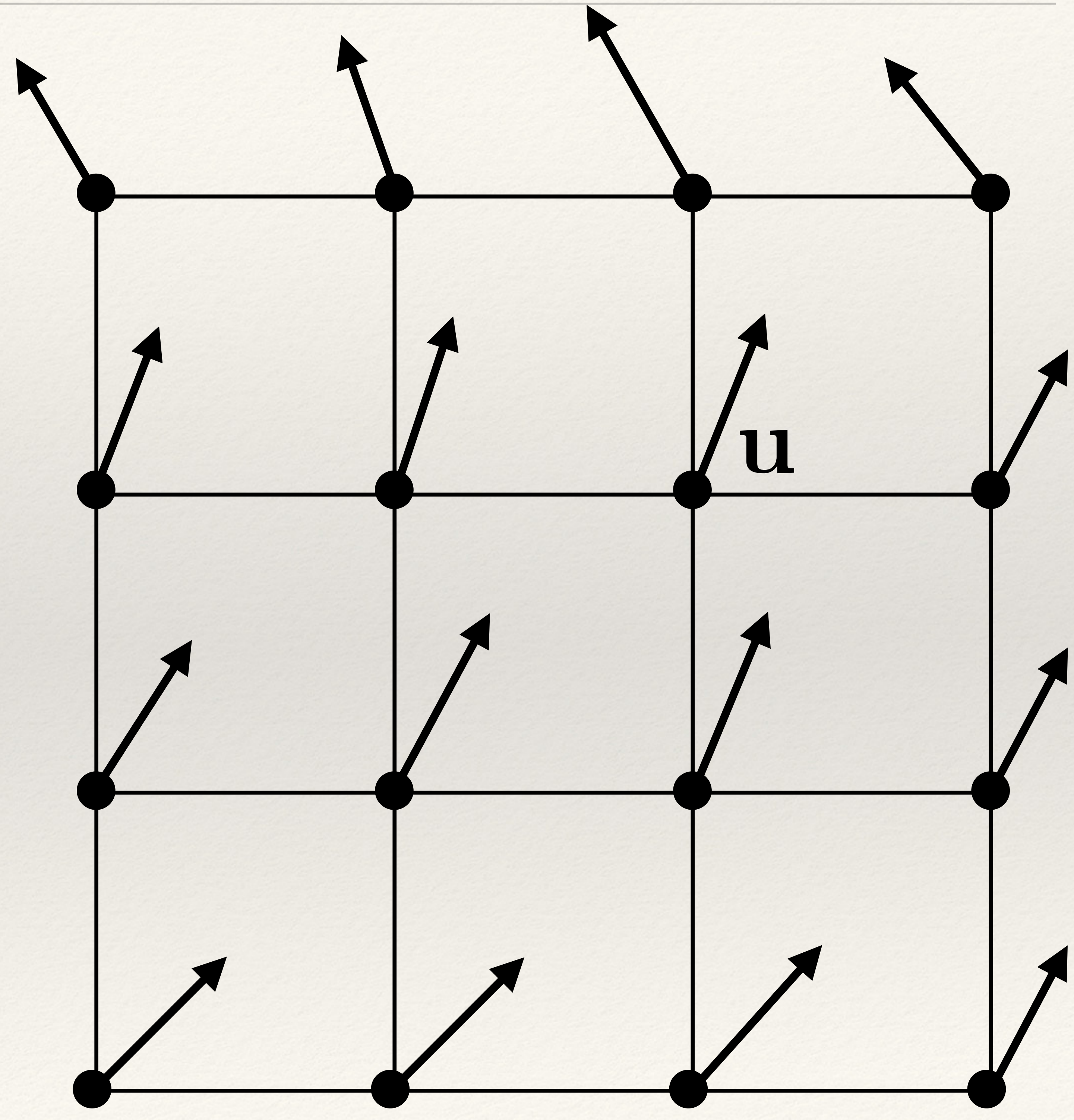
Interpolation

- Samples stored at discrete points on grid, mesh, or particles
- Elsewhere, must be interpolated there



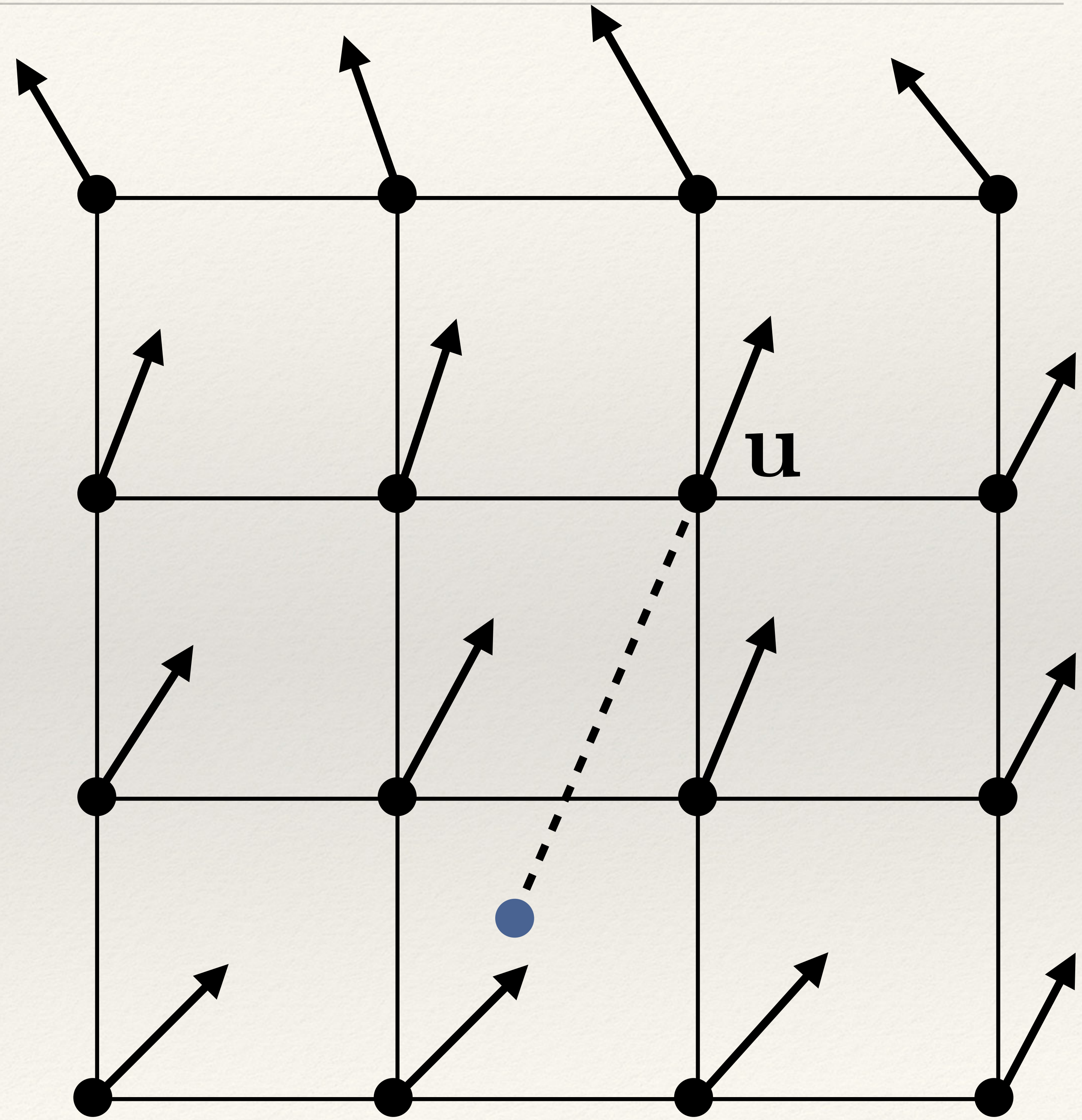
Interpolation

- Example: semi-Lagrangian advection



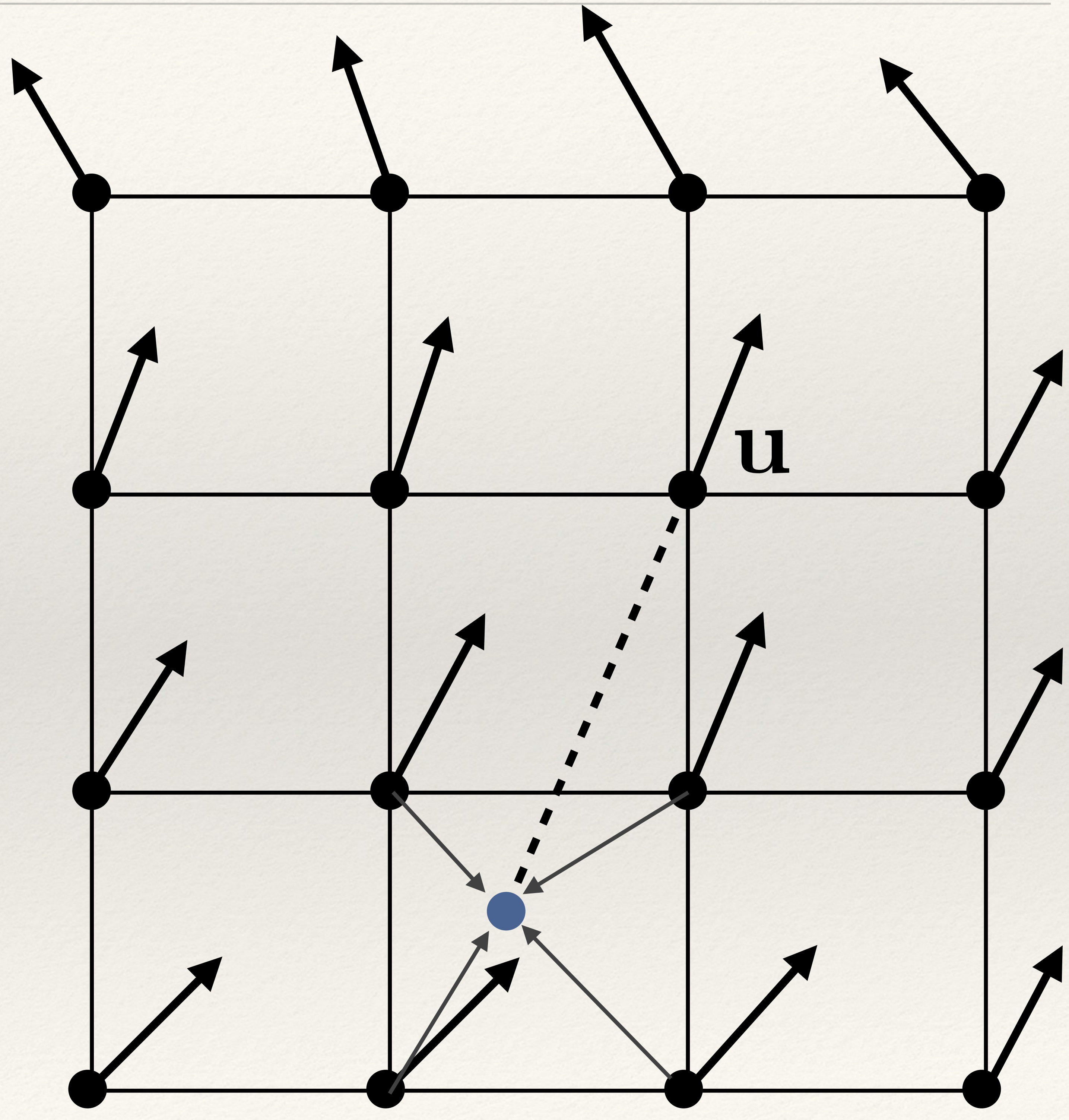
Interpolation

- Example: semi-Lagrangian advection



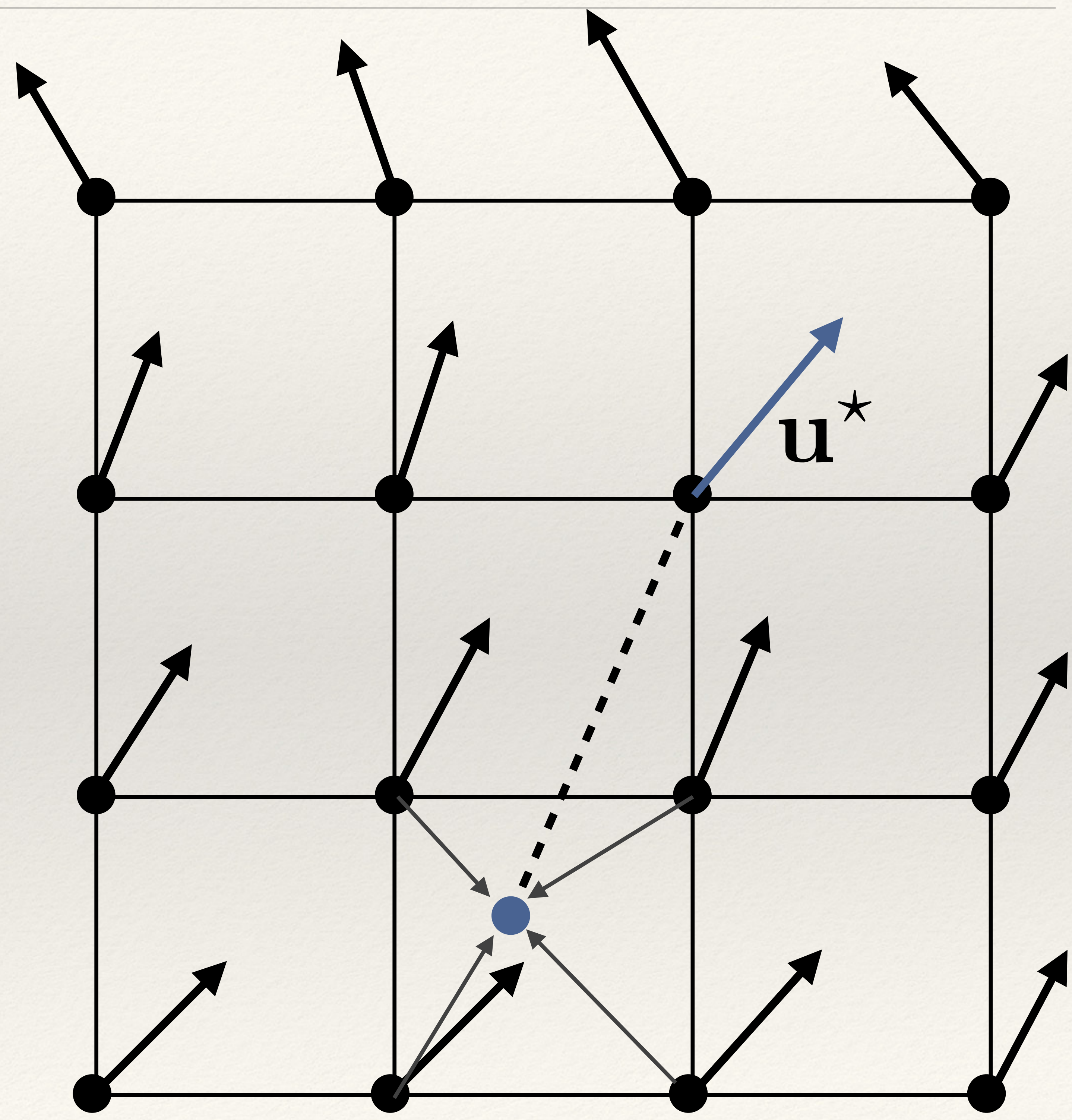
Interpolation

- Example: semi-Lagrangian advection



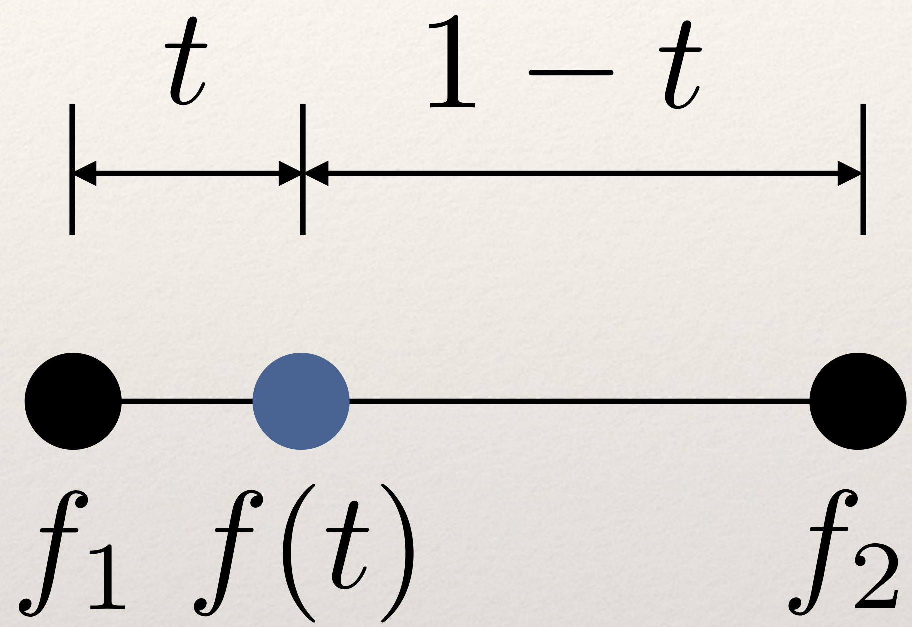
Interpolation

- Example: semi-Lagrangian advection



Linear Interpolation (1D)

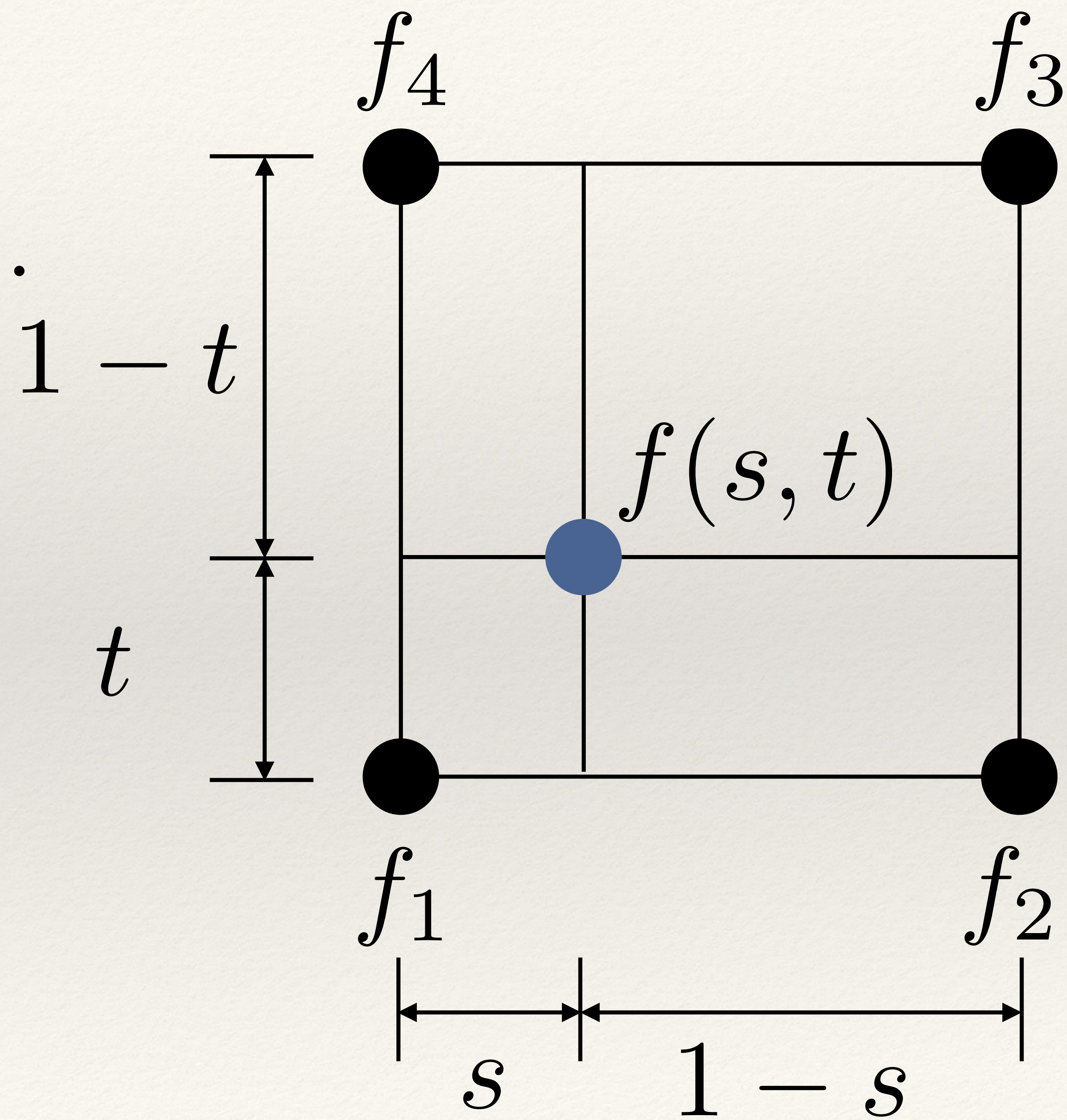
- $f(0) = f_1$
- $f(1) = f_2$
- weights sum to 1
- weight is length opposite point



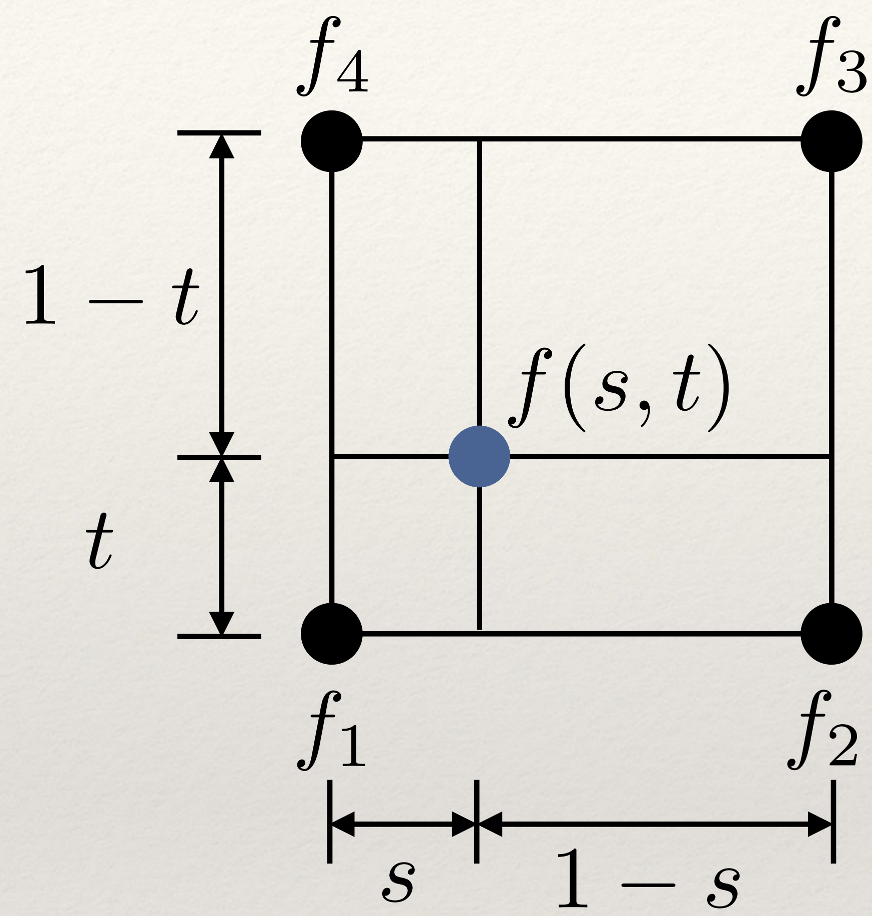
$$f(t) = (1 - t)f_1 + tf_2.$$

Bilinear Interpolation (2D)

- $f(0,0) = f_1, \cdots$
- $f(0,1) = f_4$
- weights sum to 1
- weight is area opposite point

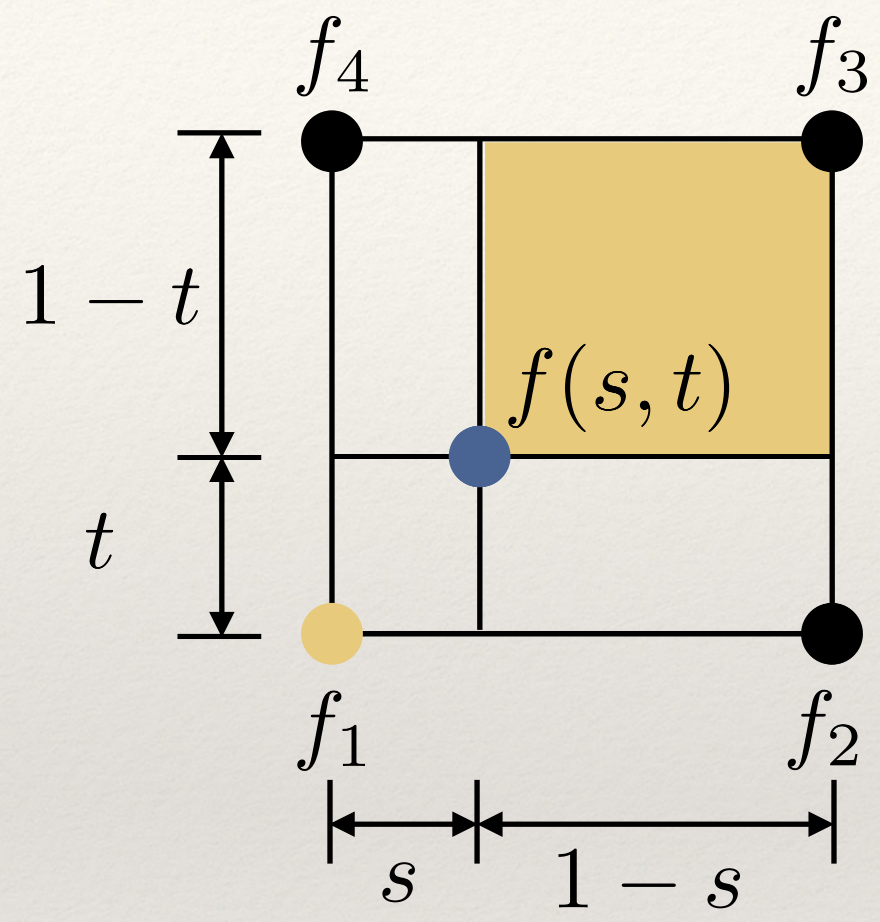


Bilinear Interpolation (2D)



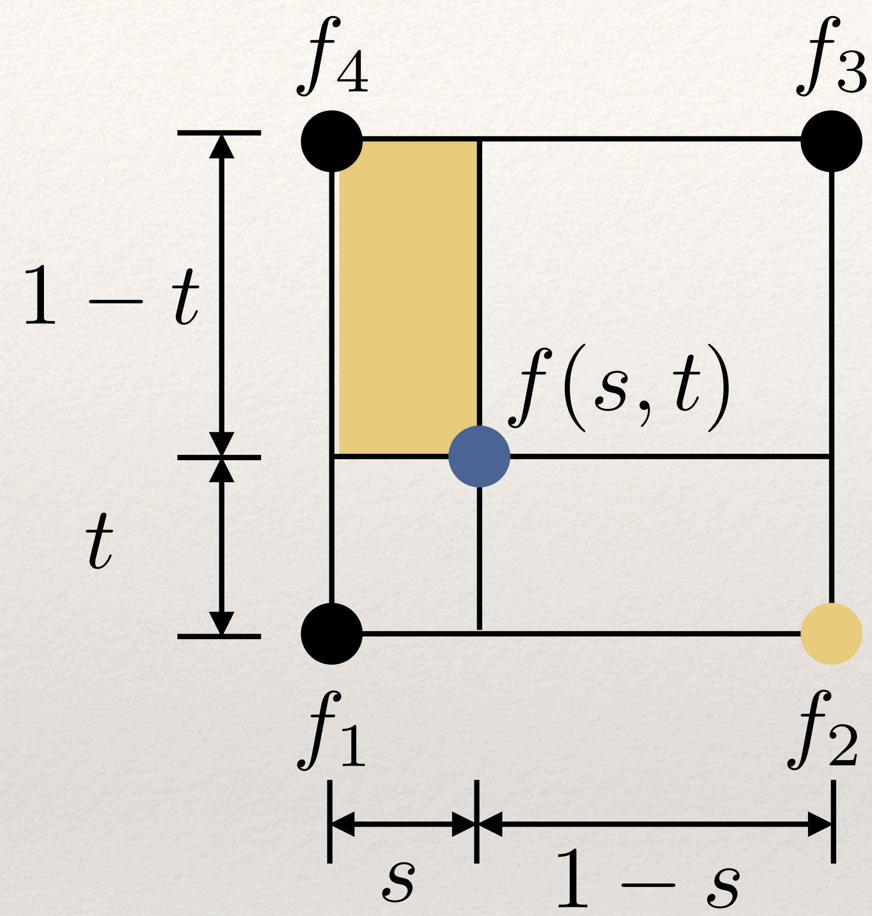
$$f(s,t) = (1-s)(1-t)f_1 + s(1-t)f_2 + stf_3 + (1-s)tf_4$$

Bilinear Interpolation (2D)



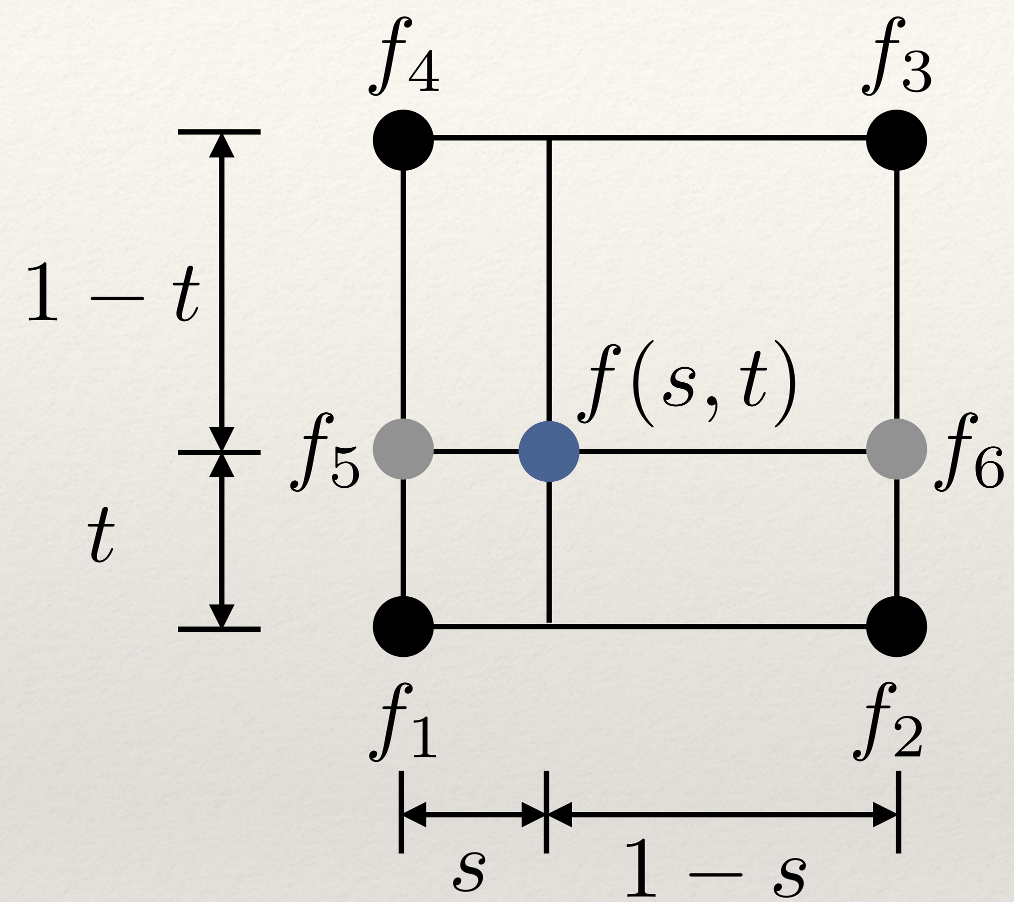
$$f(s,t) = (1-s)(1-t)f_1 + s(1-t)f_2 + stf_3 + (1-s)tf_4$$

Bilinear Interpolation (2D)



$$f(s,t) = (1-s)(1-t)f_1 + s(1-t)f_2 + stf_3 + (1-s)tf_4$$

Bilinear Interpolation (2D)

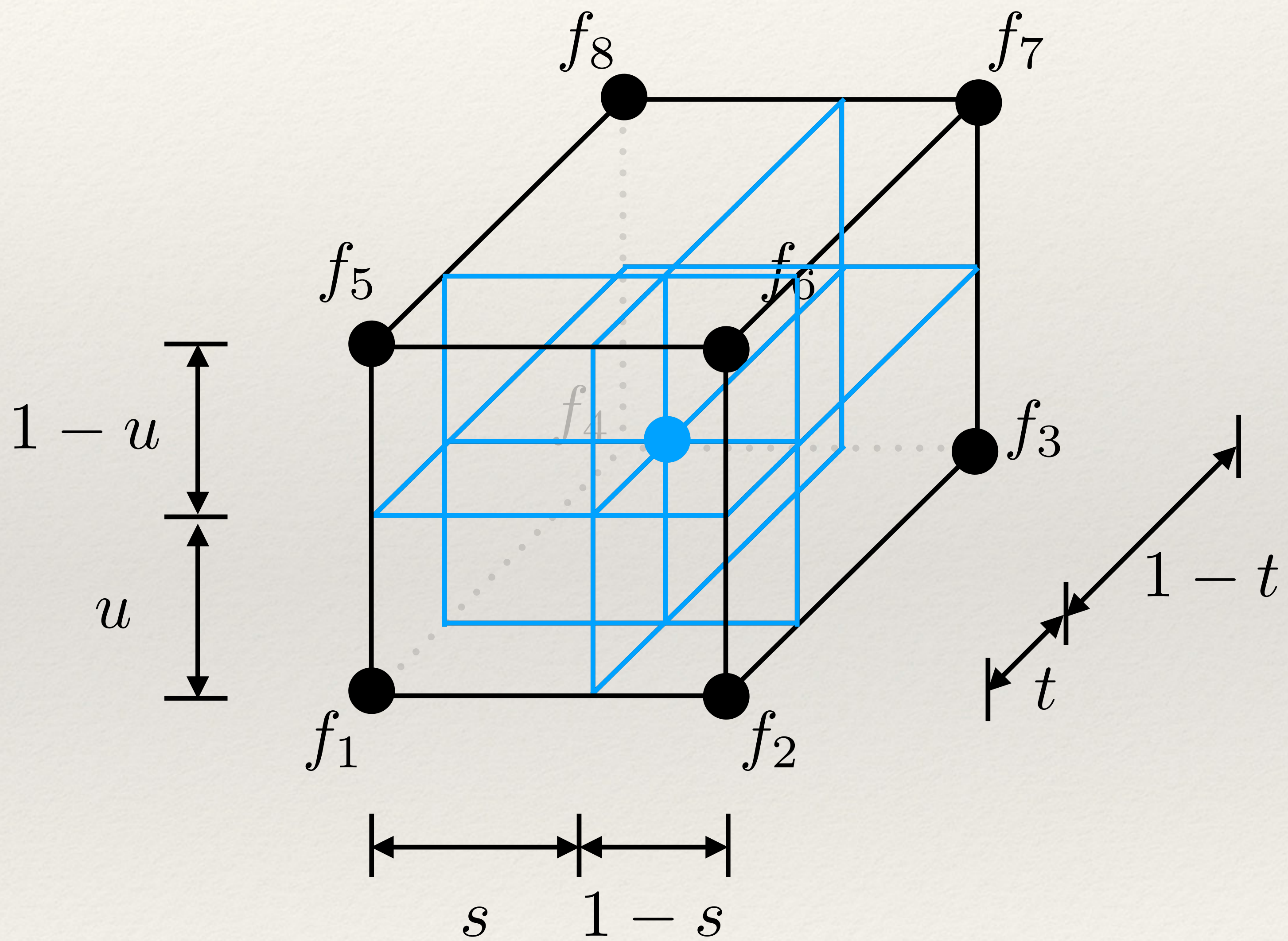


$$f_5 = (1-t)f_1 + tf_4 \qquad f_6 = (1-t)f_2 + tf_3$$

$$f(s,t) = (1-s)(1-t)f_1 + s(1-t)f_2 + stf_3 + (1-s)tf_4$$

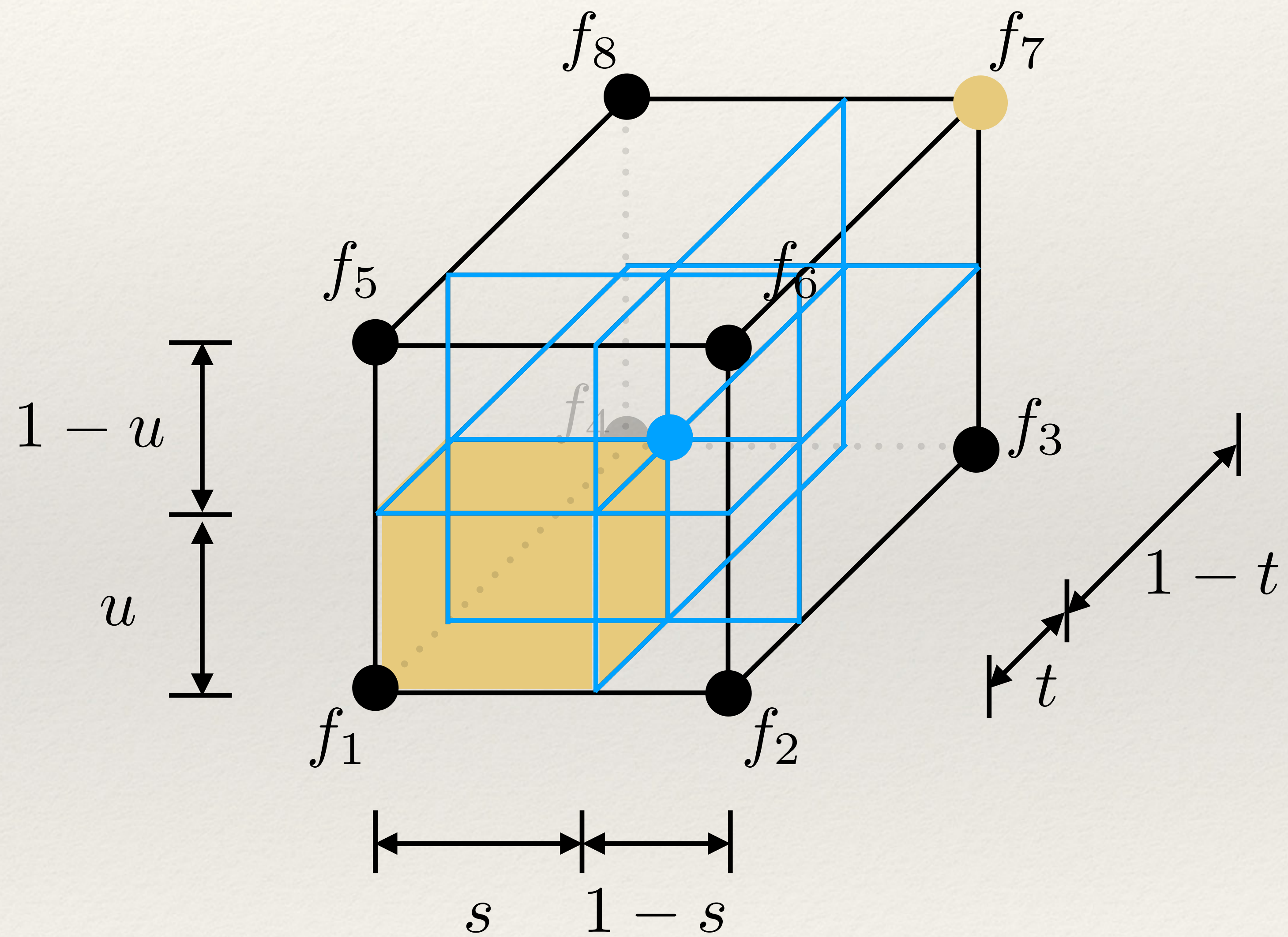
Trilinear Interpolation (3D)

$$
\begin{aligned}
f(s,t,u) = \\
(1-s)(1-t)(1-u)f_1 \\
+ s(1-t)(1-u)f_2 \\
+ st(1-u)f_3 \\
+ (1-s)t(1-u)f_4 \\
+ (1-s)(1-t)uf_5 \\
+ s(1-t)uf_6 \\
+ stuf_7 \\
+ (1-s)tuf_8
\end{aligned}
$$



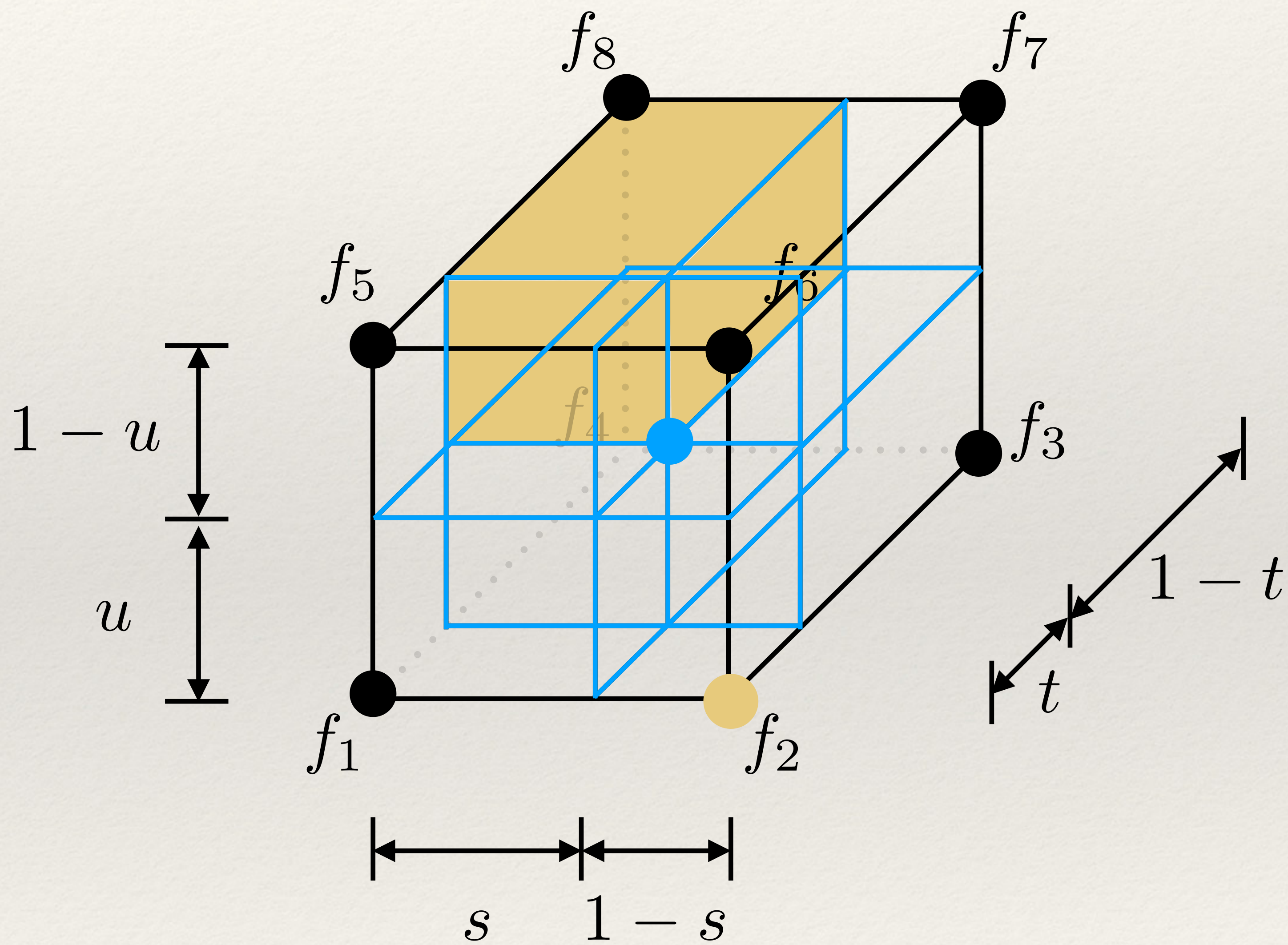
Trilinear Interpolation (3D)

$$f(s,t,u) =$$
$$(1-s)(1-t)(1-u)f_1$$
$$+\, s(1-t)(1-u)f_2$$
$$+\, st(1-u)f_3$$
$$+\, (1-s)t(1-u)f_4$$
$$+\, (1-s)(1-t)uf_5$$
$$+\, s(1-t)uf_6$$
$$+\, stuf_7$$
$$+\, (1-s)tuf_8$$



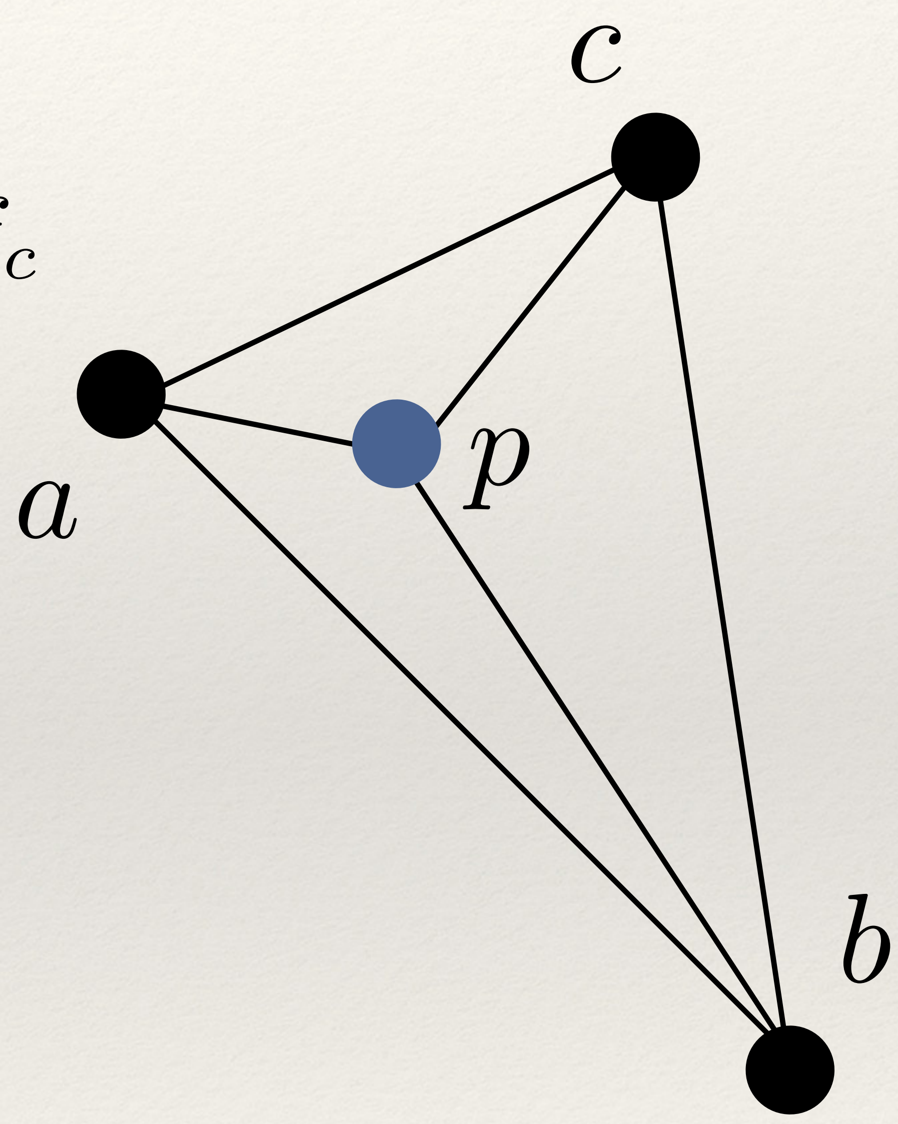
Trilinear Interpolation (3D)

$$f(s,t,u) =$$
$$(1-s)(1-t)(1-u)f_1$$
$$+\ s(1-t)(1-u)f_2$$
$$+\ st(1-u)f_3$$
$$+\ (1-s)t(1-u)f_4$$
$$+\ (1-s)(1-t)uf_5$$
$$+\ s(1-t)uf_6$$
$$+\ stuf_7$$
$$+\ (1-s)tuf_8$$



Barycentric Coordinates

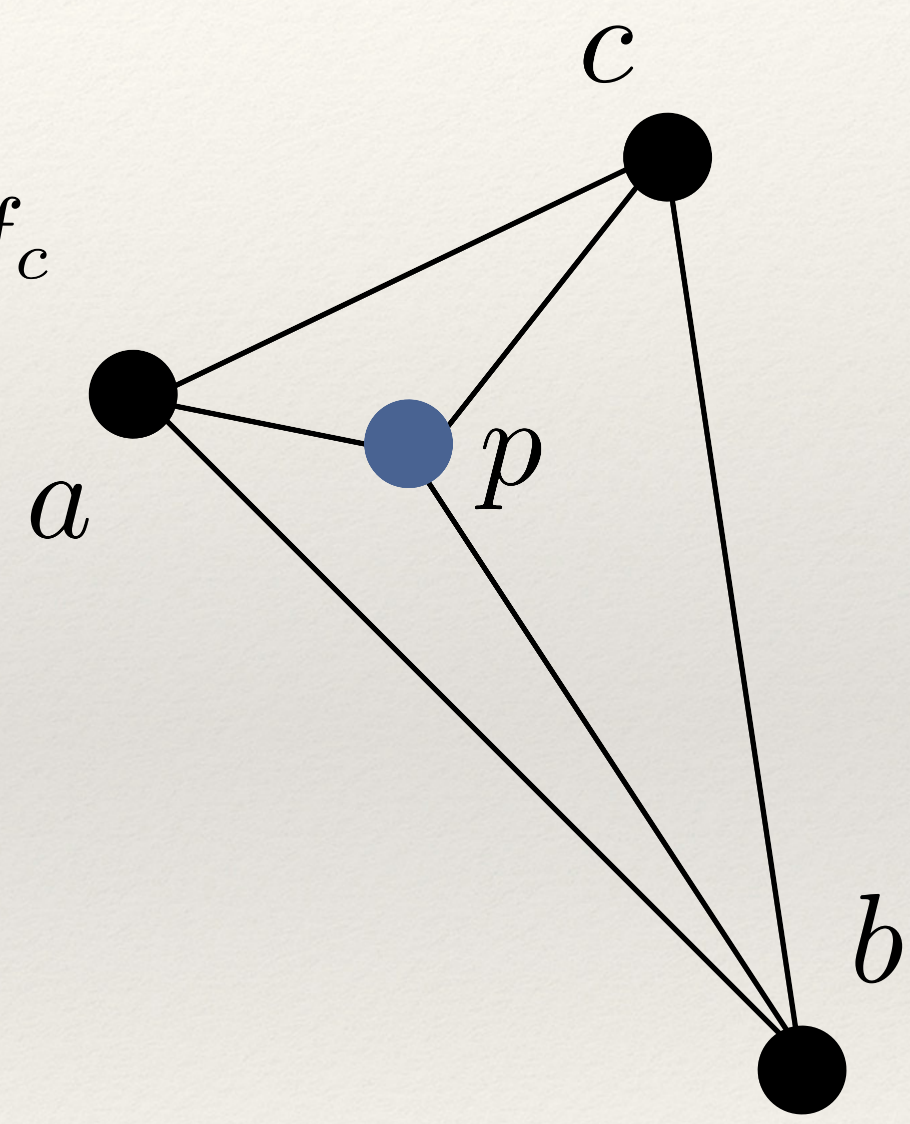
$$f_p = f(\alpha, \beta, \gamma) = \alpha f_a + \beta f_b + \gamma f_c$$



Barycentric Coordinates

$$f_p = f(\alpha, \beta, \gamma) = \alpha f_a + \beta f_b + \gamma f_c$$

$$\alpha = \frac{\text{area}(p, b, c)}{\text{area}(a, b, c)},$$
$$\beta = \frac{\text{area}(p, c, a)}{\text{area}(a, b, c)},$$
$$\gamma = \frac{\text{area}(p, a, b)}{\text{area}(a, b, c)}.$$



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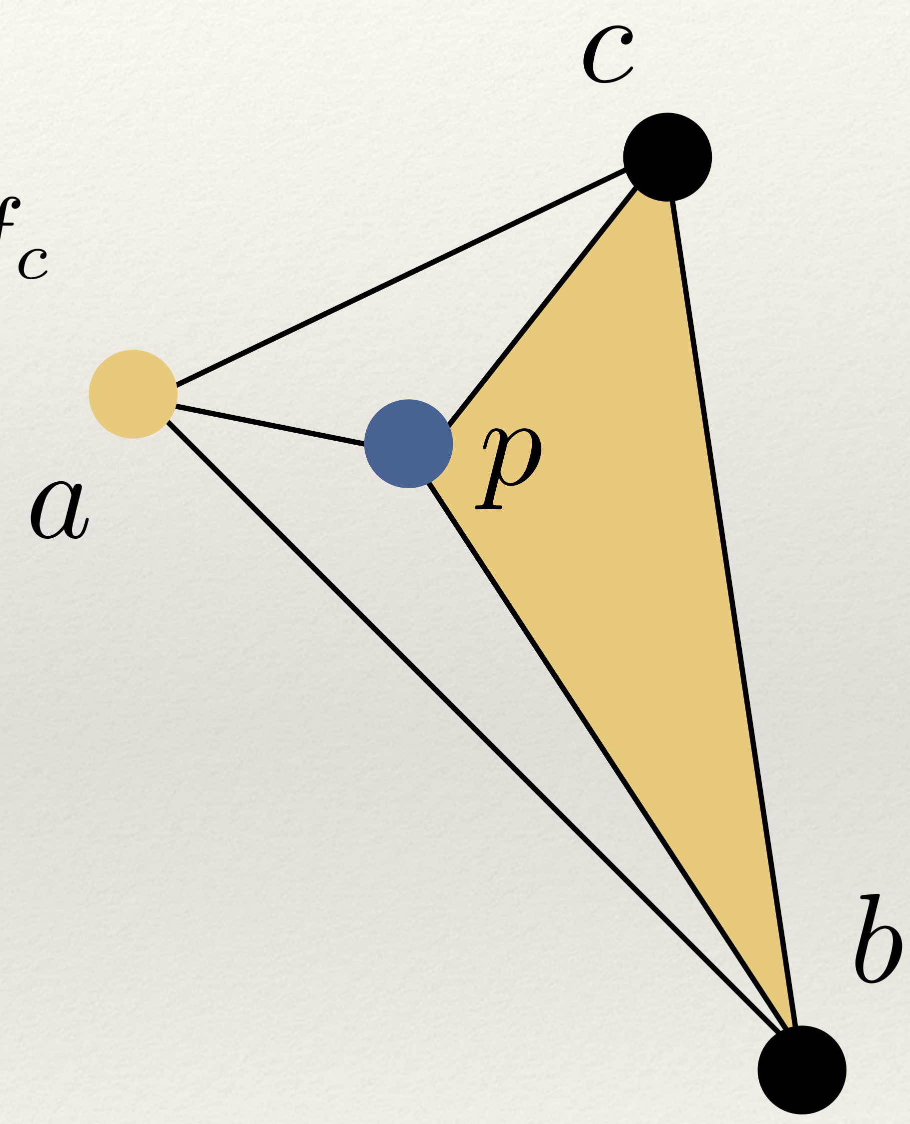

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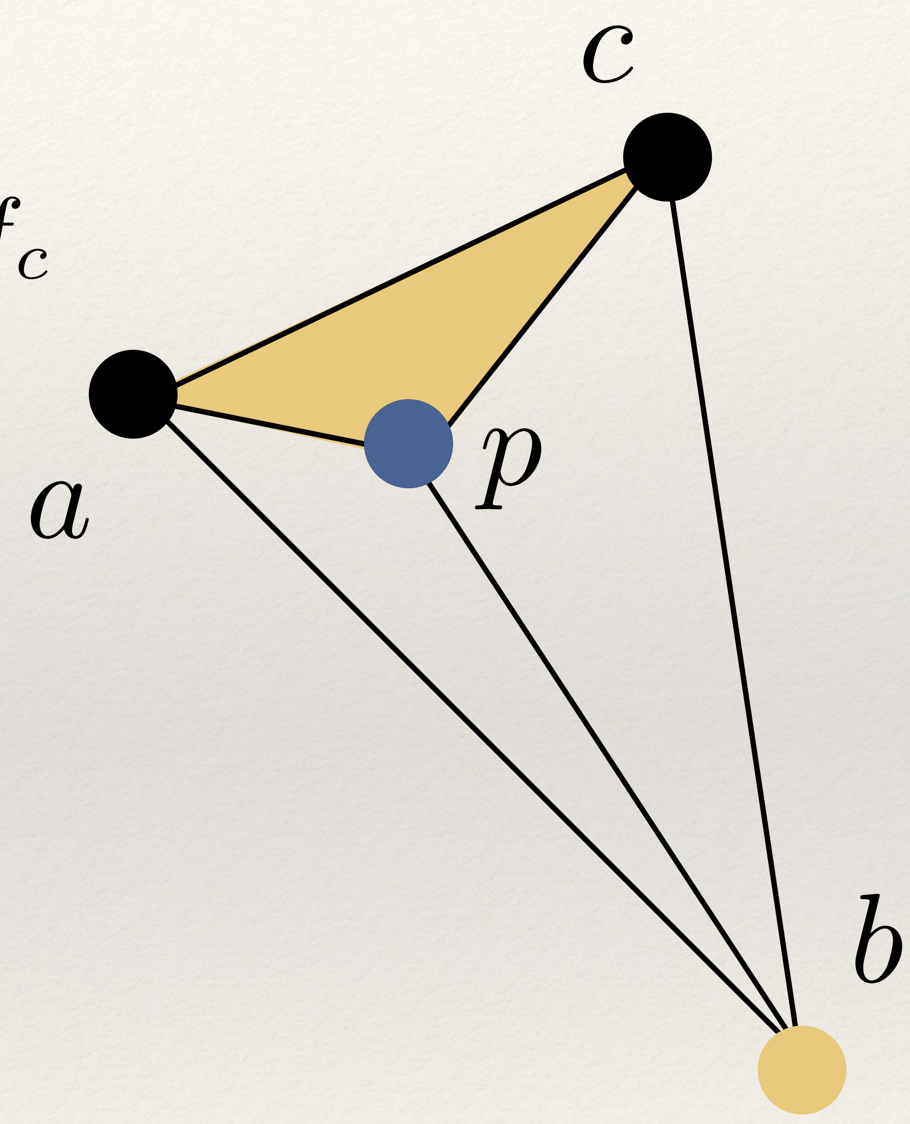

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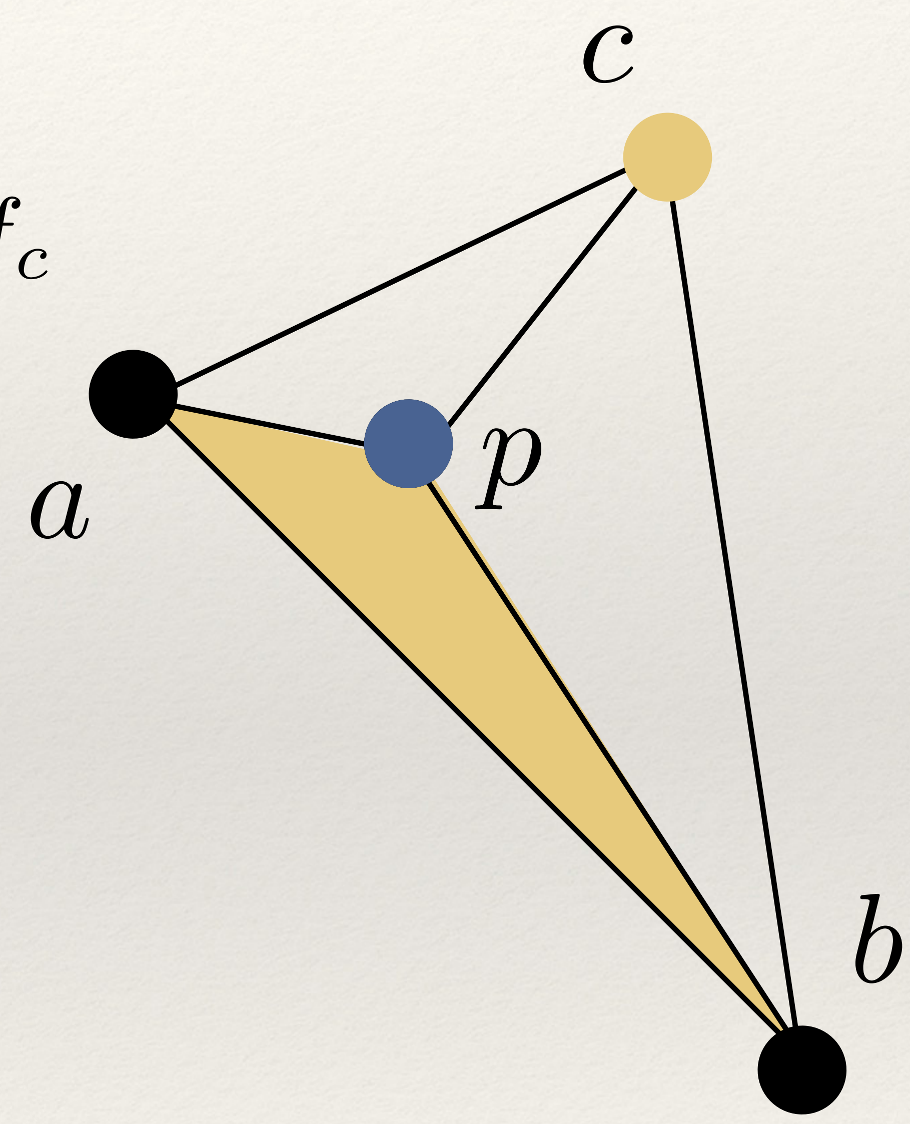

Barycentric Coordinates

$$f_p = f(\alpha, \beta, \gamma) = \alpha f_a + \beta f_b + \gamma f_c$$

$$\alpha = \frac{\text{area}(p, b, c)}{\text{area}(a, b, c)},$$

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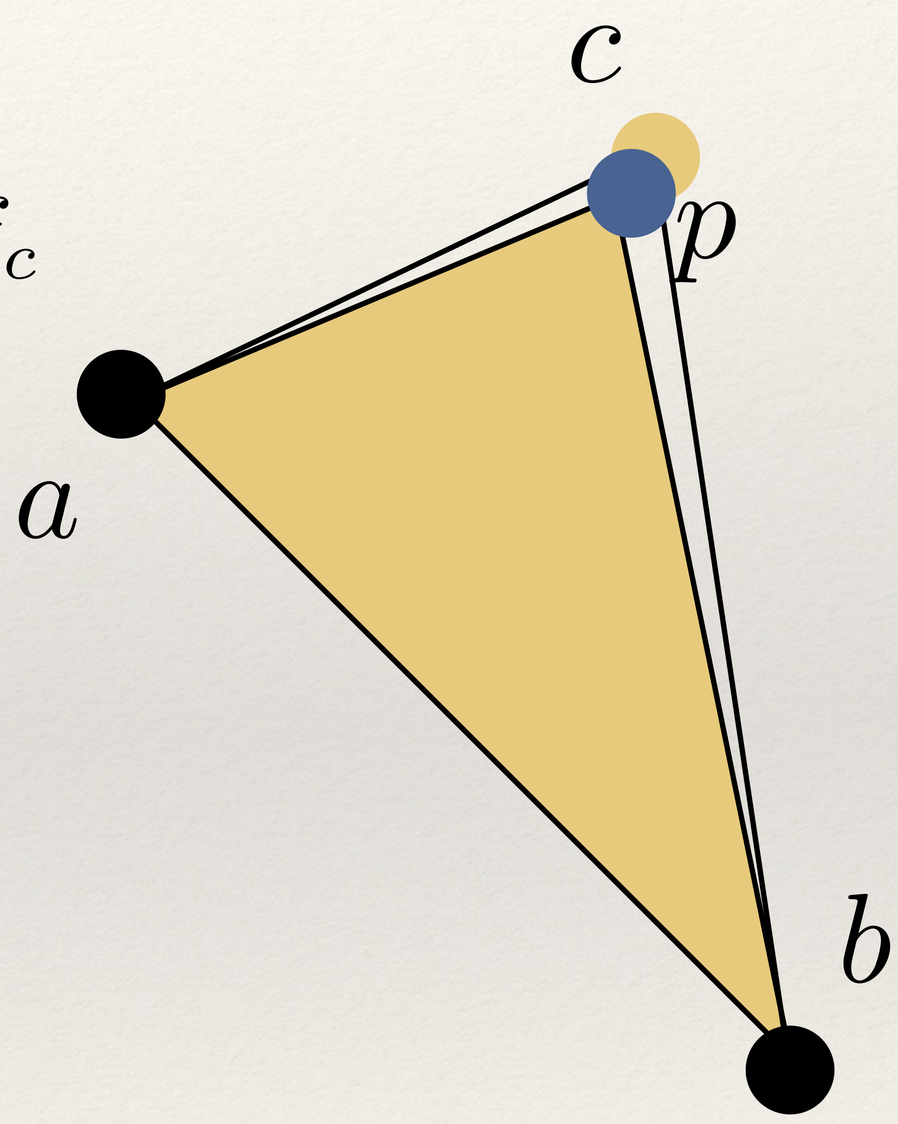
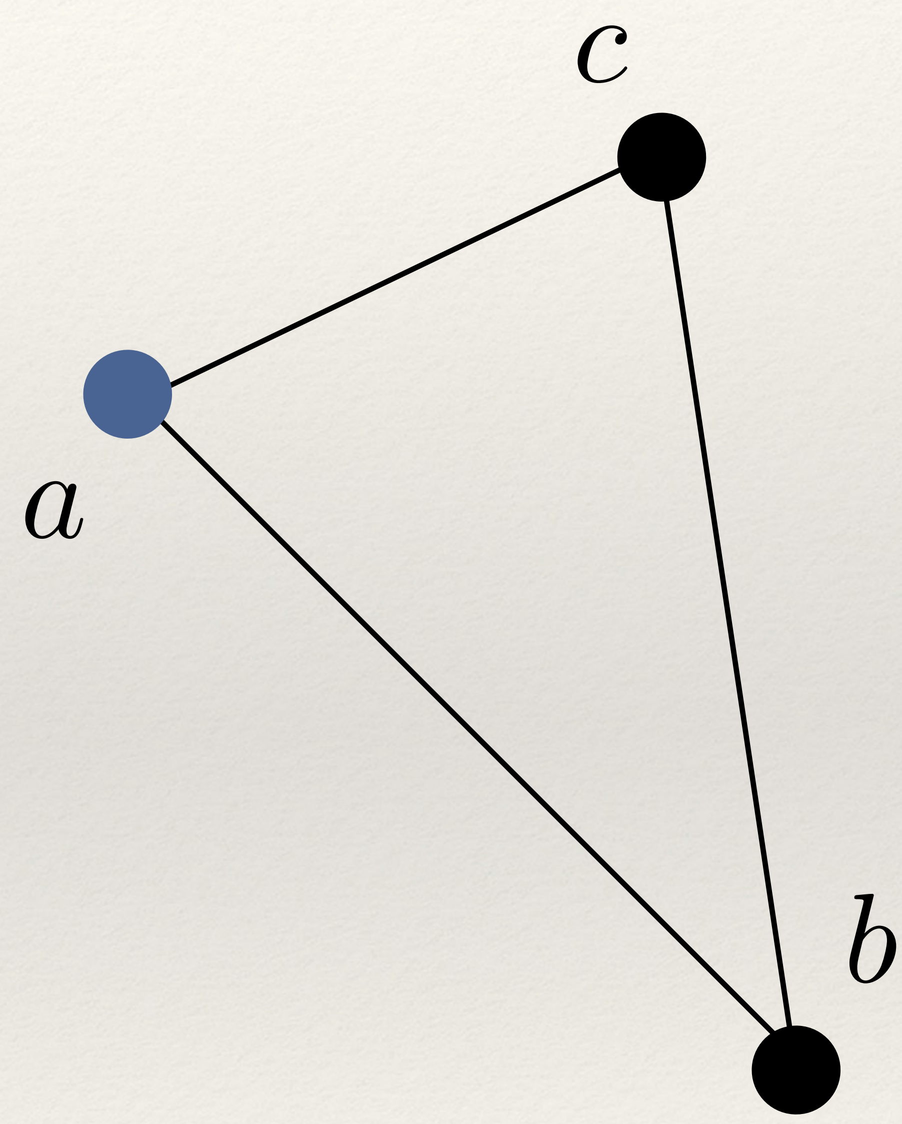


Barycentric Coordinates

- Coordinates at a vertex

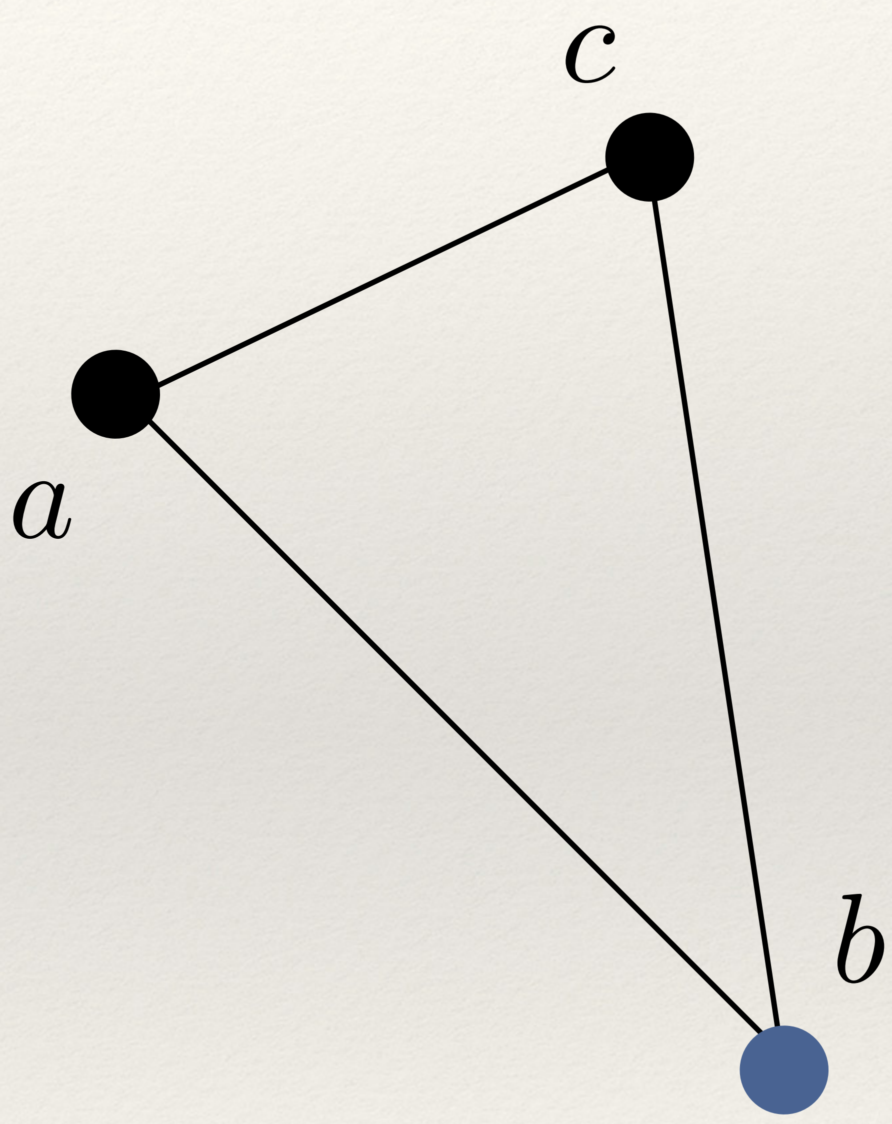
$$\alpha = 1$$
$$\beta = 0$$
$$\gamma = 0$$



Barycentric Coordinates

- Coordinates at a vertex

$$\alpha = 0$$
$$\beta = 1$$
$$\gamma = 0$$



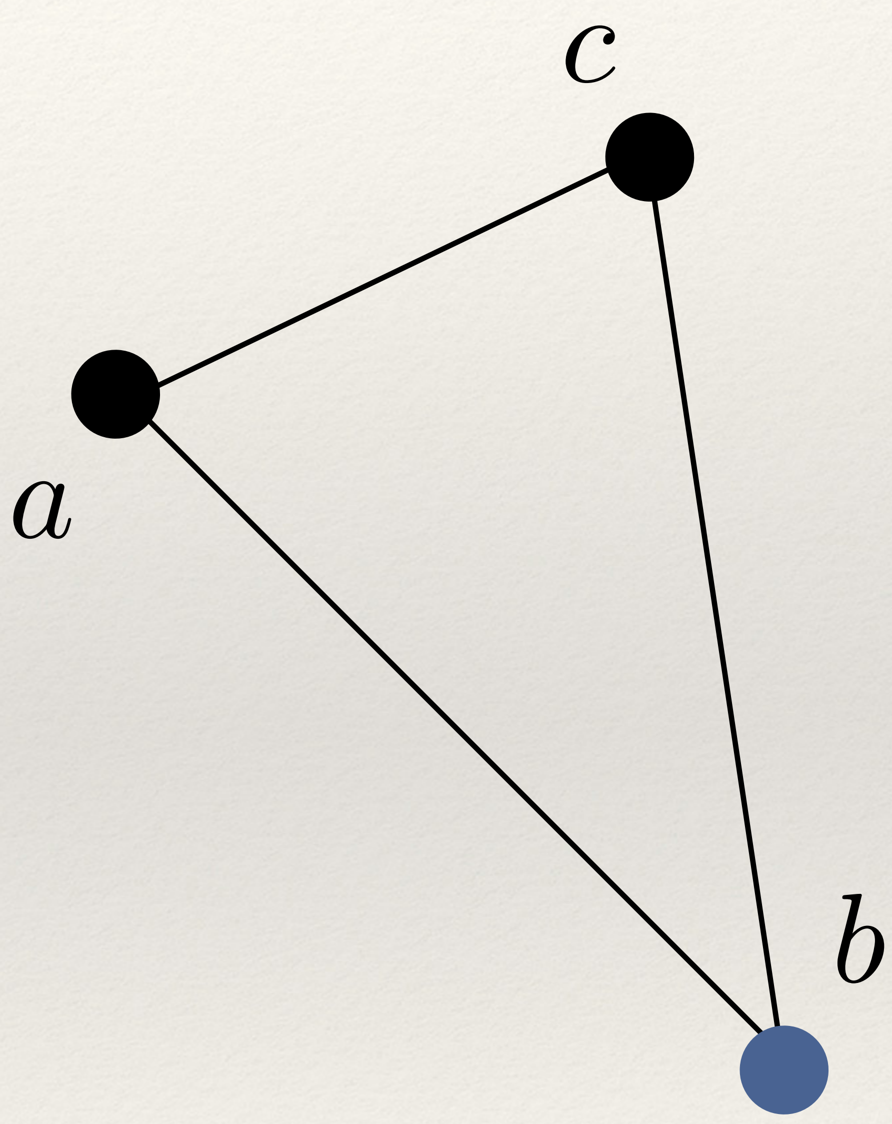
Barycentric Coordinates

- Coordinates at a vertex

$$\alpha = 0$$

$$\beta = 0$$

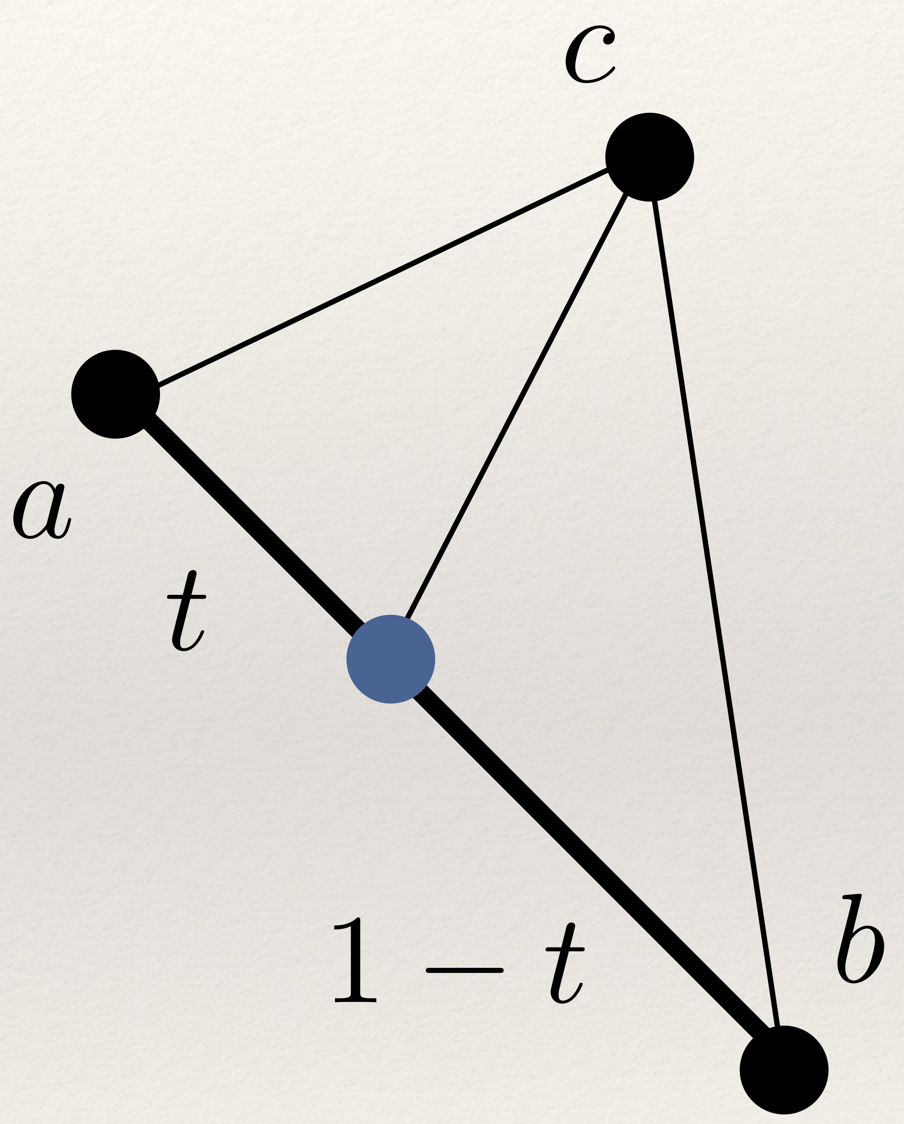
$$\gamma = 1$$



Barycentric Coordinates

- Coordinates on edge

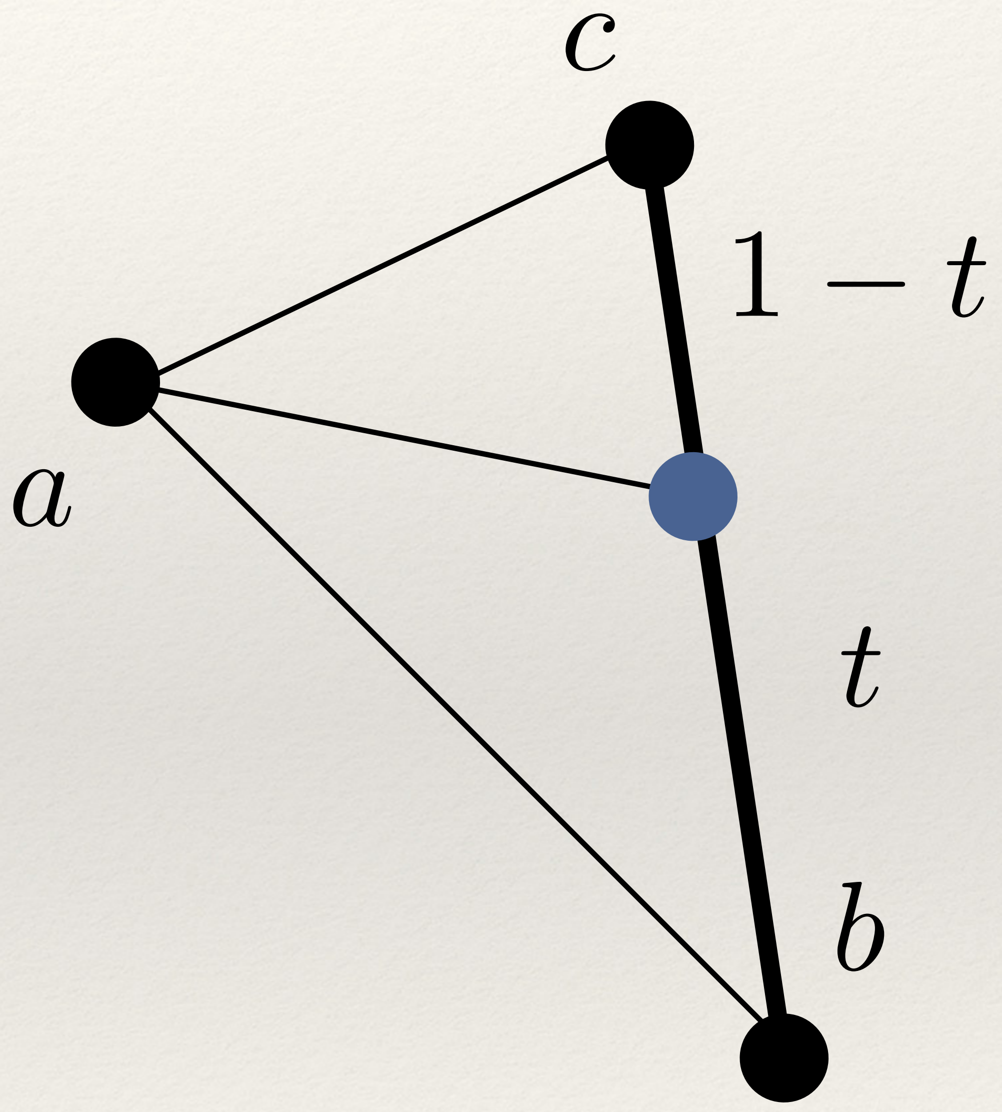
$$\alpha = 1 - t$$
$$\beta = t$$
$$\gamma = 0$$



Barycentric Coordinates

- Coordinates on edge

$$\alpha = 0$$
$$\beta = 1 - t$$
$$\gamma = t$$



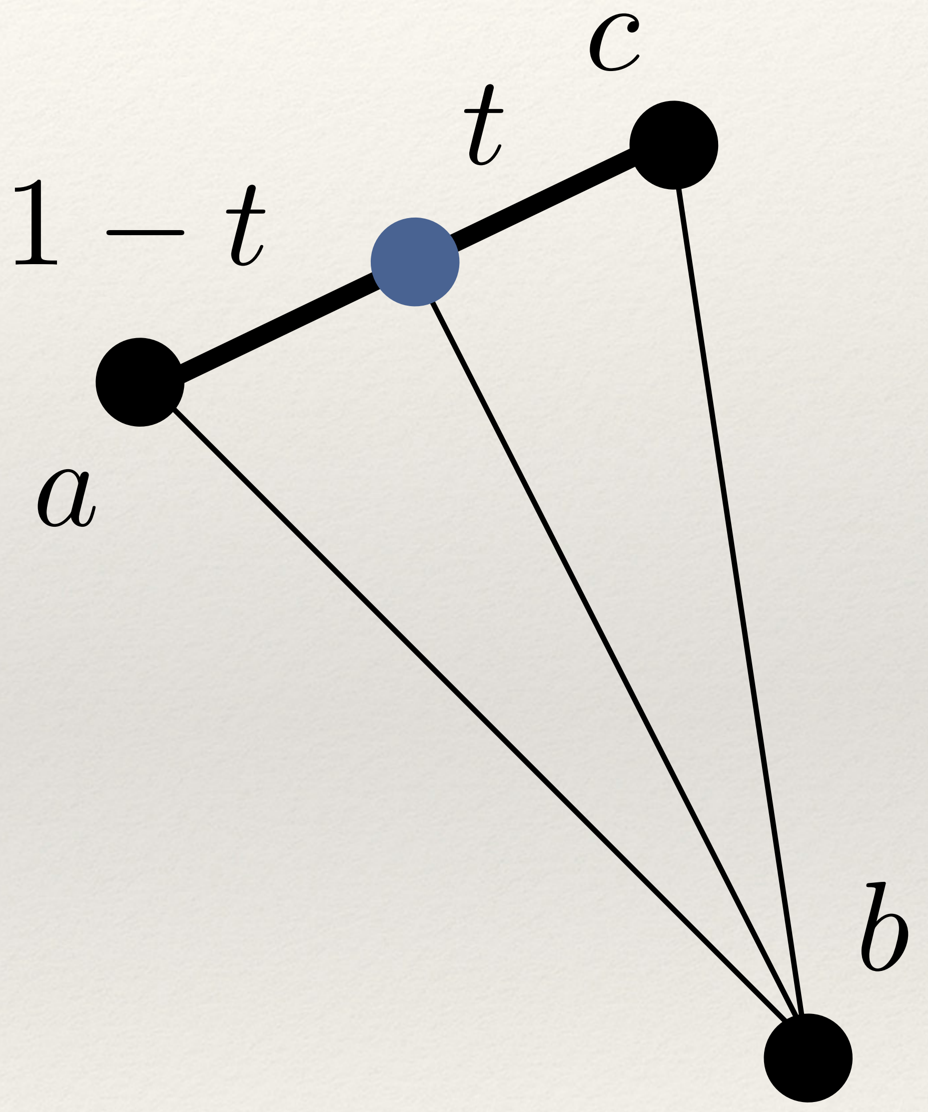
Barycentric Coordinates

- Coordinates on edge

$$\alpha = t$$

$$\beta = 0$$

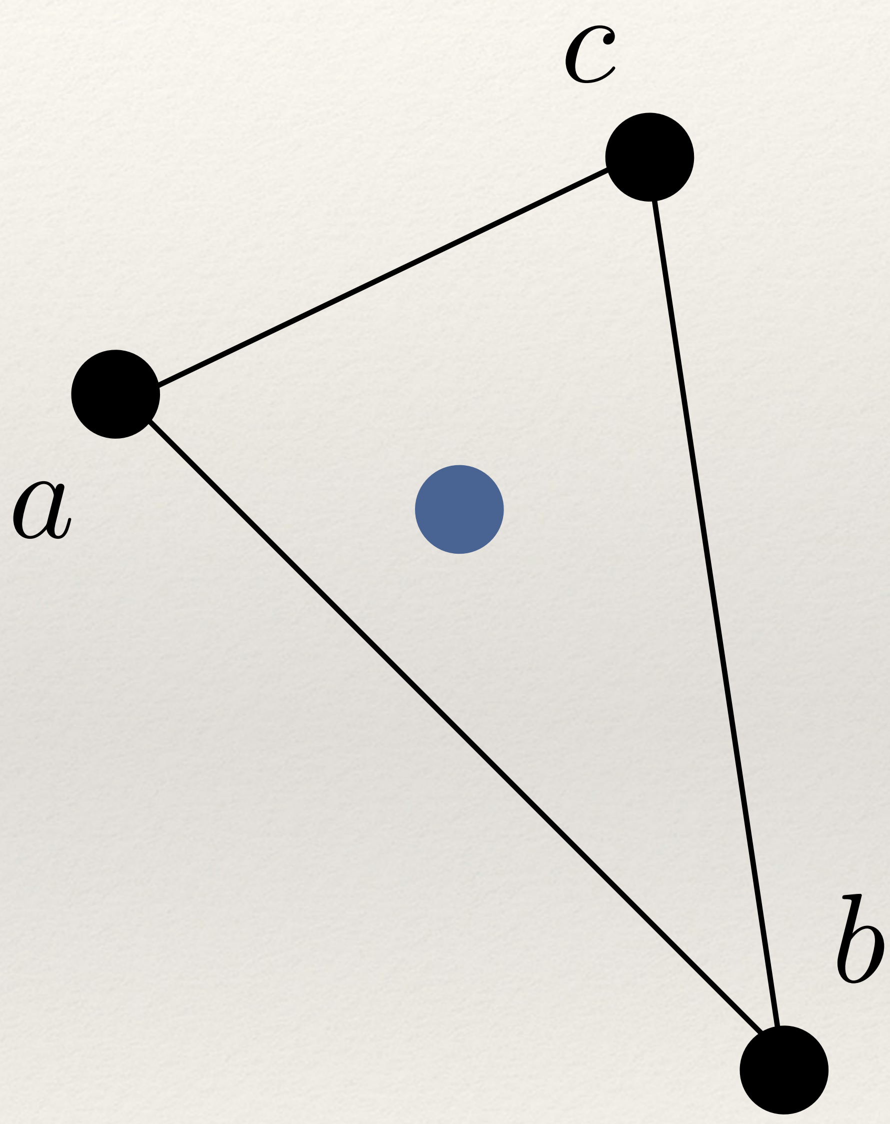
$$\gamma = 1 - t$$



Barycentric Coordinates

- Inside/outside test

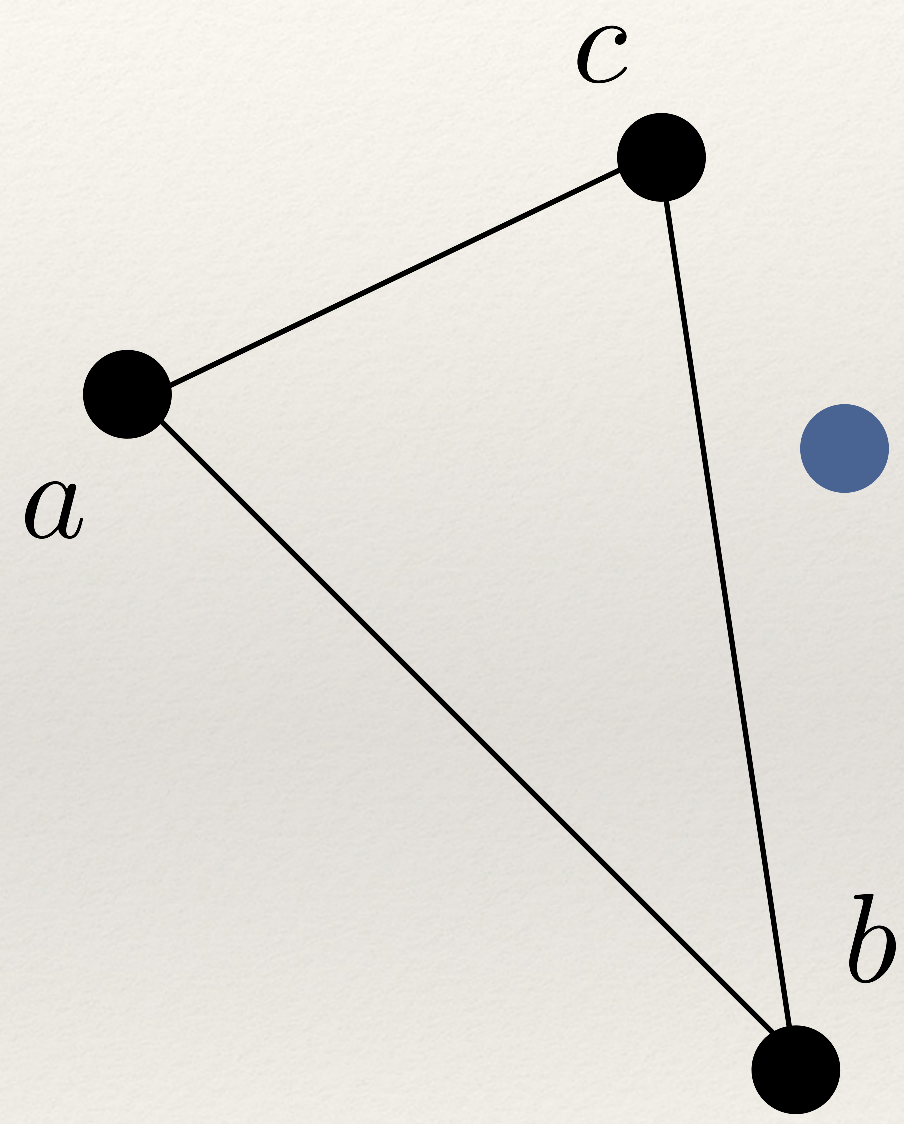
$$\alpha > 0, \beta > 0, \gamma > 0$$



Barycentric Coordinates

- Inside/outside test

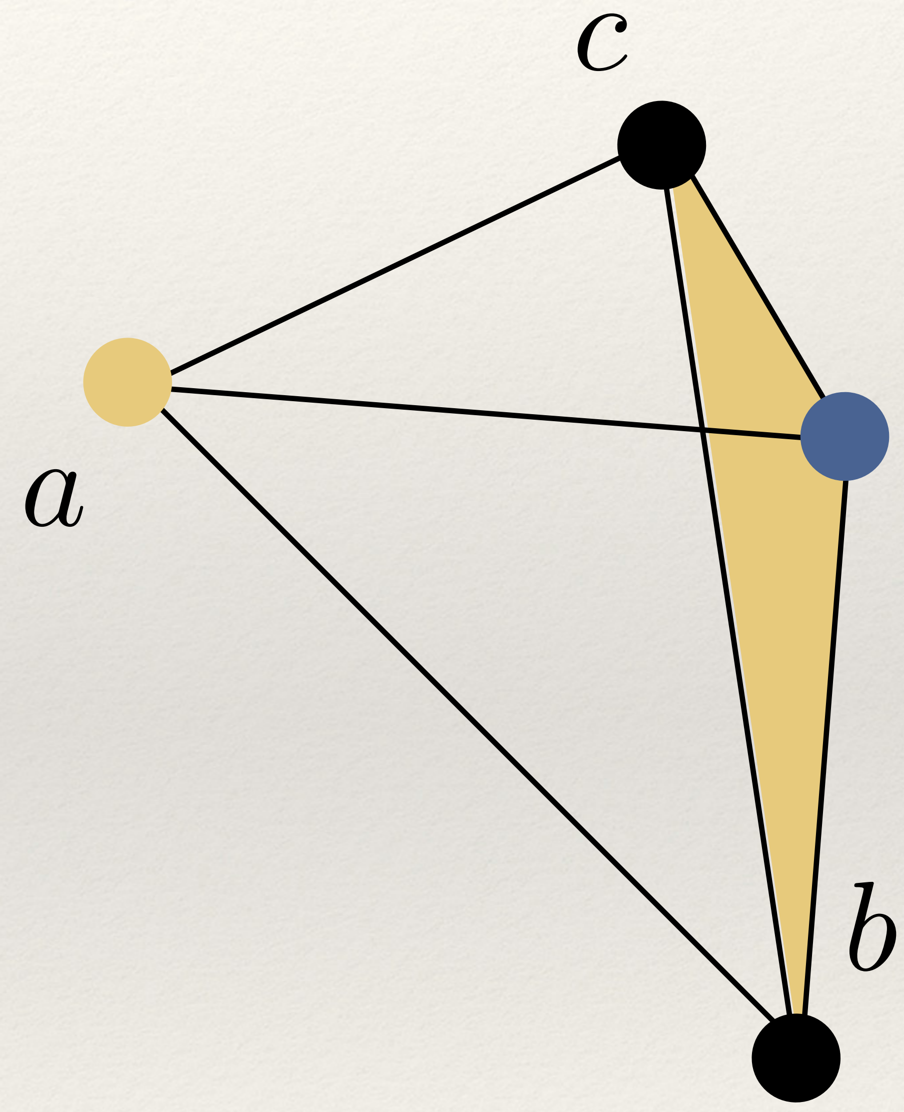
$$\alpha < 0, \beta > 0, \gamma > 0$$



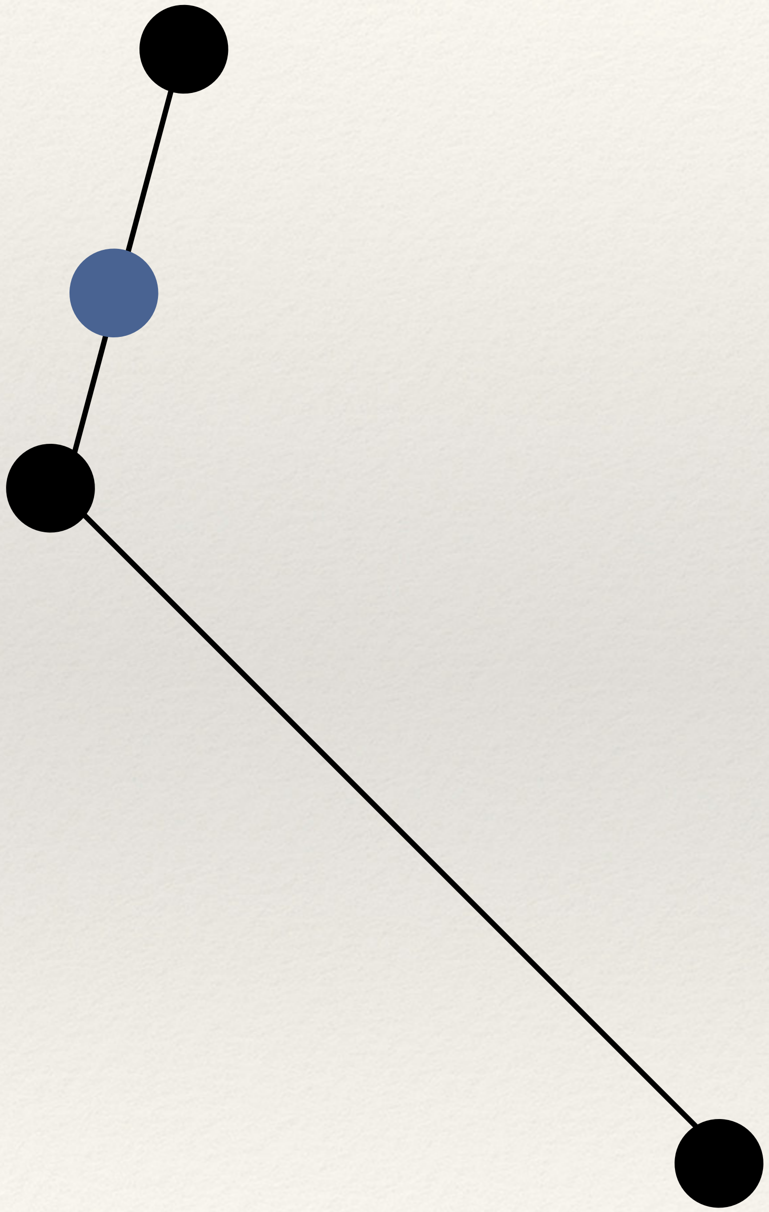
Barycentric Coordinates

- Inside/outside test

$$\alpha < 0, \beta > 0, \gamma > 0$$

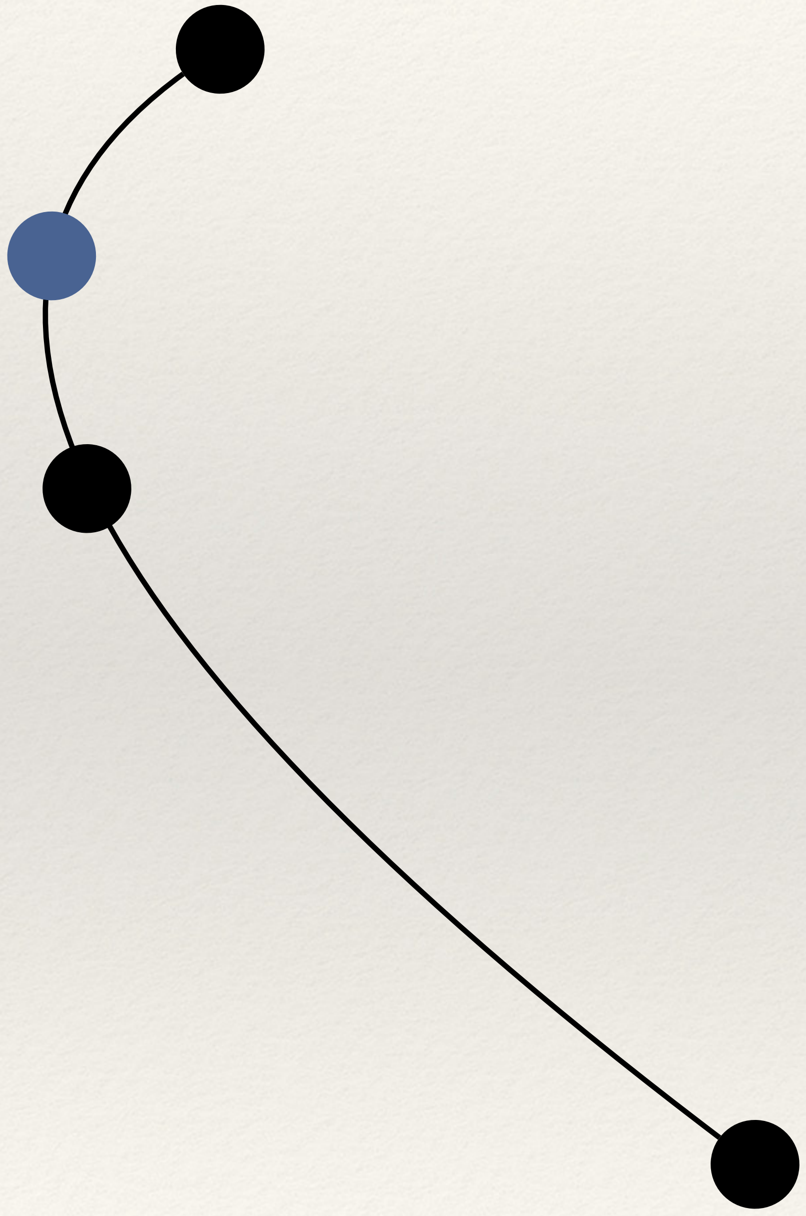


Polynomial Interpolation



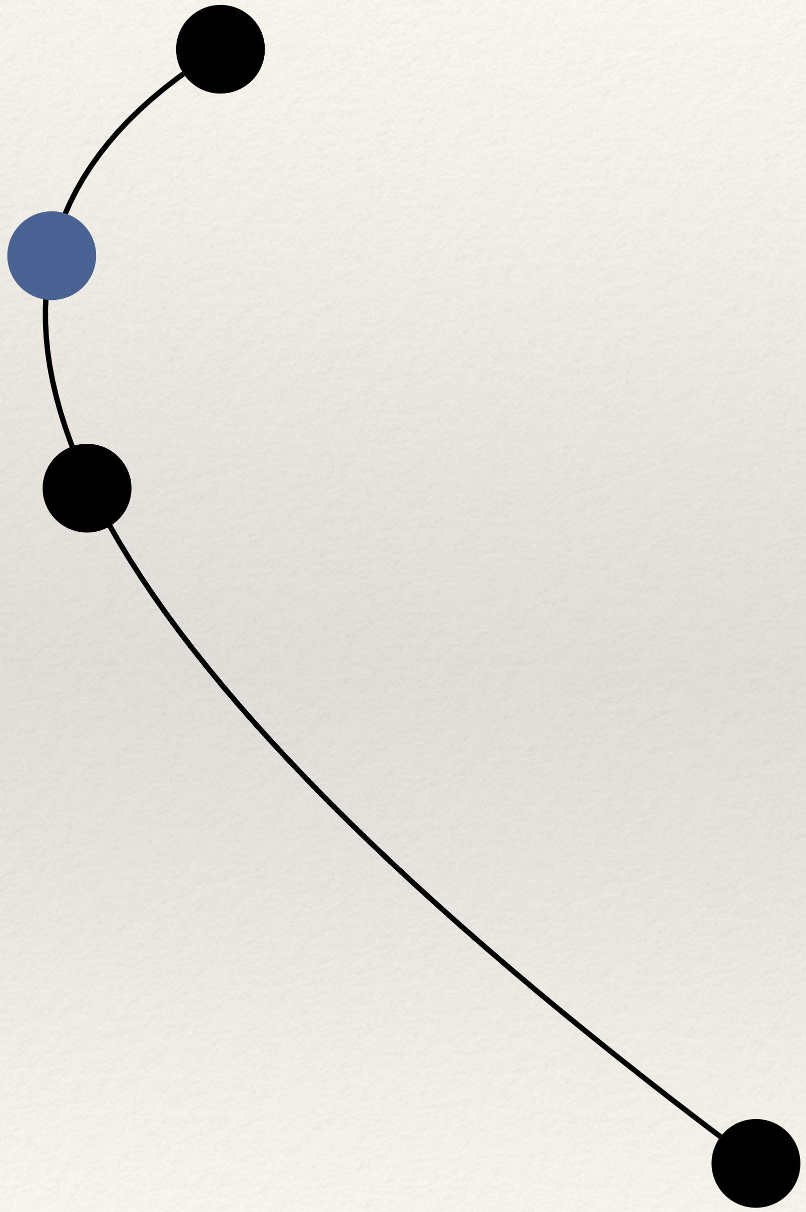
$$f(t) = at + b$$

Polynomial Interpolation



$$f(t) = at^2 + bt + c$$

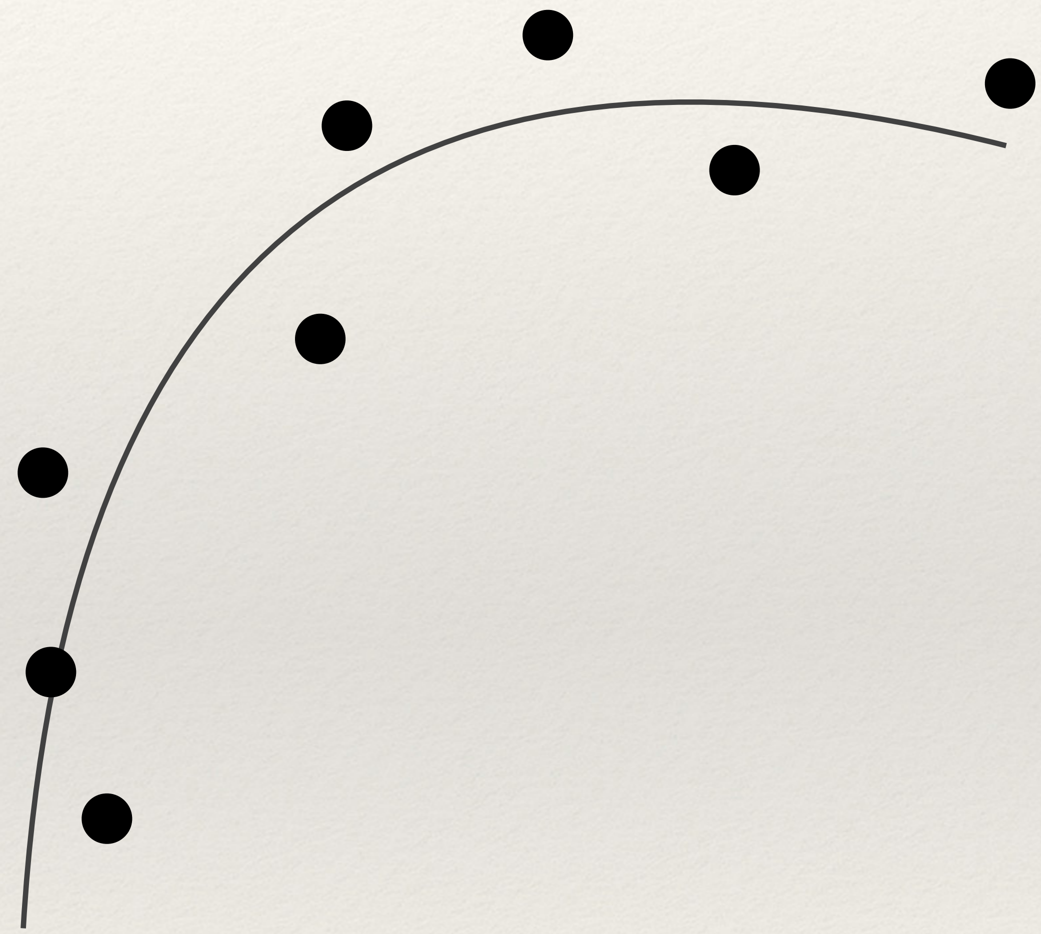
Polynomial Interpolation



- Lagrange interpolation
- Newton interpolation
- Same polynomial
- Different cost of construction and evaluation

Least Squares Approximation

- Approximate noisy or overdetermined data



Least Squares Approximation

- Given m data points

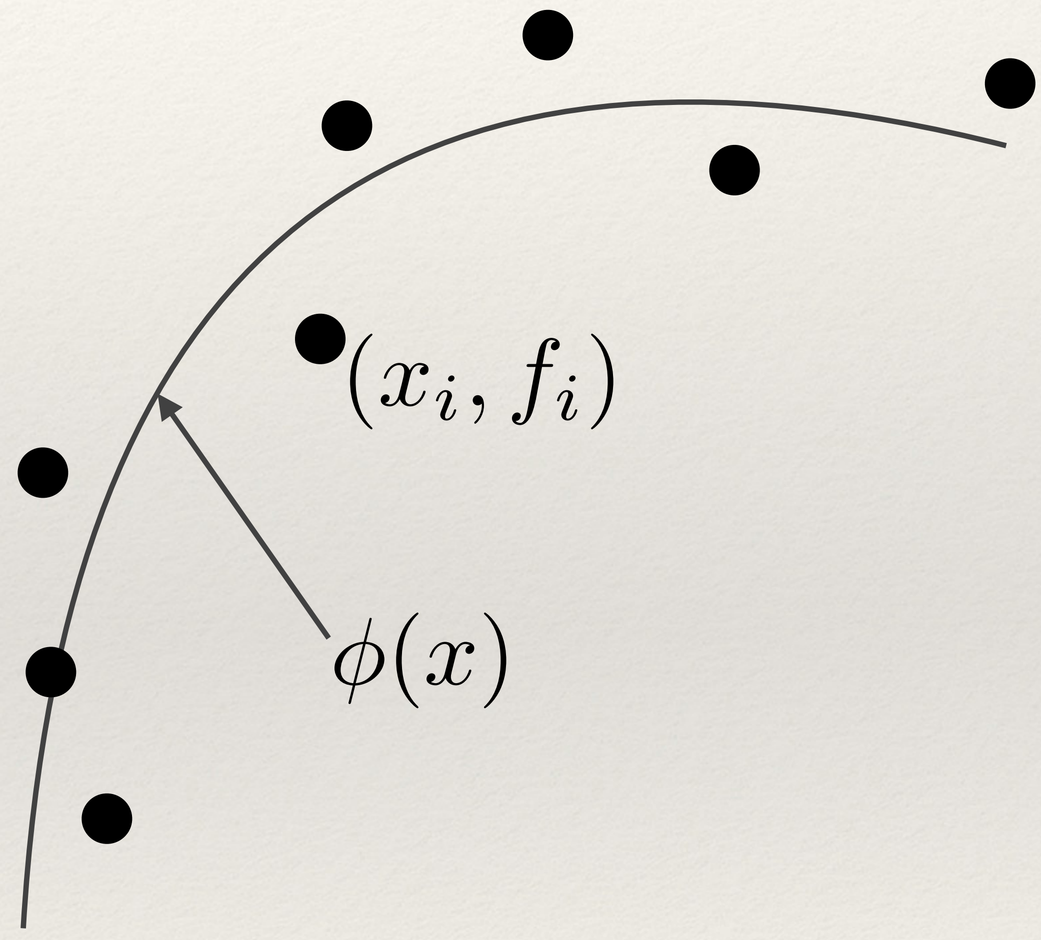
$$(x_1, f_1), (x_2, f_2) \ldots, (x_m, f_m)$$

- Given basis

$$\phi_1(x), \ldots, \phi_n(x)$$

- Find coefficients $\alpha_1, \cdots, \alpha_n$

$$\phi(x) = \alpha_1 \phi_1(x) + \ldots + \alpha_n \phi_n(x)$$



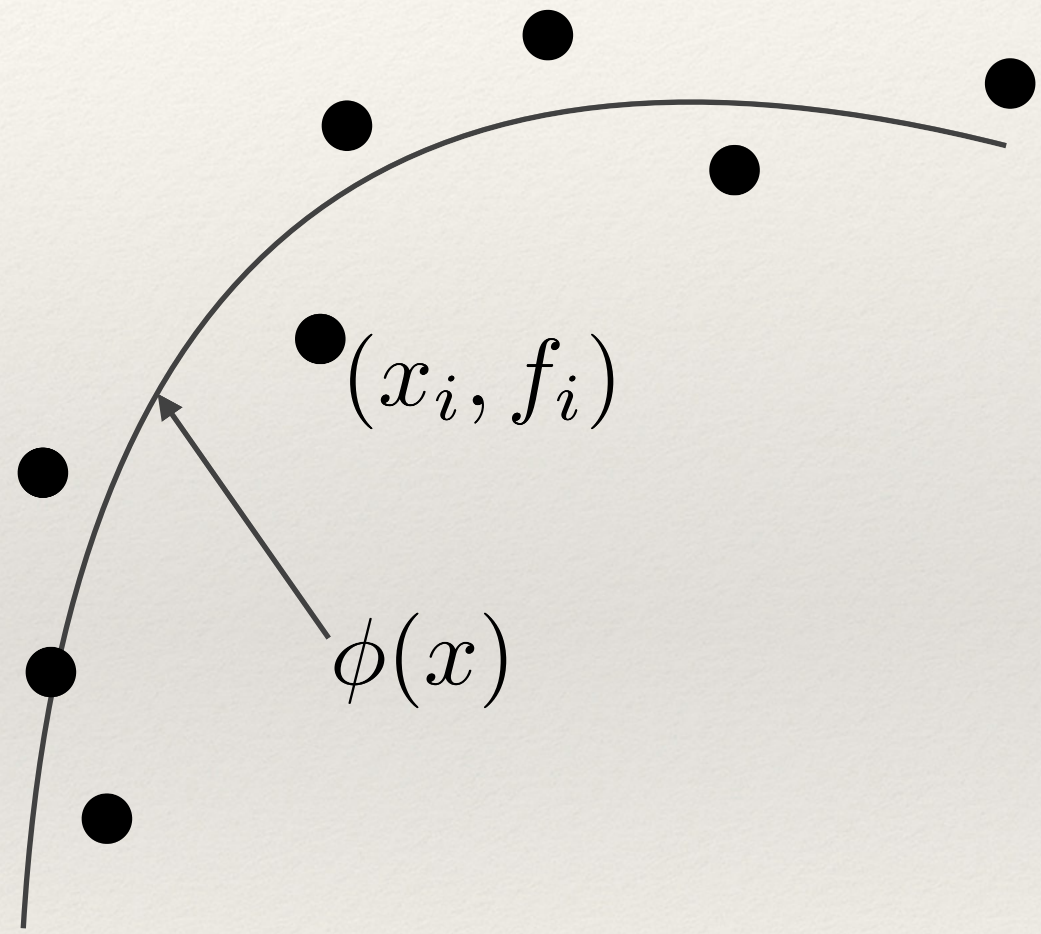
Least Squares Approximation

$$(x_1, f_1), (x_2, f_2) \ldots, (x_m, f_m)$$

$$\phi(x) = \alpha_1 \phi_1(x) + \ldots + \alpha_n \phi_n(x)$$

- minimize sum of squared errors

$$\sum_{i=1}^{m} |\phi(x_i) - f_i|^2$$

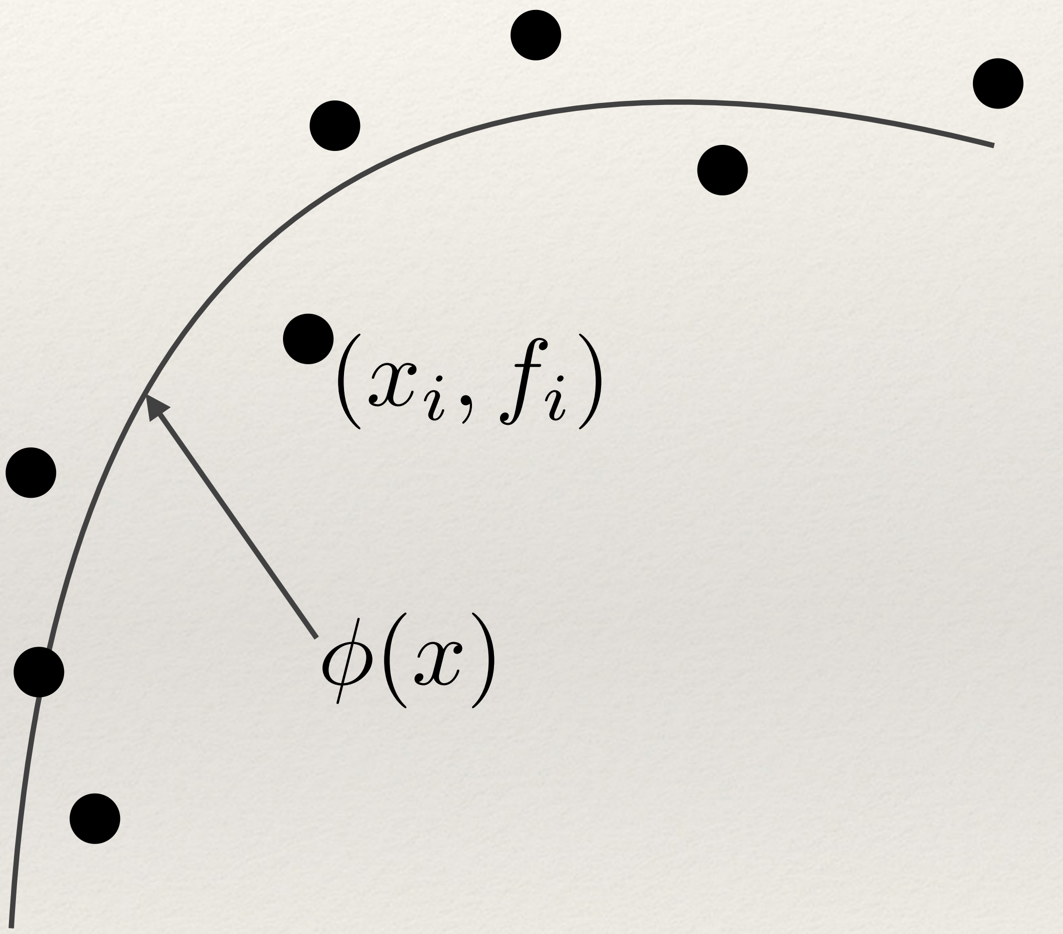


Least Squares Approximation

$$\text{argmin}_{\alpha} \|A\alpha - \mathbf{f}\|_2^2$$

- Normal equations

$$A^T A\alpha = A^T \mathbf{f}$$



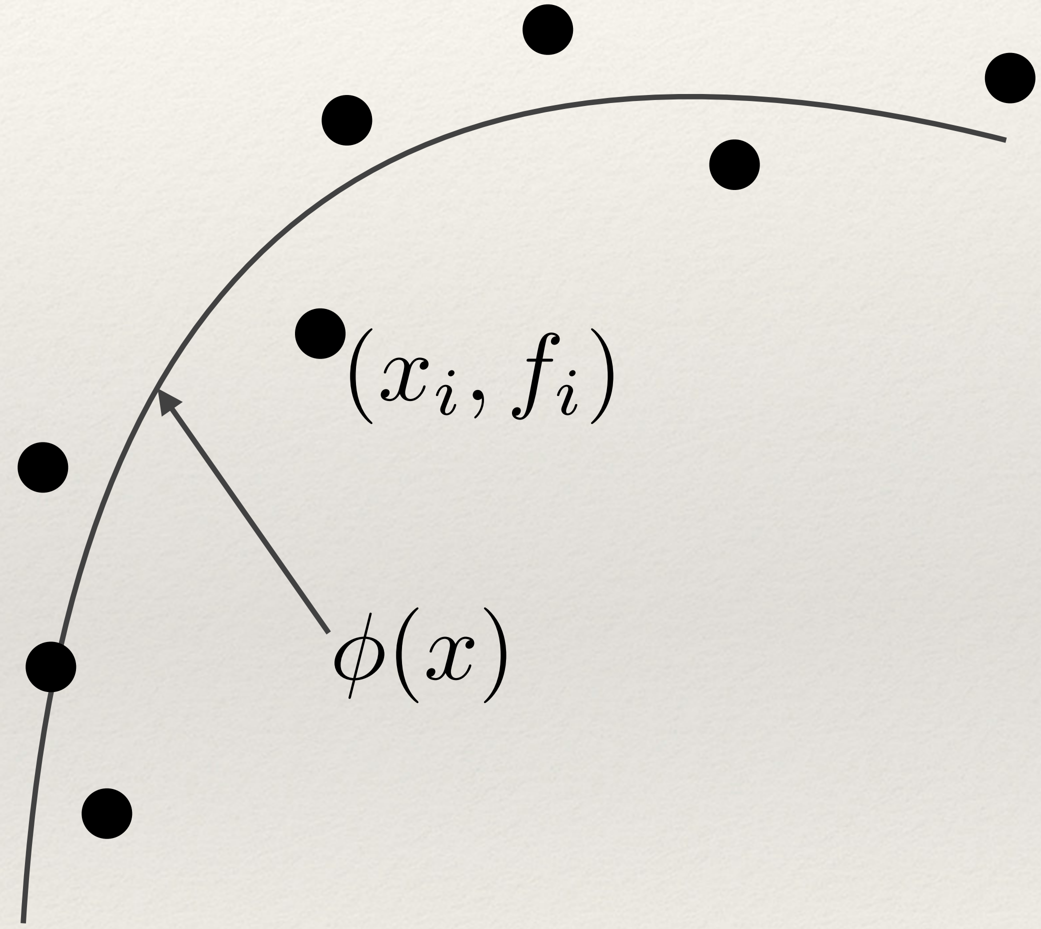
Least Squares Approximation

- Weighted least squares

$$\sum_{i=1}^{m} w_i |\phi(x_i) - f_i|^2$$

- Regularized least squares

$$\text{argmin}_\alpha \|A\alpha - \mathbf{f}\|_2^2 + \|\Gamma\alpha\|_2^2$$



Other Methods

- Bezier curves, splines
- Harmonic coordinates, mean value coordinates, Green coordinates

Finite Differences

Finite Difference Methods

- Used to discretize spatial derivatives

$$\rho(\mathbf{u}_t + \mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla p + \mu \Delta \mathbf{u} + \mathbf{f}$$

$$\nabla \cdot \mathbf{u} = 0$$

Finite Difference Methods

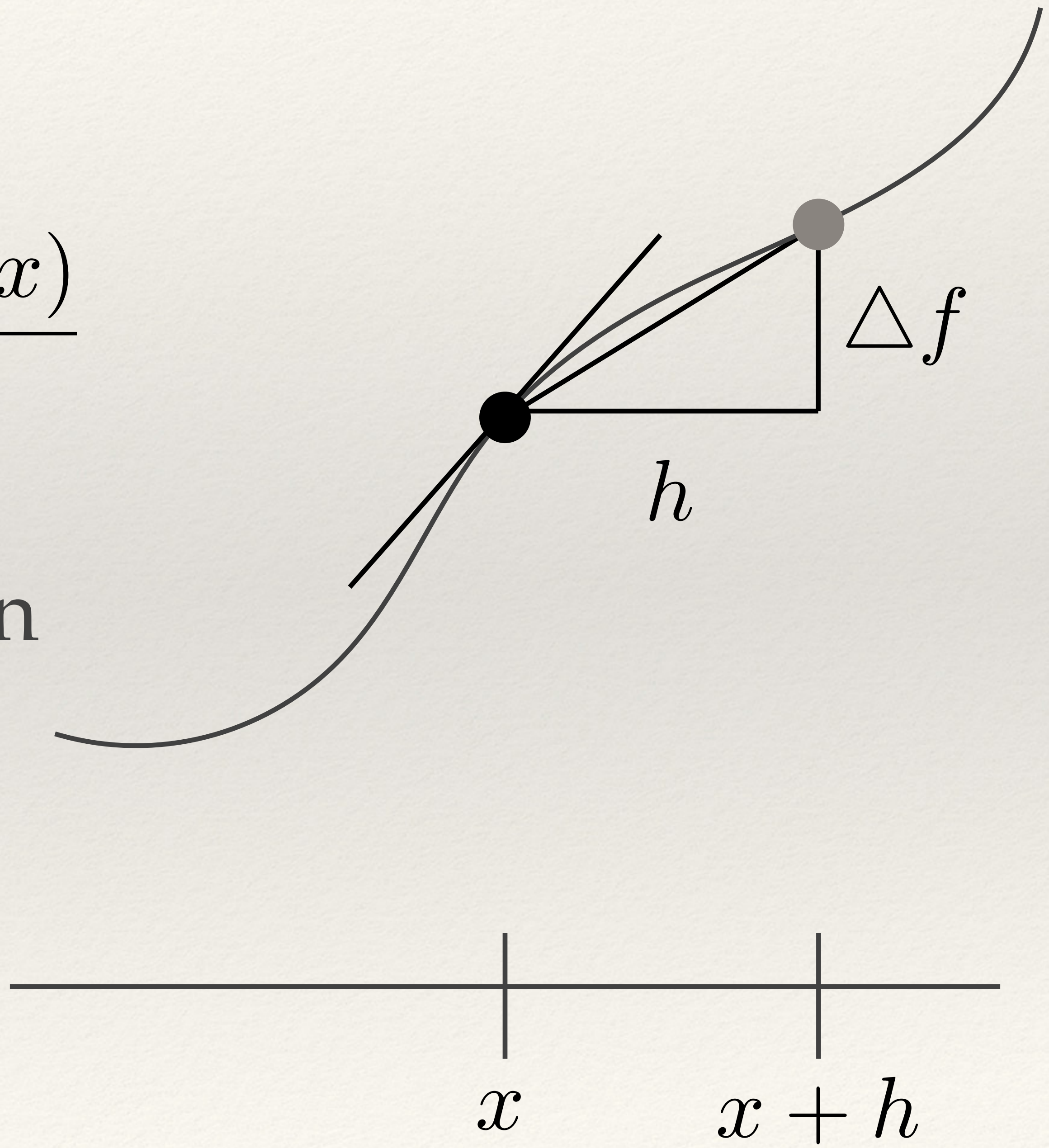
- Recall derivative of function

$$\frac{d}{dx}f(x) = \lim_{h \to 0} \frac{f(x+h) - f(x)}{h}$$

- Finite difference approximation

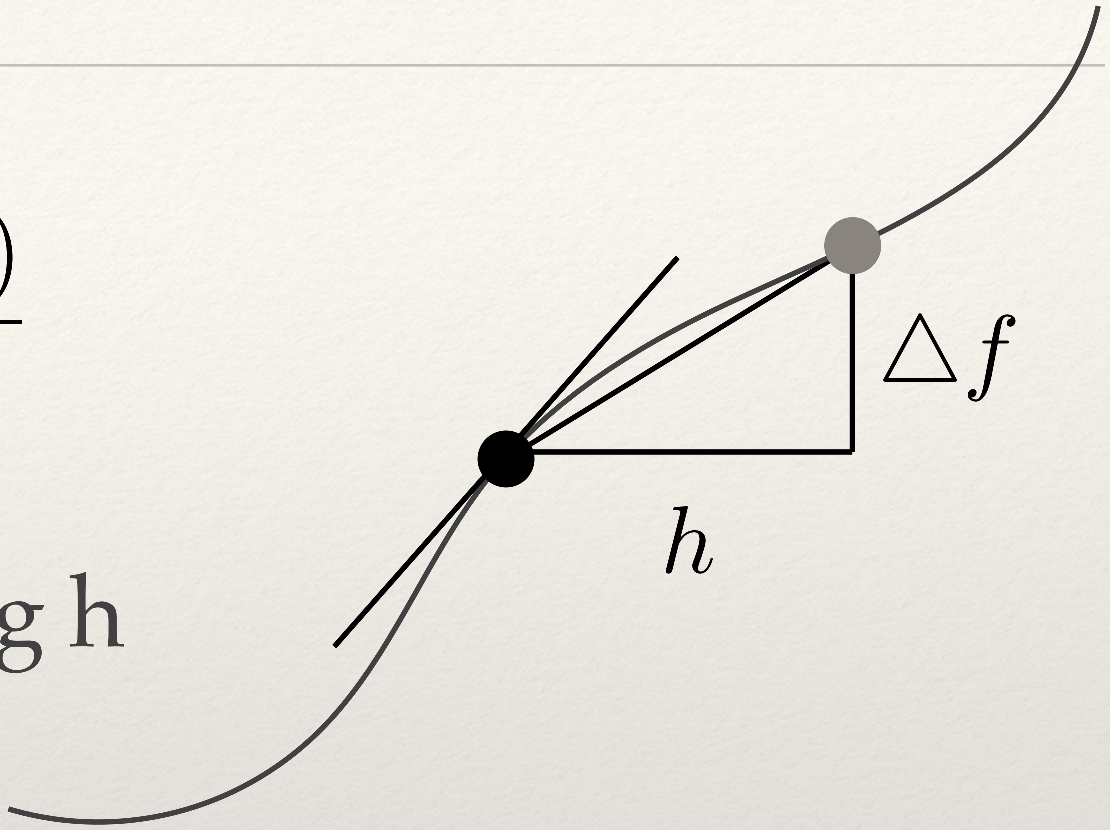
$$\frac{d}{dx}f(x) \approx \frac{f(x+h) - f(x)}{h}$$

forward difference



Finite Difference Methods

$$f'(x) \approx \frac{f(x+h) - f(x)}{h}$$



- Error decreases with decreasing h
- Taylor series

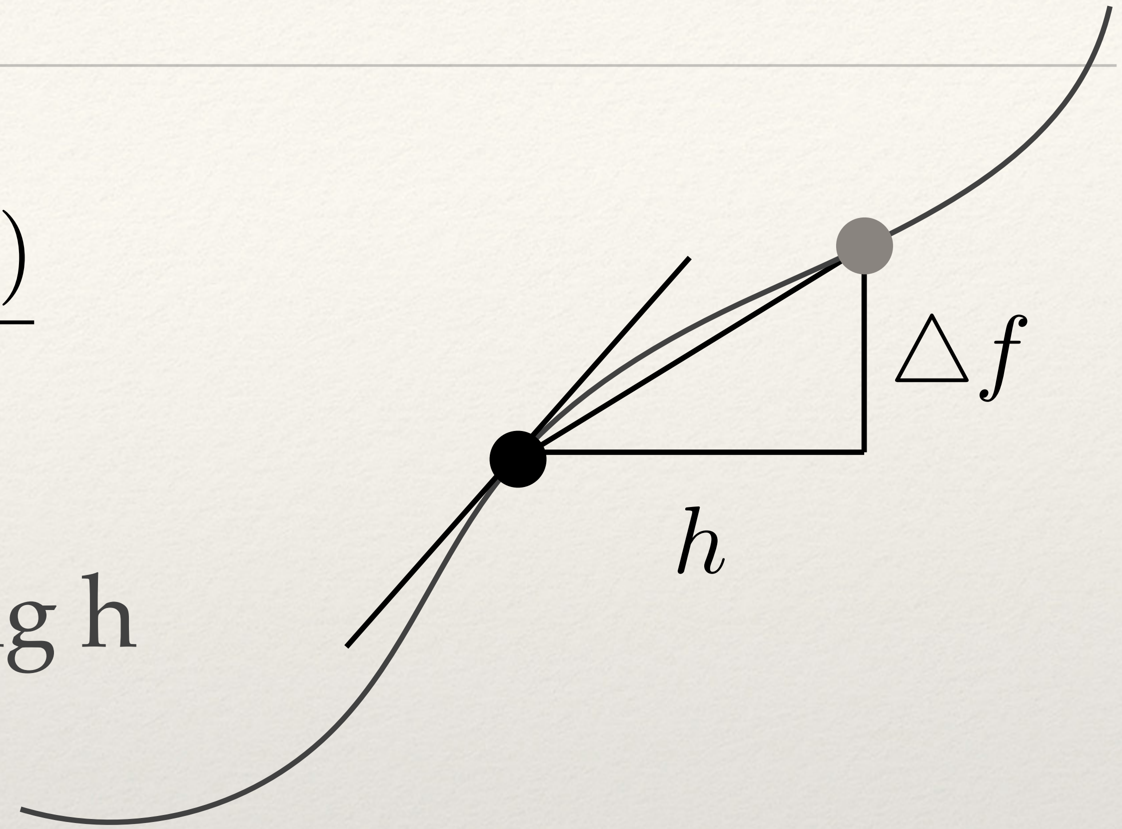
$$f(x+h) = f(x) + hf'(x) + \frac{h^2}{2}f''(x) + \ldots + \frac{h^n}{n!}f^{(n)}(x) + \ldots$$

- Rearrange

$$\frac{f(x+h) - f(x)}{h} = f'(x) + \frac{h}{2}f''(x) + \ldots$$

Finite Difference Methods

$$f'(x) \approx \frac{f(x+h) - f(x)}{h}$$



- Error decreases with decreasing h
- Taylor series

$$f(x+h) = f(x) + hf'(x) + \frac{h^2}{2} f''(x) + \ldots + \frac{h^n}{n!} f^{(n)}(x) + \ldots$$

- Rearrange

$$\frac{f(x+h) - f(x)}{h} = f'(x) + O(h)$$

first order accurate

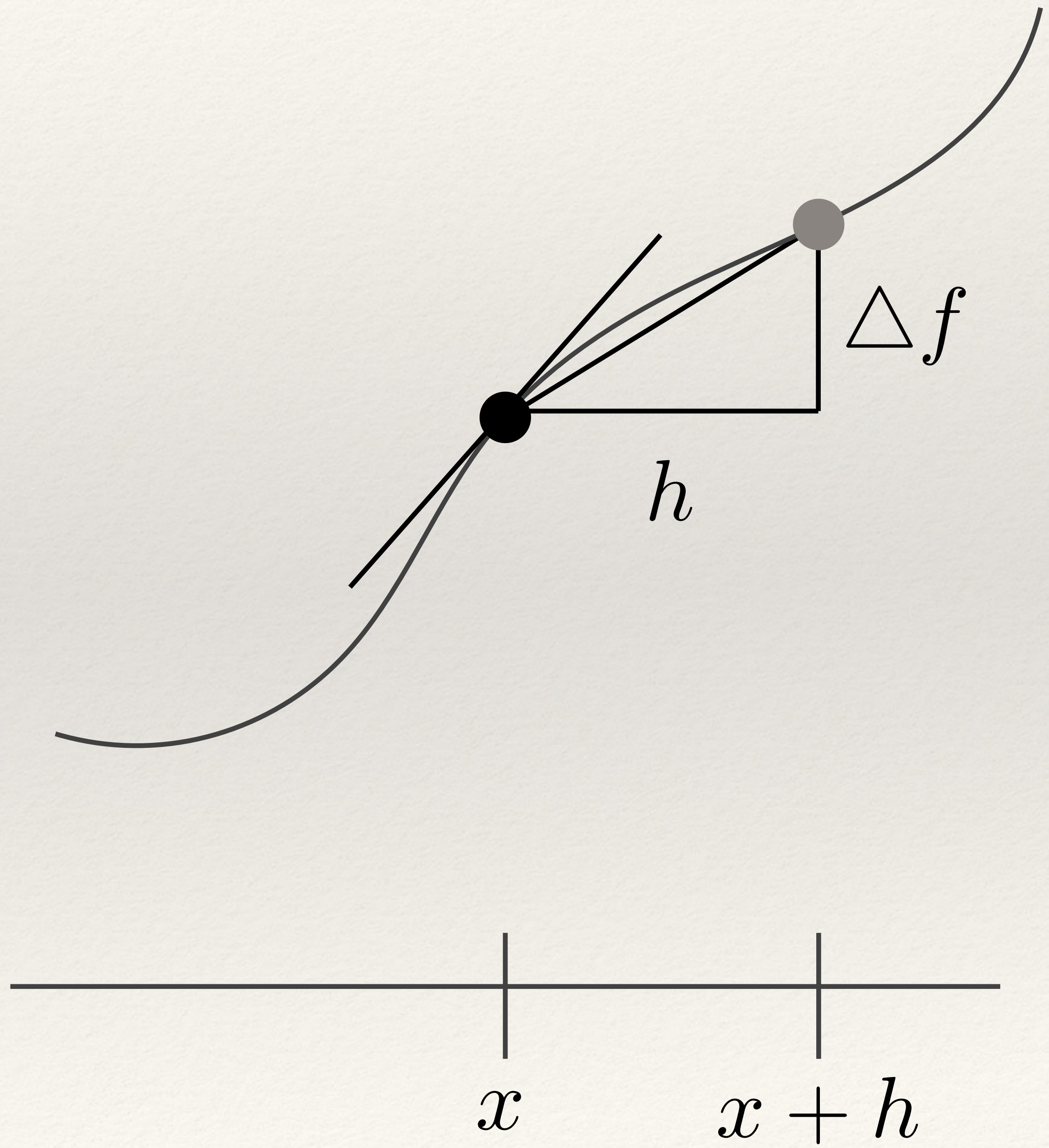
Forward and Backward Difference

- Forward difference

$$f'(x) \approx \frac{f(x+h) - f(x)}{h}$$

- Backward difference

$$f'(x) \approx \frac{f(x) - f(x-h)}{h}$$



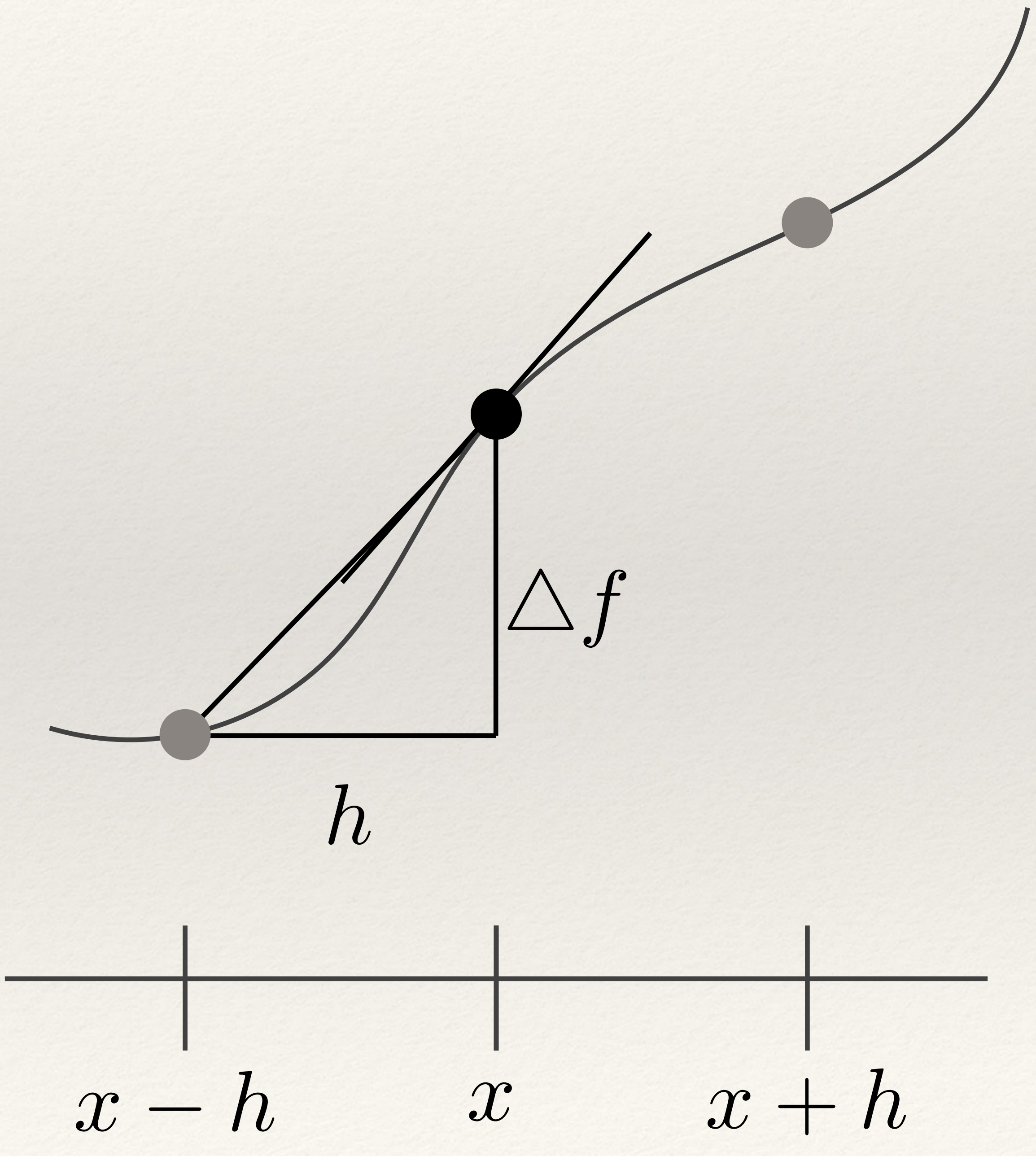
Forward and Backward Difference

- Forward difference

$$f'(x) \approx \frac{f(x+h) - f(x)}{h}$$

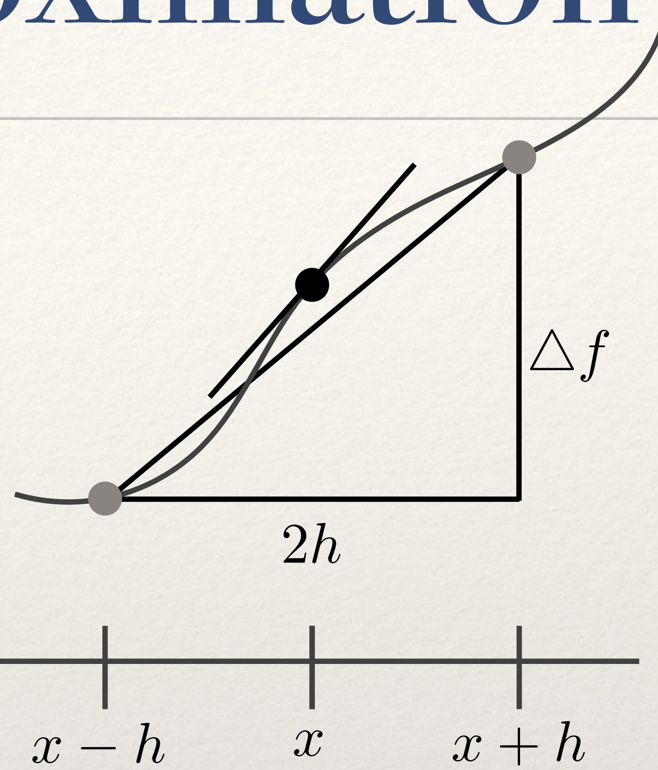
- Backward difference

$$f'(x) \approx \frac{f(x) - f(x-h)}{h}$$



Central Difference Approximation

$$f'(x) \approx \frac{f(x+h) - f(x-h)}{2h}$$



- Taylor series

$$f(x+h) = f(x) + hf'(x) + \frac{h^2}{2} f''(x) + O(h^3),$$

$$f(x-h) = f(x) - hf'(x) + \frac{h^2}{2} f''(x) - O(h^3).$$

- Combine, rearrange

$$\frac{f(x+h) - f(x-h)}{2h} = f'(x) + O(h^2)$$

second order accurate

Discretization Error

- Forward difference

$$\frac{f(x+h)-f(x)}{h} = f'(x) + \frac{h}{2} f''(x) + \dots$$

- Central difference

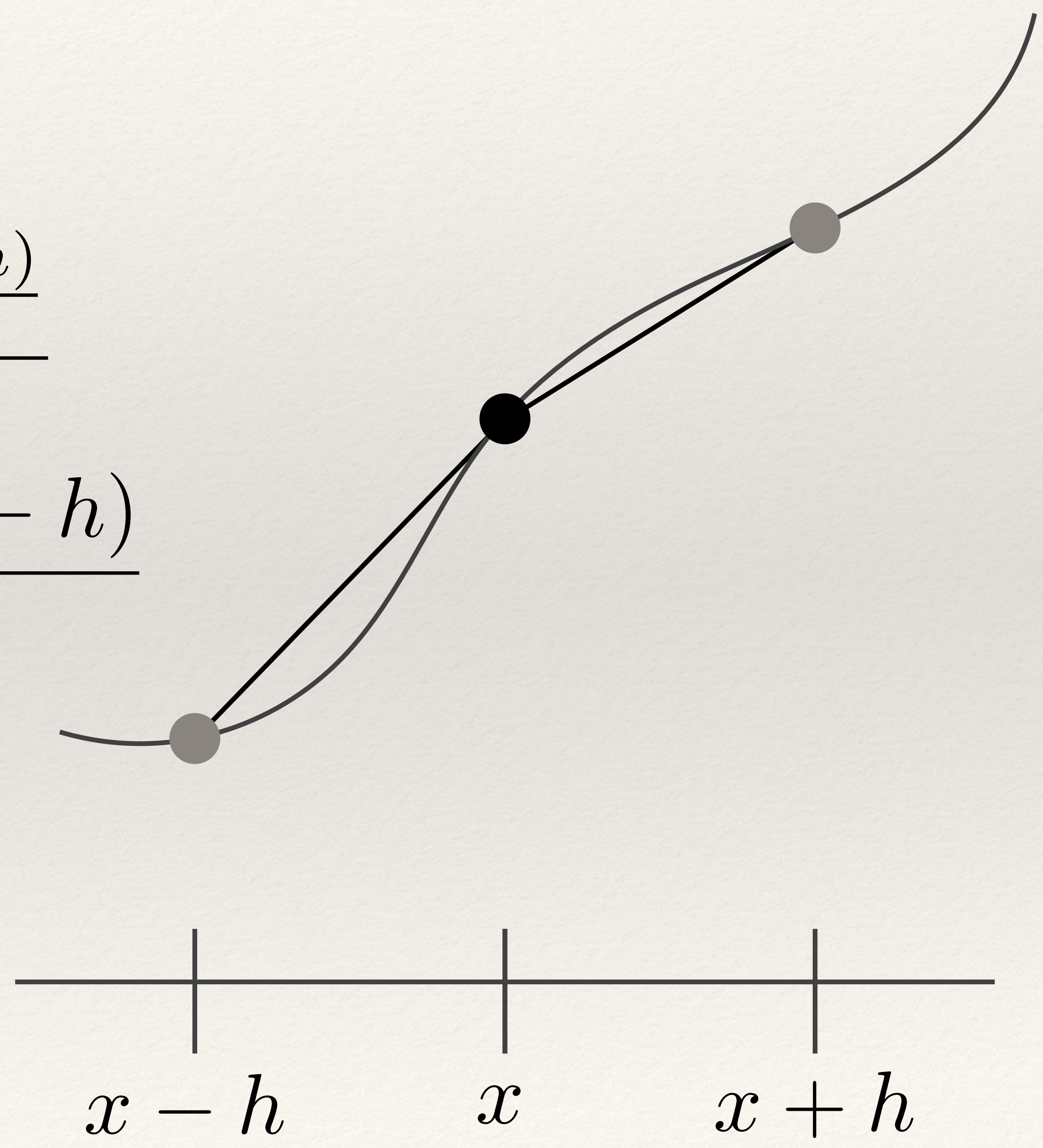
$$\frac{f(x+h)-f(x-h)}{2h} = f'(x) + \frac{h^2}{6} f'''(x) + \dots$$

Higher Derivatives

$$f''(x) \approx \frac{f'(x+\frac{h}{2}) - f'(x-\frac{h}{2})}{h}$$

$$\approx \frac{\frac{f(x+h)-f(x)}{h} - \frac{f(x)-f(x-h)}{h}}{h}$$

$$\approx \frac{f(x+h) - 2f(x) + f(x-h)}{h^2}$$

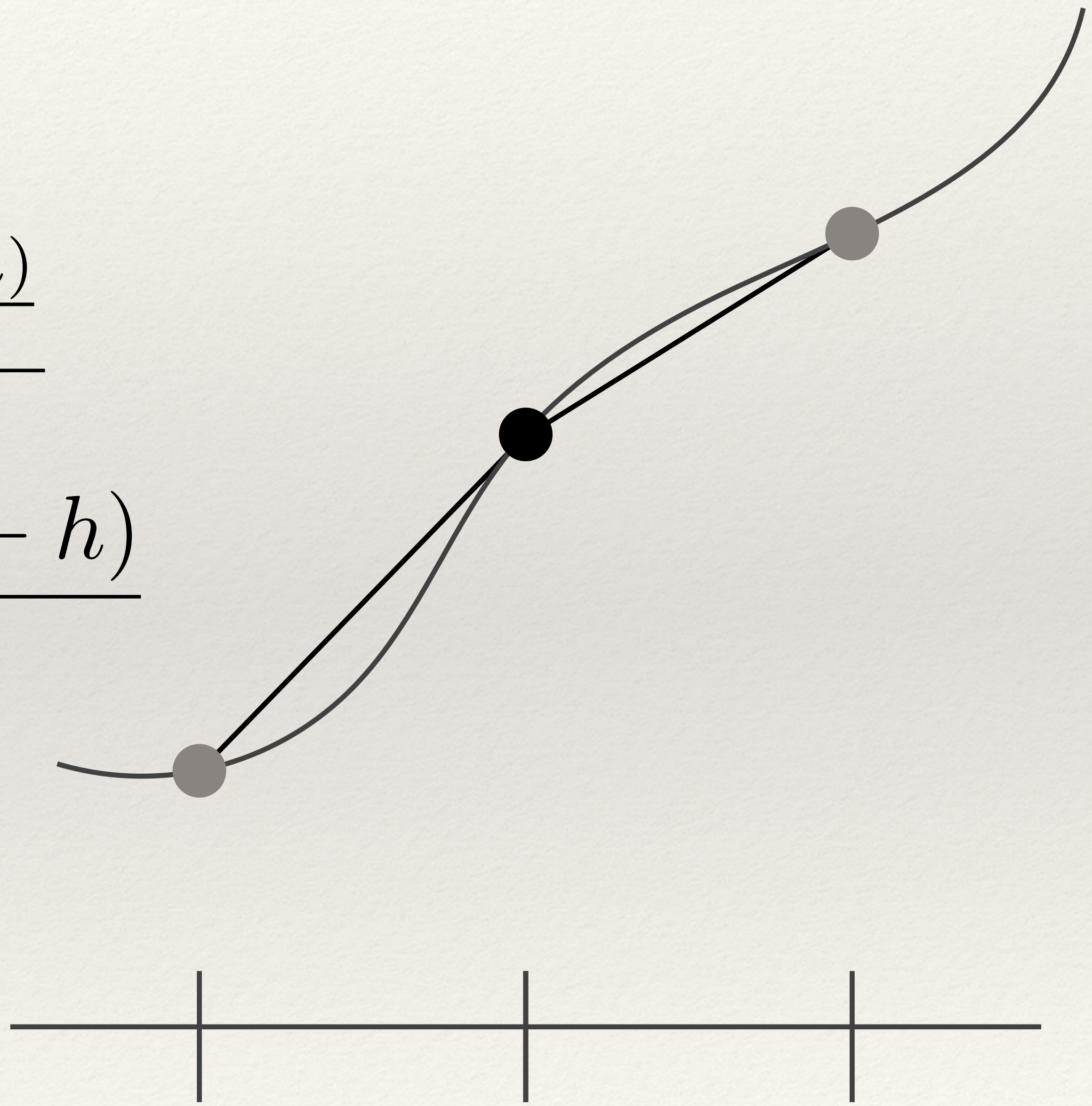


Higher Derivatives

$$f''(x) \approx \frac{f'(x+\frac{h}{2}) - f'(x-\frac{h}{2})}{h}$$

$$\approx \frac{\frac{f(x+h)-f(x)}{h} - \frac{f(x)-f(x-h)}{h}}{h}$$

$$\approx \frac{f(x+h) - 2f(x) + f(x-h)}{h^2}$$

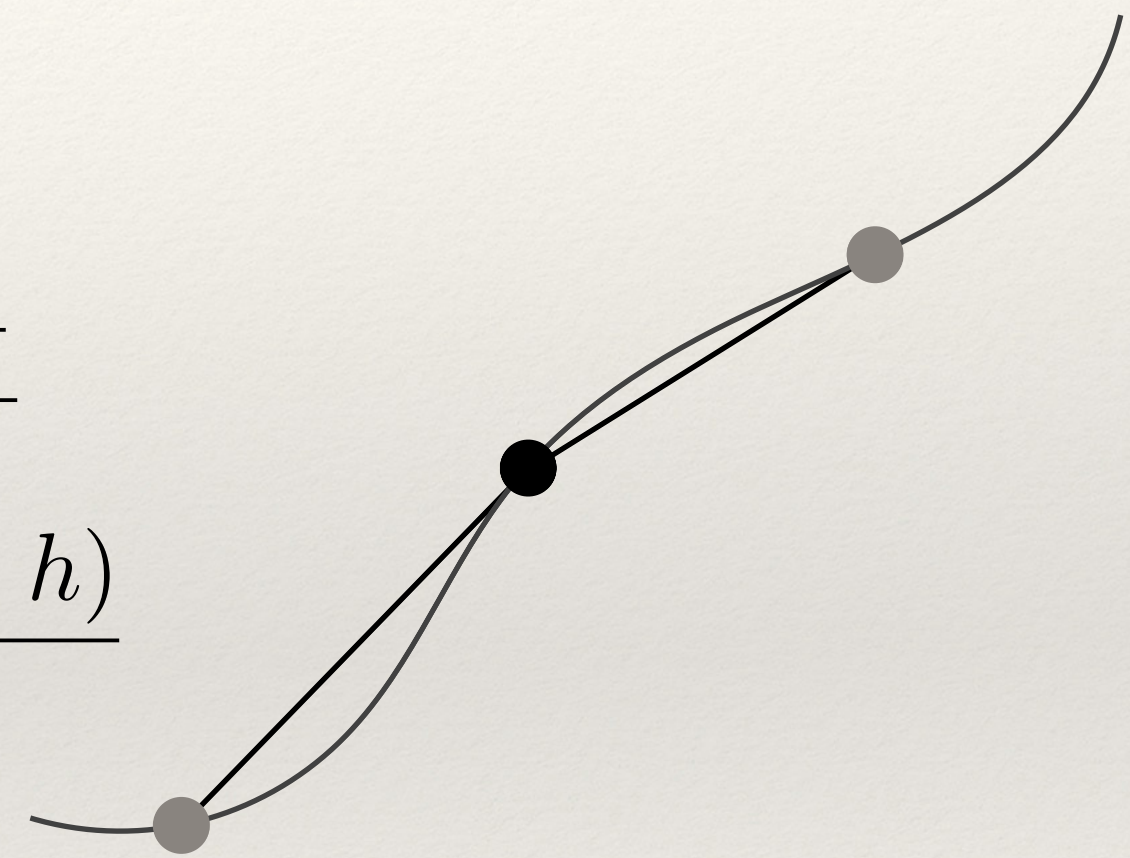


Higher Derivatives

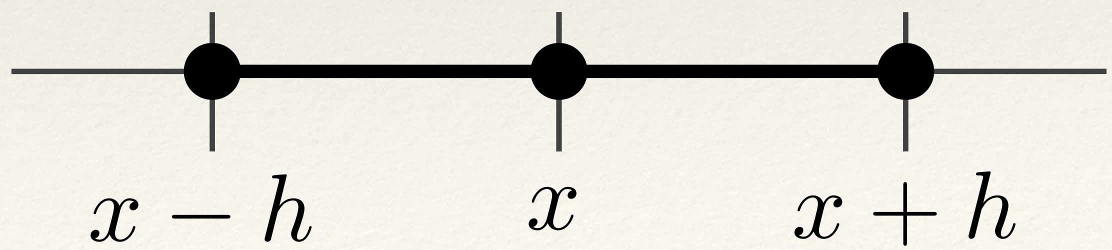
$$f''(x) \approx \frac{f'(x+\frac{h}{2}) - f'(x-\frac{h}{2})}{h}$$

$$\approx \frac{\frac{f(x+h)-f(x)}{h} - \frac{f(x)-f(x-h)}{h}}{h}$$

$$\approx \frac{f(x+h) - 2f(x) + f(x-h)}{h^2}$$



3 - point stencil



Laplacian Operator

$$\rho(\mathbf{u}_t + \mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla p + \mu \Delta \mathbf{u} + \mathbf{f}$$

$$\nabla \cdot \mathbf{u} = 0$$

- In 2D $\quad \Delta u = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}$

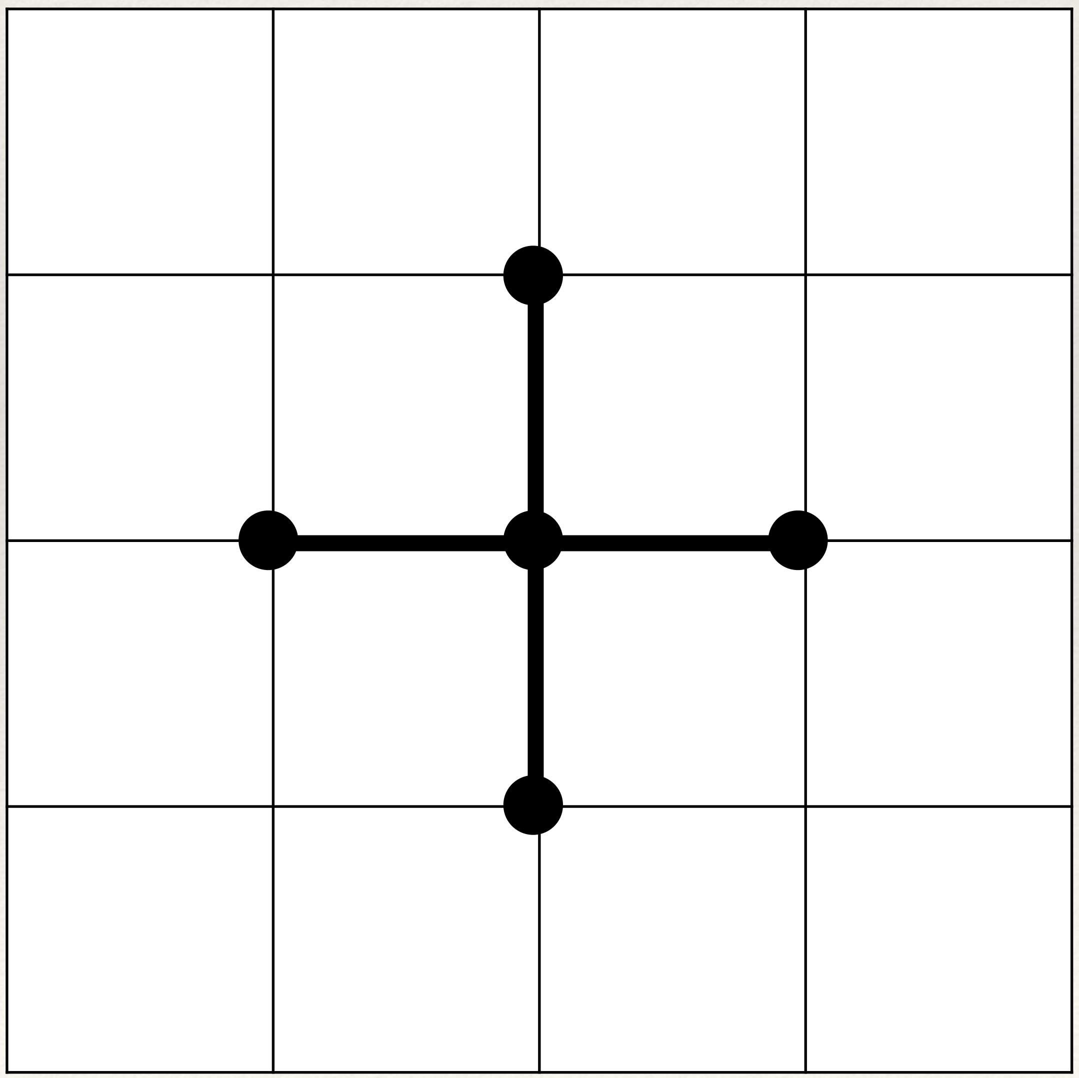
$$\frac{\partial^2 u(x,y)}{\partial x^2} \approx \frac{u(x+h,y) - 2u(x,y) + u(x-h,y)}{h^2}$$

$$\frac{\partial^2 u(x,y)}{\partial y^2} \approx \frac{u(x,y+h) - 2u(x,y) + u(x,y-h)}{h^2}$$

Laplacian Operator

$$\Delta u \approx \frac{u_{i+1,j} + u_{i-1,j} + u_{i,j+1} + u_{i,j-1} - 4u_{i,j}}{h^2}$$

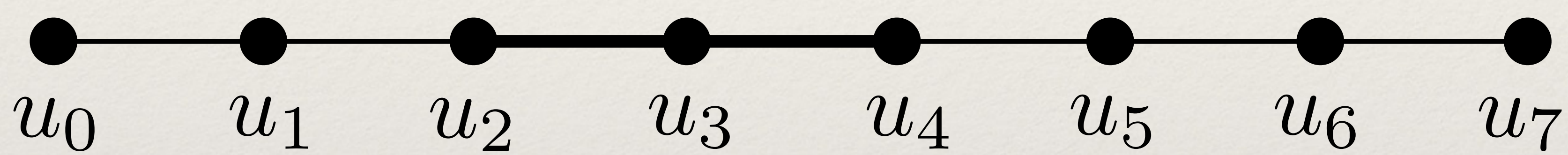
5 - point stencil



Poisson Equation (1D)

$$u_{xx} = f, \quad x \in \Omega$$

$$u(x) = \bar{u}(x), \quad x \in \partial\Omega$$



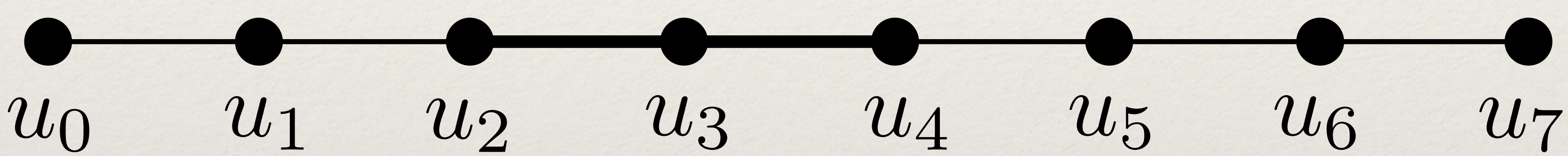
- At each interior node $$\frac{u_{i-1} - 2u_i + u_{i+1}}{h^2} = f_i$$

- Boundary nodes $$u_0 = \bar{u}(x_0), u_7 = \bar{u}(x_7)$$

Poisson Equation (1D)

$$u_{xx} = f, \quad x \in \Omega$$

$$u(x) = \bar{u}(x), \quad x \in \partial\Omega$$



linear system

$$\frac{1}{h^2}\begin{pmatrix} -2 & 1 & 0 & 0 & 0 & 0 \\ 1 & -2 & 1 & 0 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 & 0 \\ 0 & 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 0 & 1 & -2 & 1 \\ 0 & 0 & 0 & 0 & 1 & -2 \end{pmatrix}\begin{pmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ u_6 \end{pmatrix} = \begin{pmatrix} f_1 - \frac{\bar{u}(x_0)}{h^2} \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 - \frac{\bar{u}(x_7)}{h^2} \end{pmatrix}$$

Finite Elements

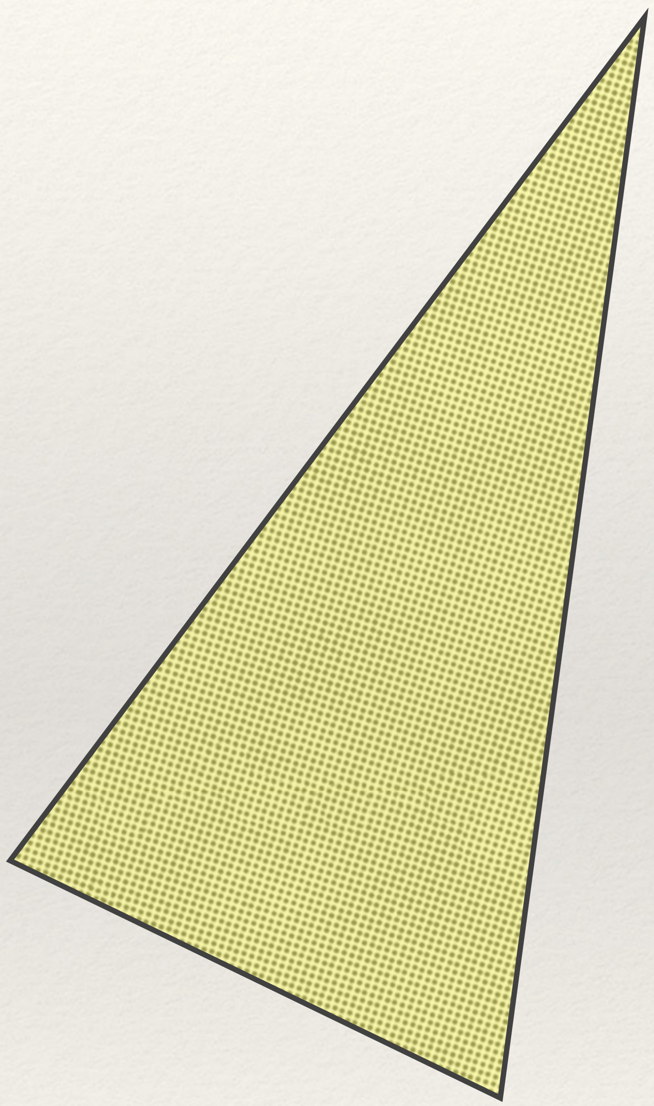
Finite Elements

- Discretize the space of representable functions, instead of discretizing derivatives
- Method:
  - Discretize space into a finite set of elements
  - Choose a set of basis functions over the elements (e.g. piecewise linear)
  - *Galerkin* projection onto these basis functions
  - Solve the problem

Lets try an example:

Linear Finite Elements for Elasticity

Choose Element Type: Triangle



Choose Basis Functions: Piecewise Linear

Project Deformation Function onto the Piecewise Linear Function Space

Project Deformation Function onto the Piecewise Linear Function Space

$$\mathbf{x}(\mathbf{u}) = \mathbf{x}(\mathbf{u}_0) + \mathbf{F}\left(\mathbf{u} - \mathbf{u}_0\right)$$

Solve the Problem

Solve the Problem

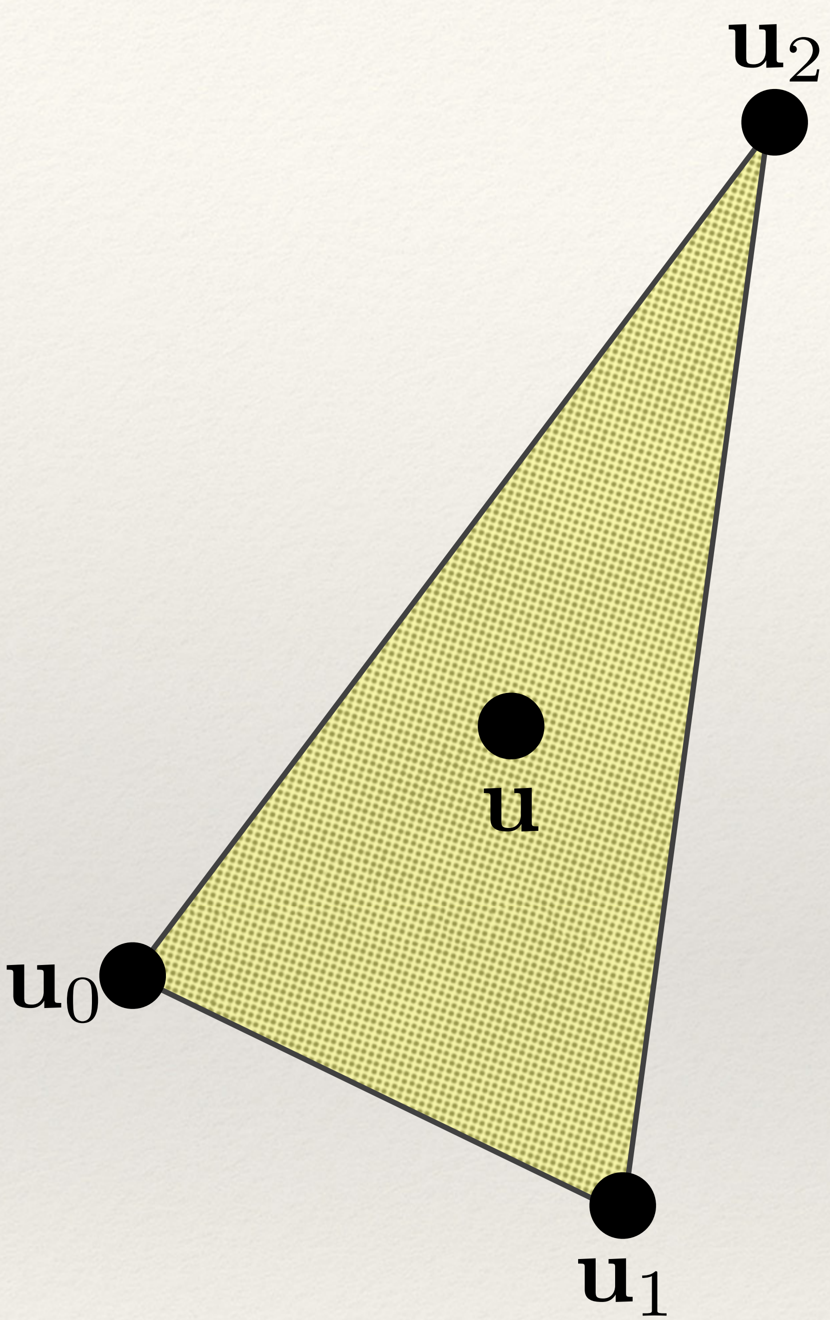
We know we can compute forces from $\mathbf{F}$

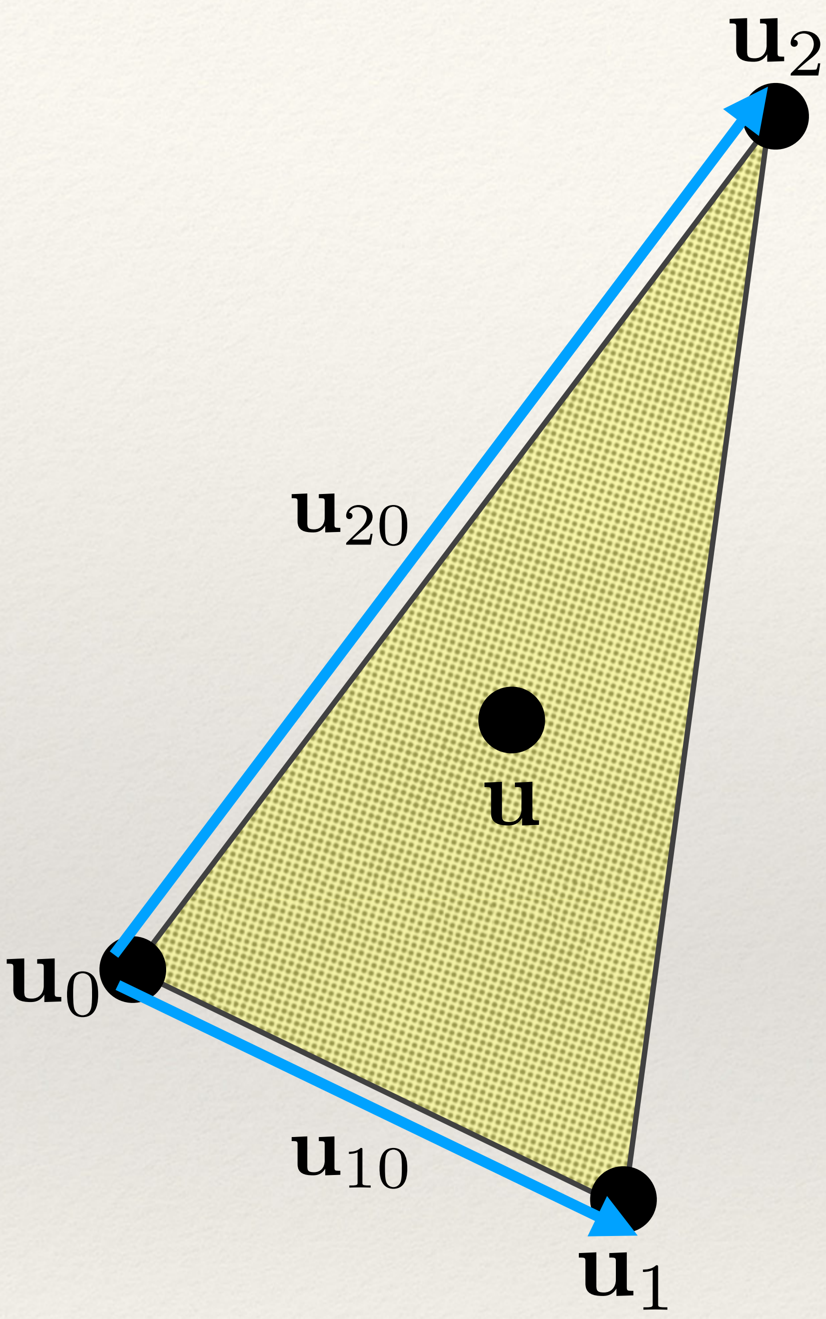
Solve the Problem

We know we can compute forces from $\mathbf{F}$

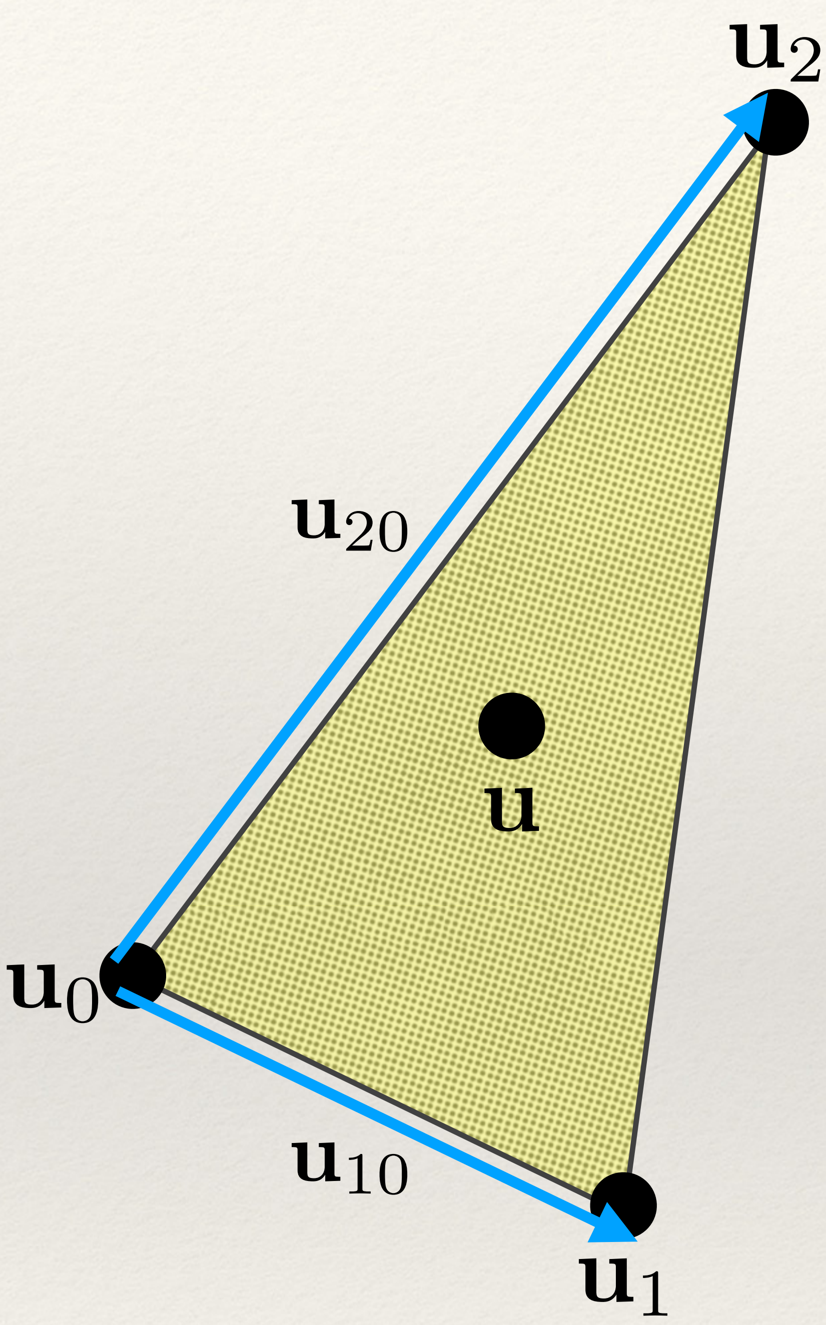
But, how do we compute $\mathbf{F}$?

$$\Big(\text{in } \mathbf{x}(\mathbf{u}) = \mathbf{x}(\mathbf{u}_0) + \mathbf{F}\,(\mathbf{u} - \mathbf{u}_0) \Big)$$

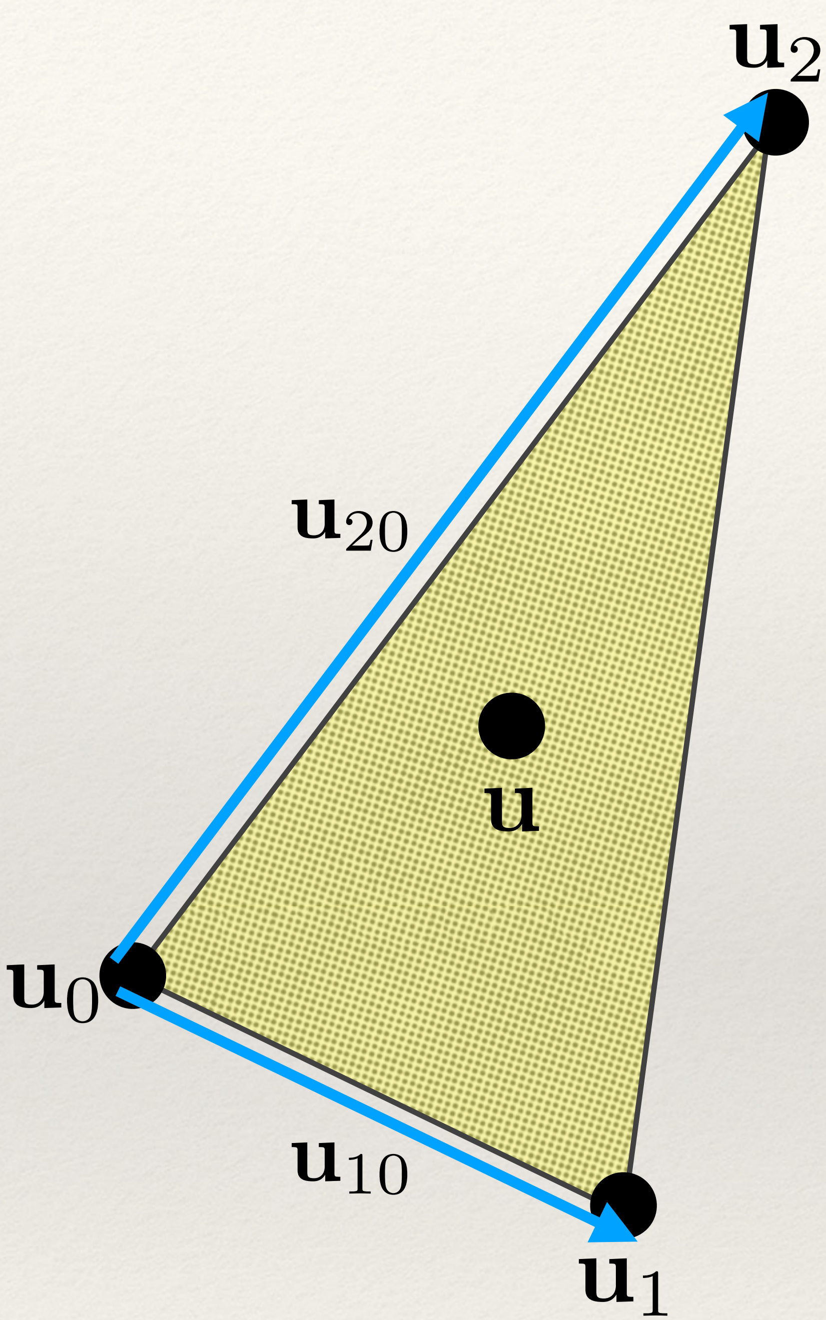

$\mathbf{u}_2$
$\mathbf{u}$
$\mathbf{u}_0$
$\mathbf{u}_1$



$\mathbf{u}_2$
$\mathbf{u}_{20}$
$\mathbf{u}$
$\mathbf{u}_0$
$\mathbf{u}_{10}$
$\mathbf{u}_1$

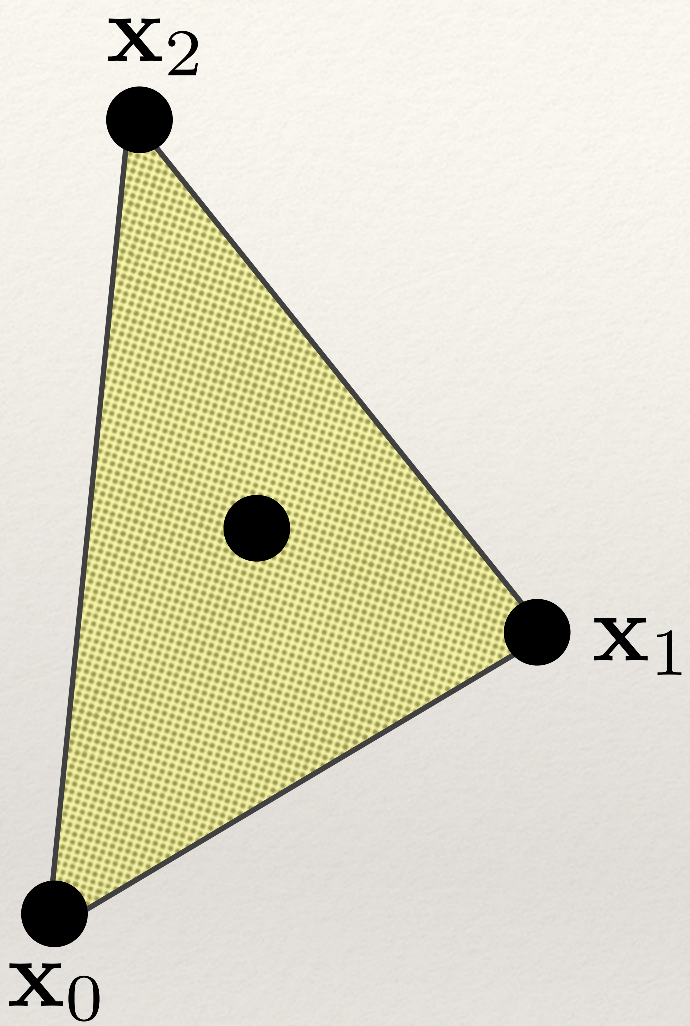


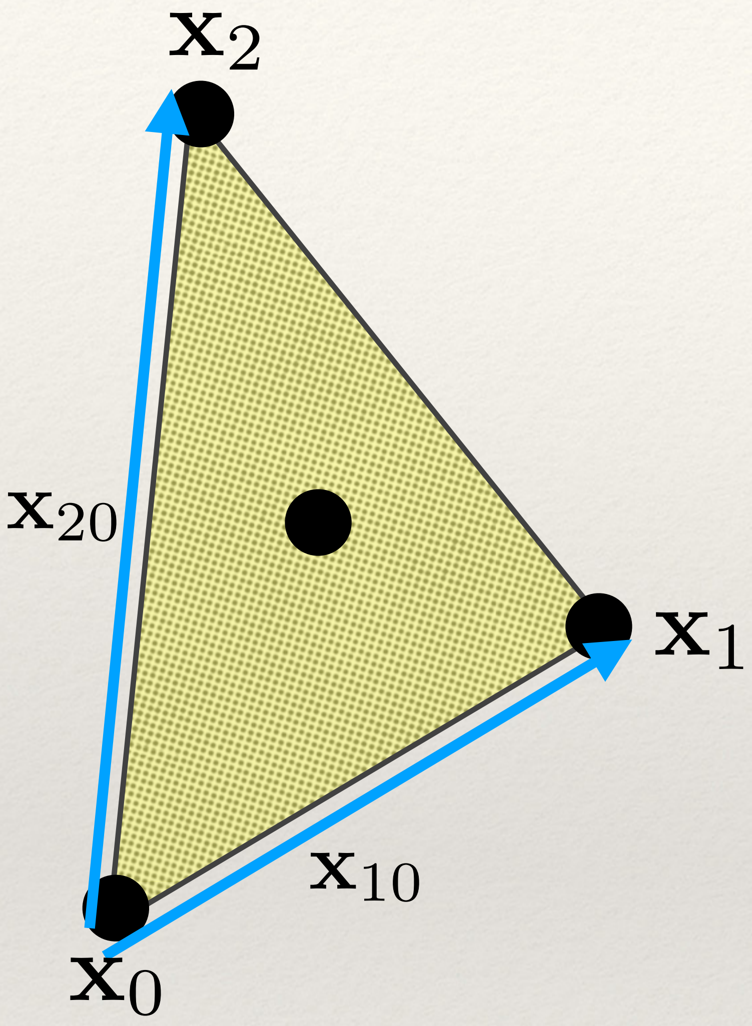
$$\mathbf{u} = \mathbf{u}_0 + \alpha\left(\mathbf{u}_1 - \mathbf{u}_0\right) + \beta\left(\mathbf{u}_2 - \mathbf{u}_0\right)$$

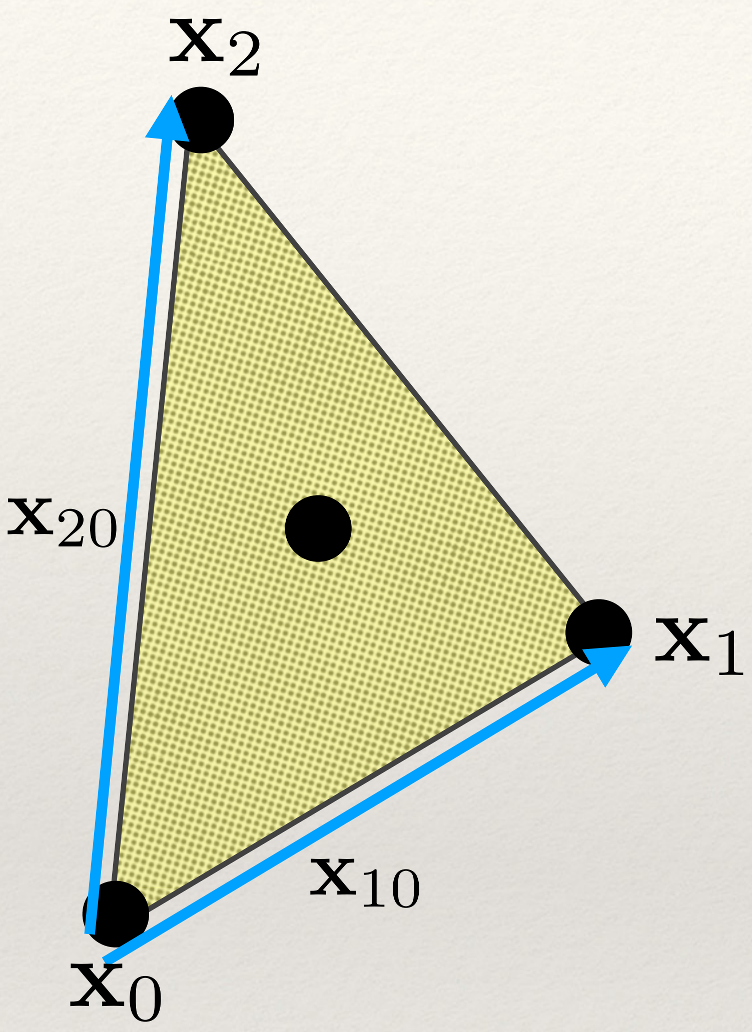


$$\mathbf{u} = \mathbf{u}_0 + \alpha\left(\mathbf{u}_1 - \mathbf{u}_0\right) + \beta\left(\mathbf{u}_2 - \mathbf{u}_0\right)$$

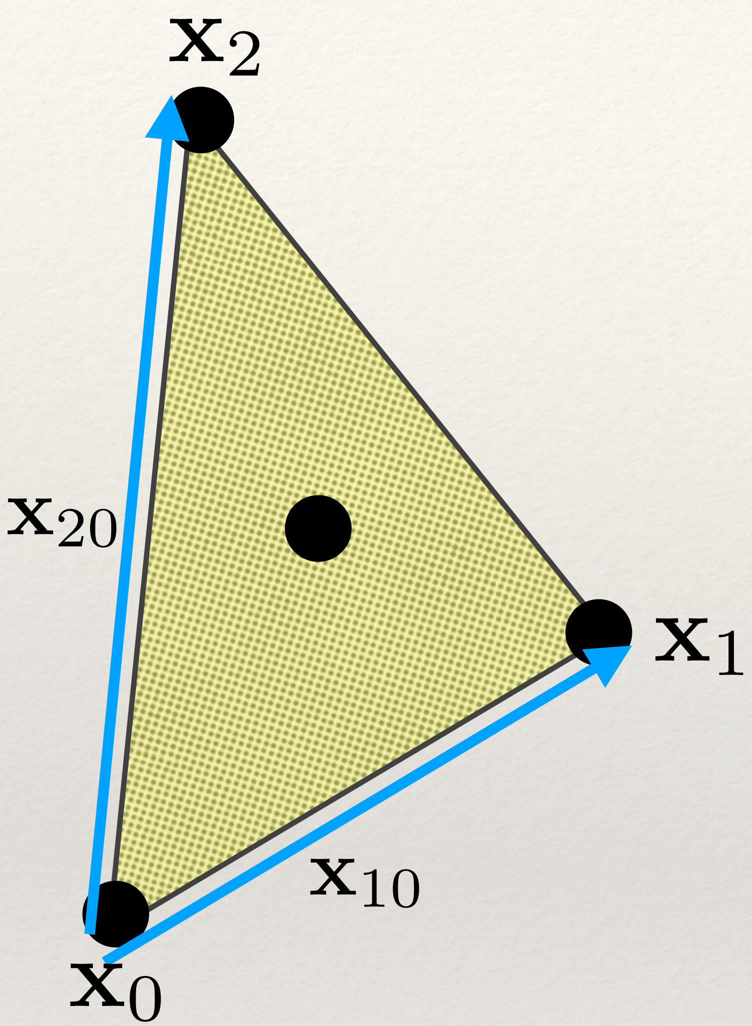
$$\mathbf{u} = \mathbf{u}_0 + \begin{pmatrix}\mathbf{u}_{10} & \mathbf{u}_{20}\end{pmatrix}\begin{pmatrix}\alpha \\ \beta\end{pmatrix}$$


$\mathbf{x}_2$
$\mathbf{x}_1$
$\mathbf{x}_0$


$\mathbf{x}_2$
$\mathbf{x}_{20}$
$\mathbf{x}_1$
$\mathbf{x}_{10}$
$\mathbf{x}_0$



$$\mathbf{x} = \mathbf{x}_0 + \alpha\left(\mathbf{x}_1 - \mathbf{x}_0\right) + \beta\left(\mathbf{x}_2 - \mathbf{x}_0\right)$$

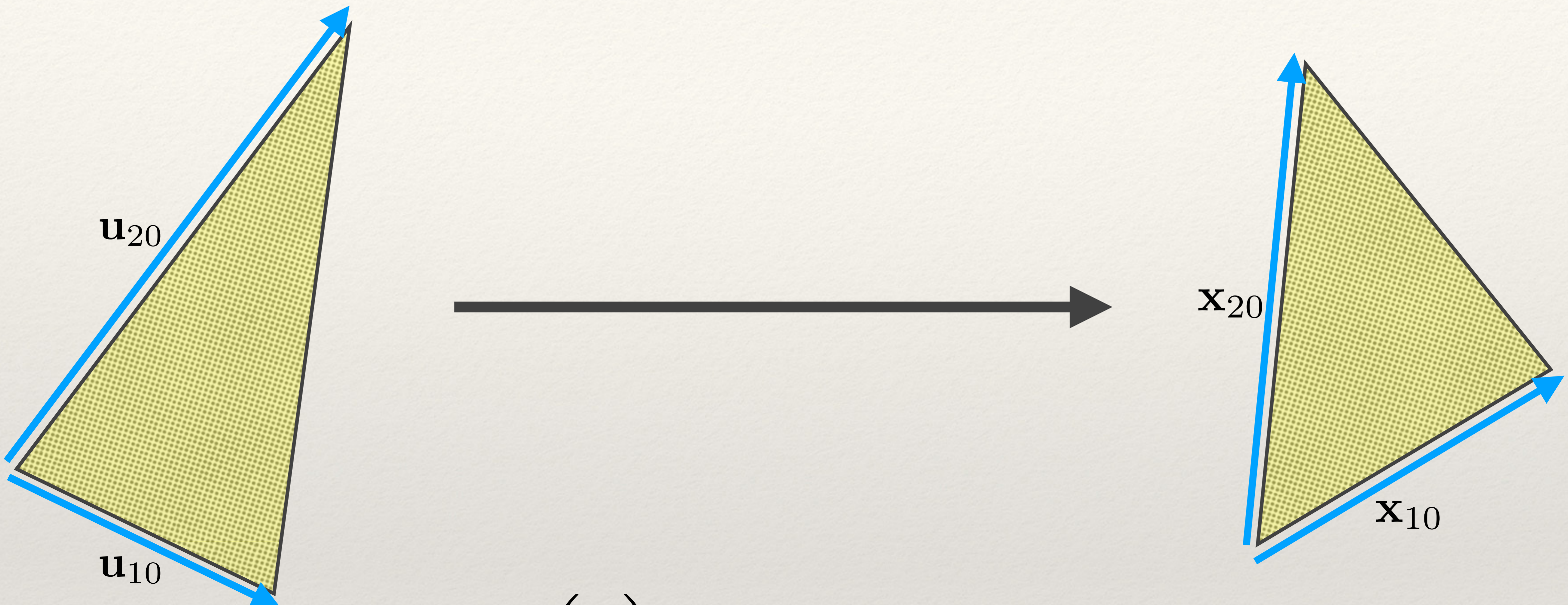


$$\mathbf{x} = \mathbf{x}_0 + \alpha\left(\mathbf{x}_1 - \mathbf{x}_0\right) + \beta\left(\mathbf{x}_2 - \mathbf{x}_0\right)$$

$$\mathbf{x} = \mathbf{x}_0 + \begin{pmatrix}\mathbf{x}_{10} & \mathbf{x}_{20}\end{pmatrix}\begin{pmatrix}\alpha \\ \beta\end{pmatrix}$$

Rest / Material

World

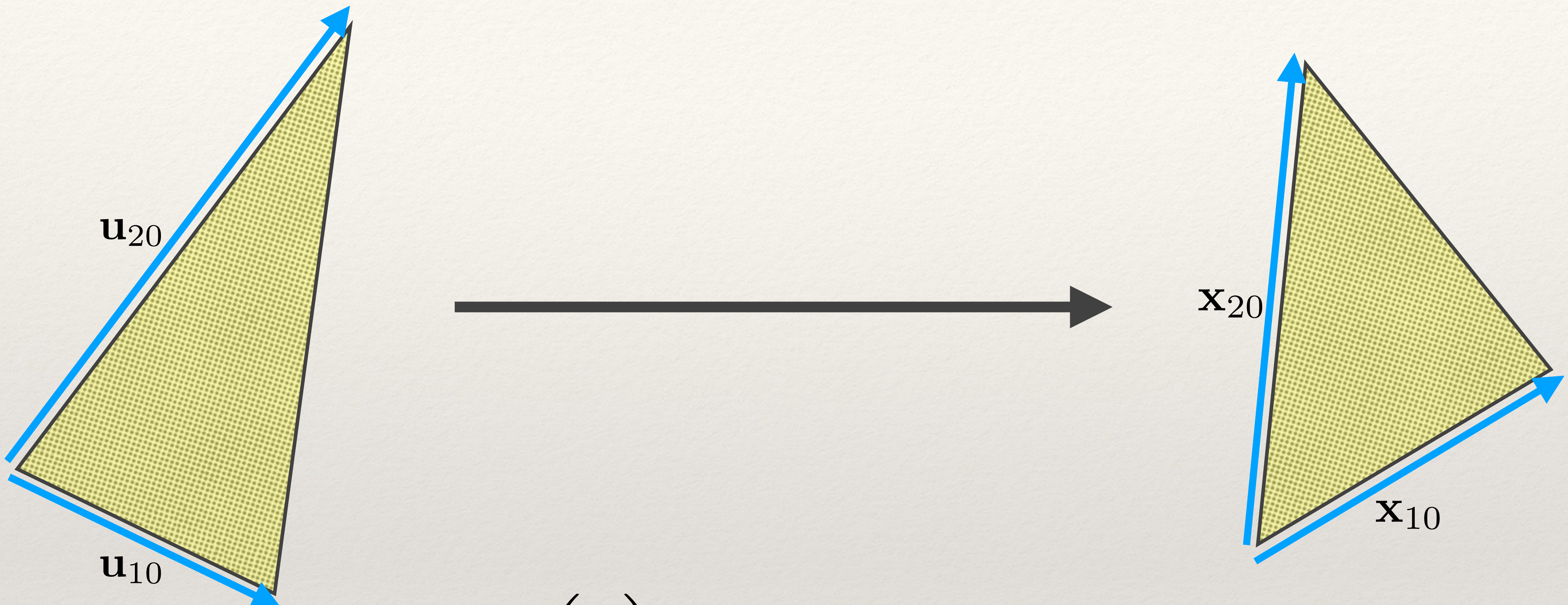


$$\mathbf{u} = \mathbf{u}_0 + \begin{pmatrix} \mathbf{u}_{10} & \mathbf{u}_{20} \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

$$\mathbf{x} = \mathbf{x}_0 + \begin{pmatrix} \mathbf{x}_{10} & \mathbf{x}_{20} \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

Rest/Material

World

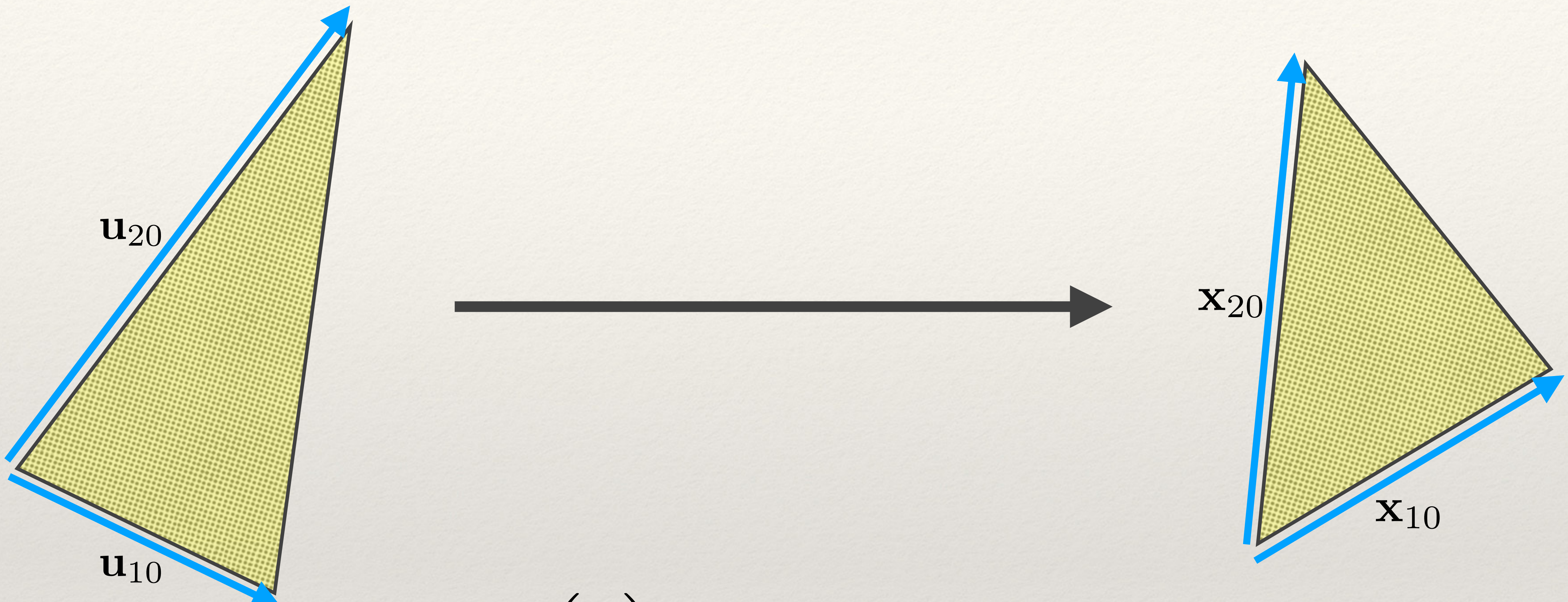


$$\mathbf{u} = \mathbf{u}_0 + \begin{pmatrix} \mathbf{u}_{10} & \mathbf{u}_{20} \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

$$\mathbf{x} = \mathbf{x}_0 + \begin{pmatrix} \mathbf{x}_{10} & \mathbf{x}_{20} \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

$$\mathbf{x}(\mathbf{u}) = \mathbf{x}_0 + \begin{pmatrix} \mathbf{x}_{10} & \mathbf{x}_{20} \end{pmatrix} \begin{pmatrix} \mathbf{u}_{10} & \mathbf{u}_{20} \end{pmatrix}^{-1} (\mathbf{u} - \mathbf{u}_0)$$

Rest/Material World



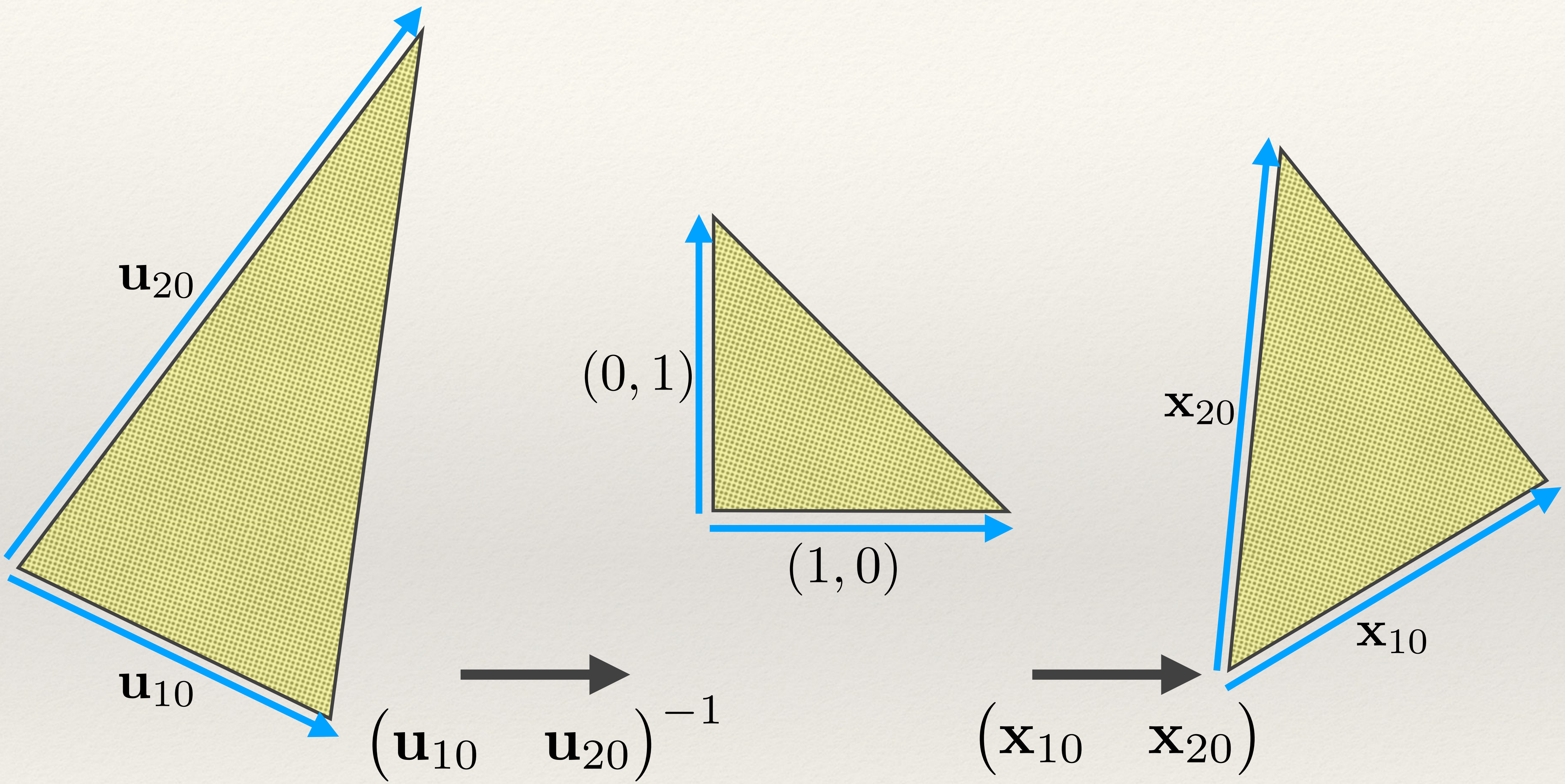
$$\mathbf{u} = \mathbf{u}_0 + \begin{pmatrix} \mathbf{u}_{10} & \mathbf{u}_{20} \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

$$\mathbf{x} = \mathbf{x}_0 + \begin{pmatrix} \mathbf{x}_{10} & \mathbf{x}_{20} \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

$$\mathbf{x}(\mathbf{u}) = \mathbf{x}_0 + \begin{pmatrix} \mathbf{x}_{10} & \mathbf{x}_{20} \end{pmatrix} \begin{pmatrix} \mathbf{u}_{10} & \mathbf{u}_{20} \end{pmatrix}^{-1} (\mathbf{u} - \mathbf{u}_0)$$

$$\mathbf{F} = \begin{pmatrix} \mathbf{x}_{10} & \mathbf{x}_{20} \end{pmatrix} \begin{pmatrix} \mathbf{u}_{10} & \mathbf{u}_{20} \end{pmatrix}^{-1}$$

Rest/Material Canonical World



$$\mathbf{F} = \begin{pmatrix}\mathbf{x}_{10} & \mathbf{x}_{20}\end{pmatrix}\begin{pmatrix}\mathbf{u}_{10} & \mathbf{u}_{20}\end{pmatrix}^{-1}$$

Solve the Problem

$$\epsilon = \frac{1}{2}\left(\tilde{\mathbf{F}}^T + \tilde{\mathbf{F}}\right) - \mathbf{I}$$

where $\mathbf{F} = \mathbf{Q}\tilde{\mathbf{F}}$

Solve the Problem

$$\epsilon = \frac{1}{2}\left(\tilde{\mathbf{F}}^T + \tilde{\mathbf{F}}\right) - \mathbf{I}$$

where $\mathbf{F} = \mathbf{Q}\tilde{\mathbf{F}}$

$$\sigma = \lambda \mathrm{Tr}\left(\epsilon\right)\mathbf{I} + 2\mu\epsilon$$

Solve the Problem

$$\epsilon = \frac{1}{2}\left(\tilde{\mathbf{F}}^T + \tilde{\mathbf{F}}\right) - \mathbf{I}$$

where $\mathbf{F} = \mathbf{Q}\tilde{\mathbf{F}}$

$$\sigma = \lambda \mathrm{Tr}\left(\epsilon\right)\mathbf{I} + 2\mu\epsilon$$

$$\mathbf{f} = \mathbf{Q}\sigma\mathbf{n}_i$$

Solve the Problem

$$\epsilon = \frac{1}{2}\left(\tilde{\mathbf{F}}^T + \tilde{\mathbf{F}}\right) - \mathbf{I}$$

where $\mathbf{F} = \mathbf{Q}\tilde{\mathbf{F}}$

$$\sigma = \lambda \mathrm{Tr}\left(\epsilon\right)\mathbf{I} + 2\mu\epsilon$$

$$\mathbf{f} = \mathbf{Q}\sigma\mathbf{n}_i$$

where $\mathbf{n}_i$
are the normals of the opposite faces
in rest space

IV. Temporal Integration

Explicit Integration

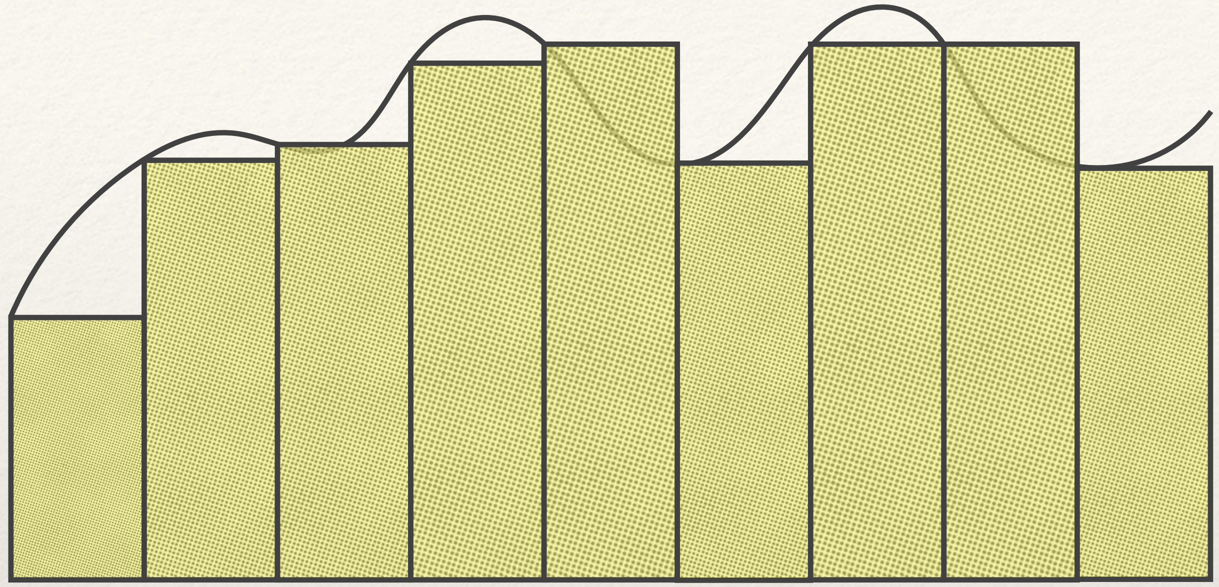
Explicit formula for (*t*+1)
in terms of quantities known at time *t*

$$\mathbf{x}_p(t + \Delta t) = \mathbf{x}_p(t) + \Delta t \cdot \mathbf{v}(\mathbf{x}_p, t)$$

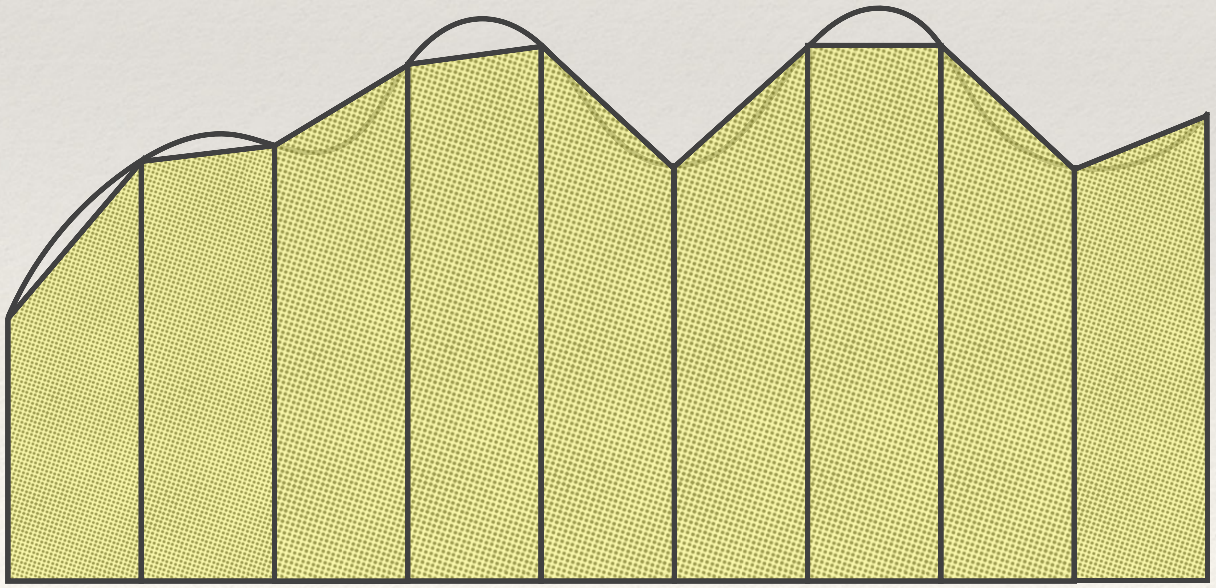
Note: everything on the right hand side
is evaluated at time *t*

Choose Your Integration Scheme Wisely

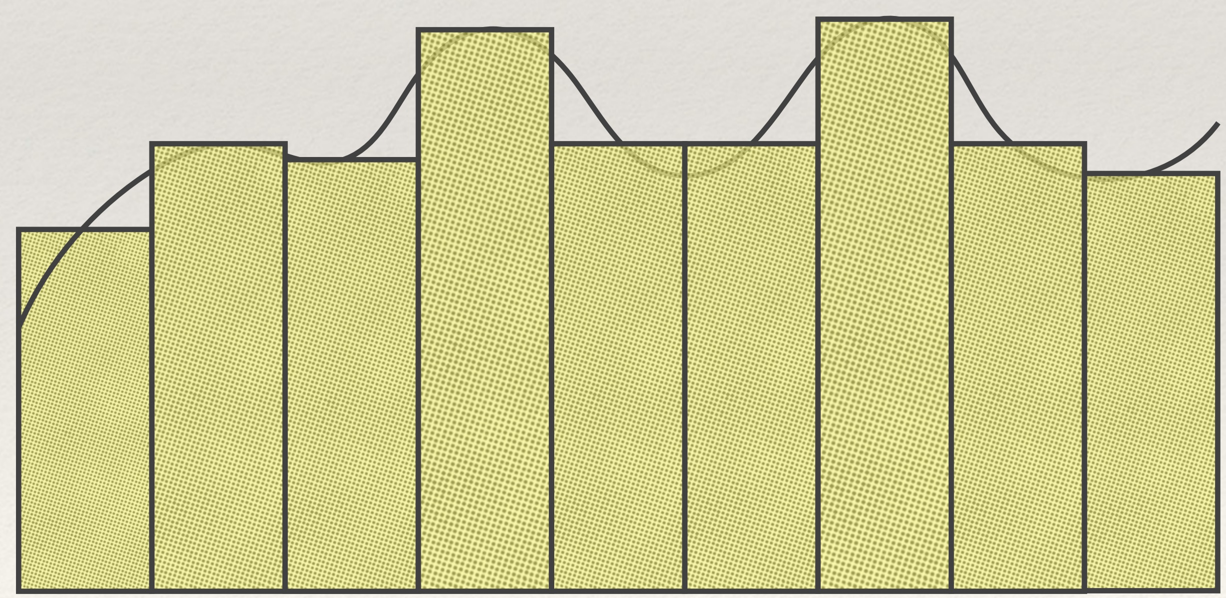
Trapezoidal Rule vs. Midpoint Method



Forward Euler

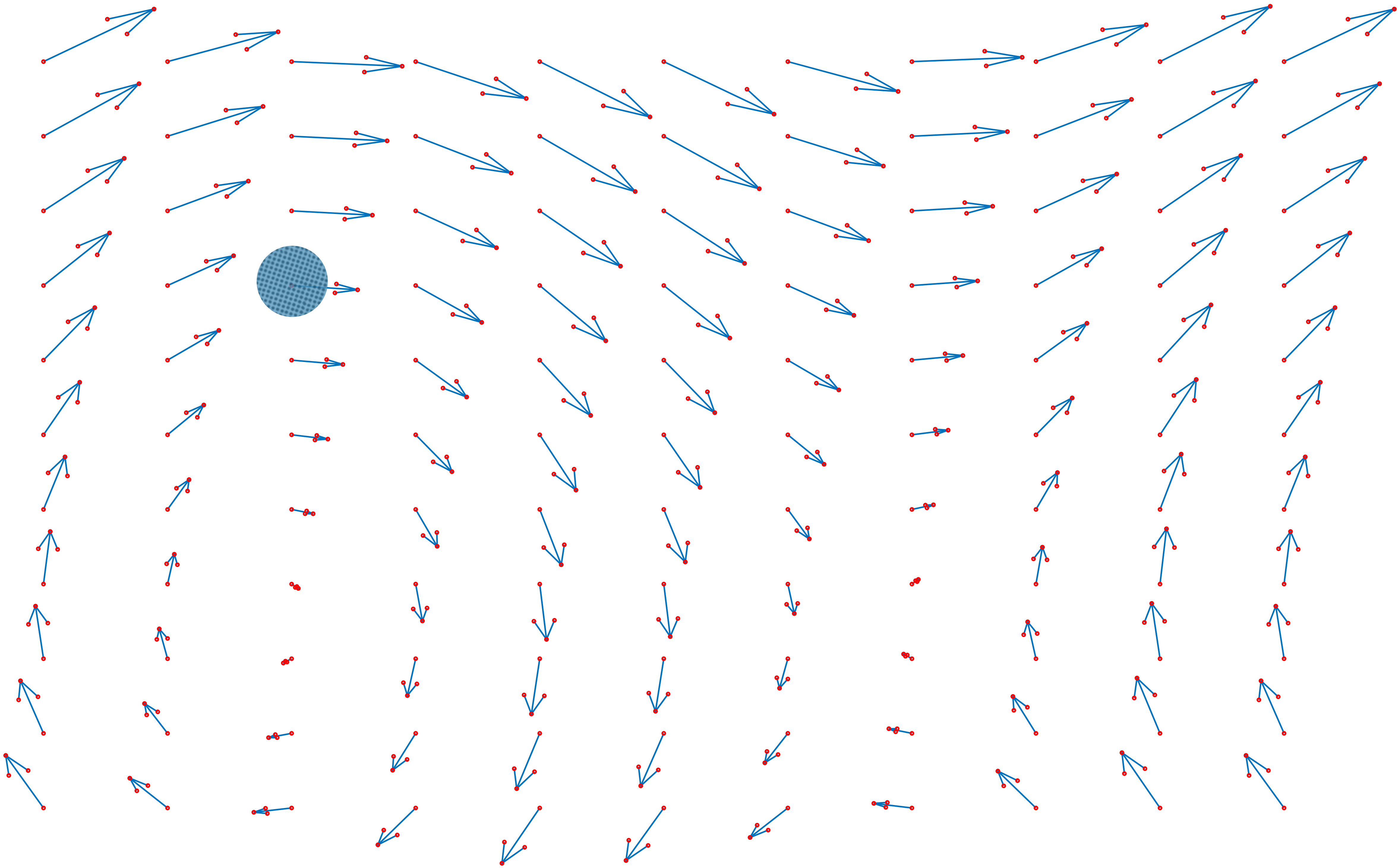


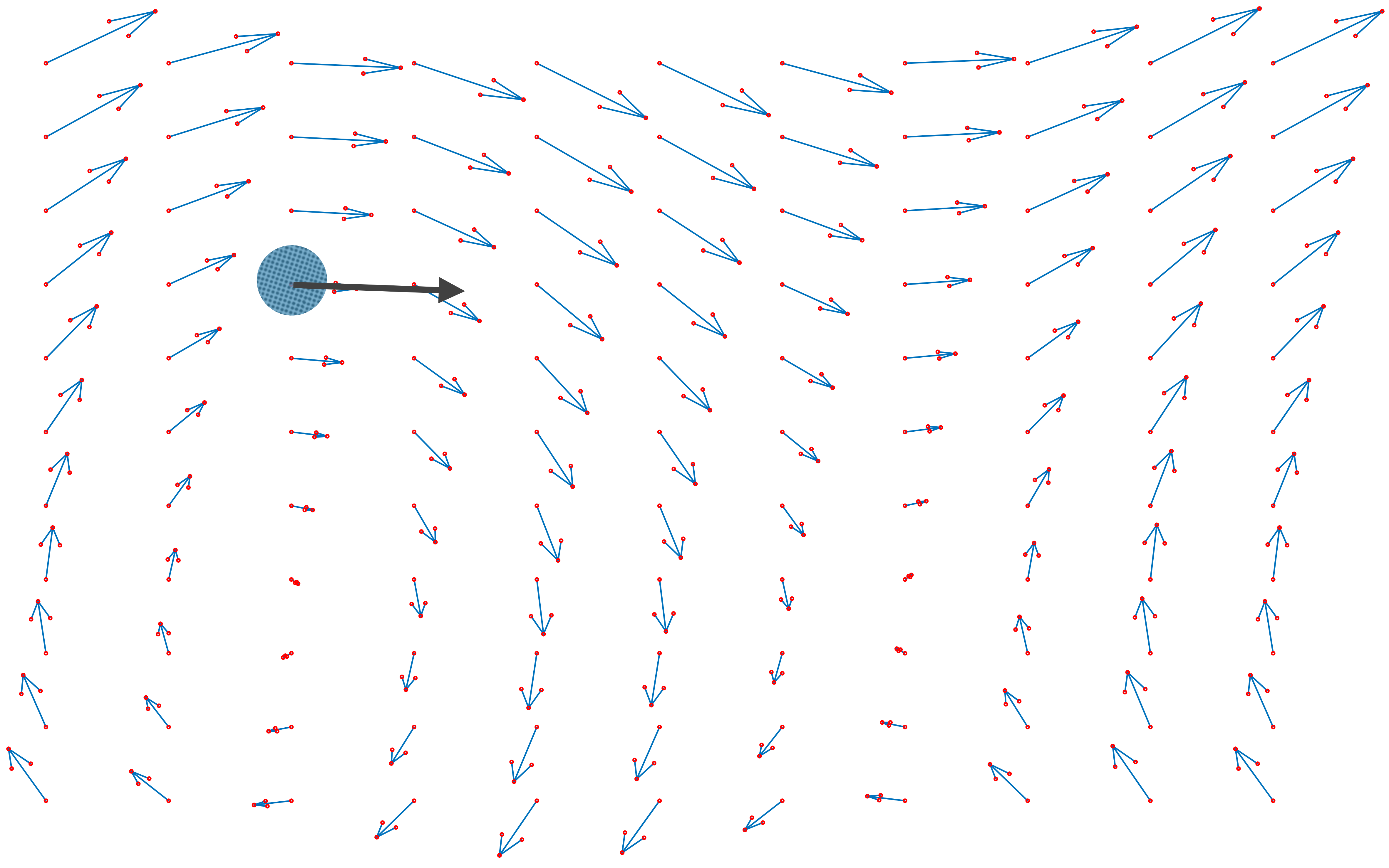
Trapezoidal Rule

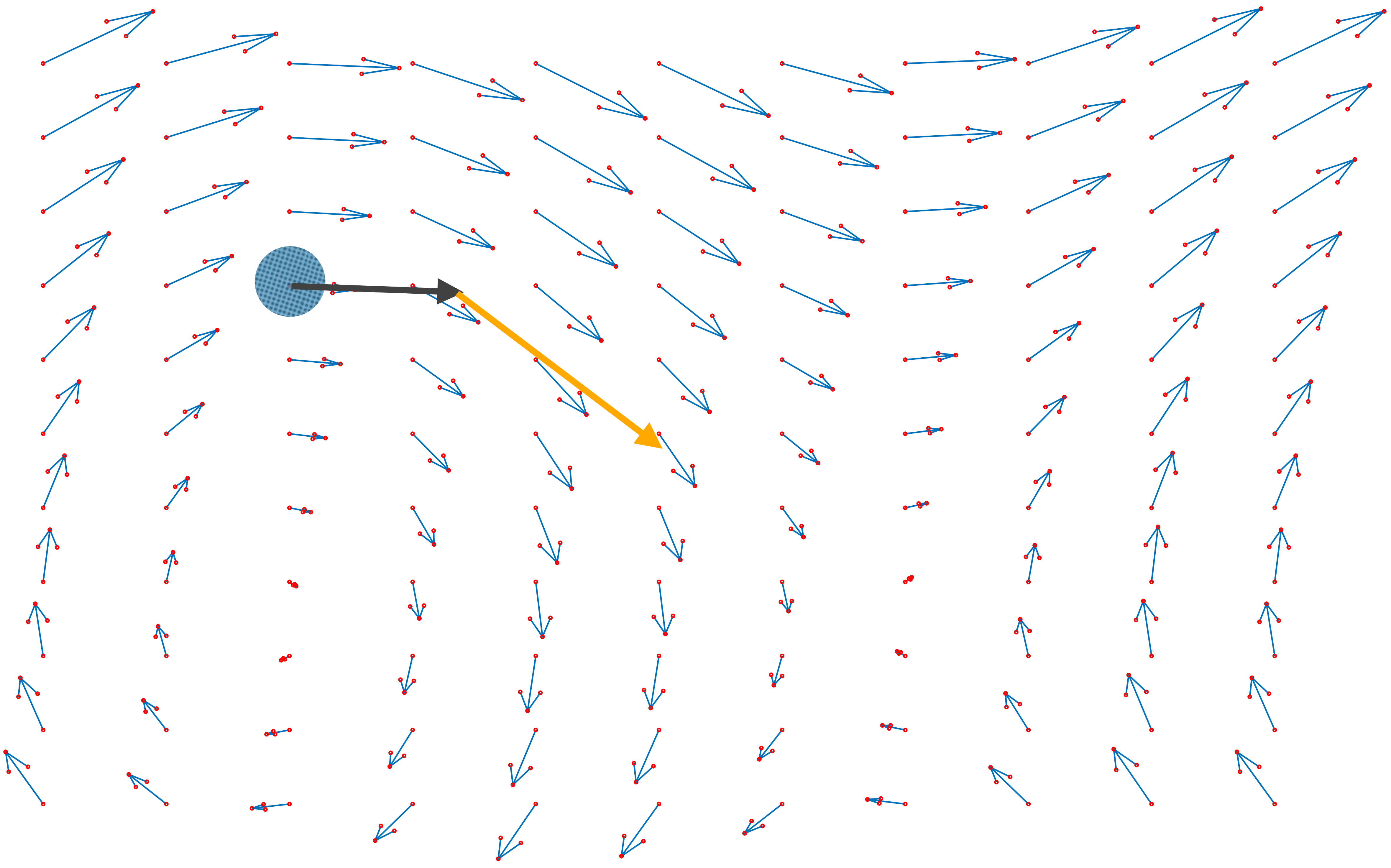


Midpoint Method

Trapazoidal Rule







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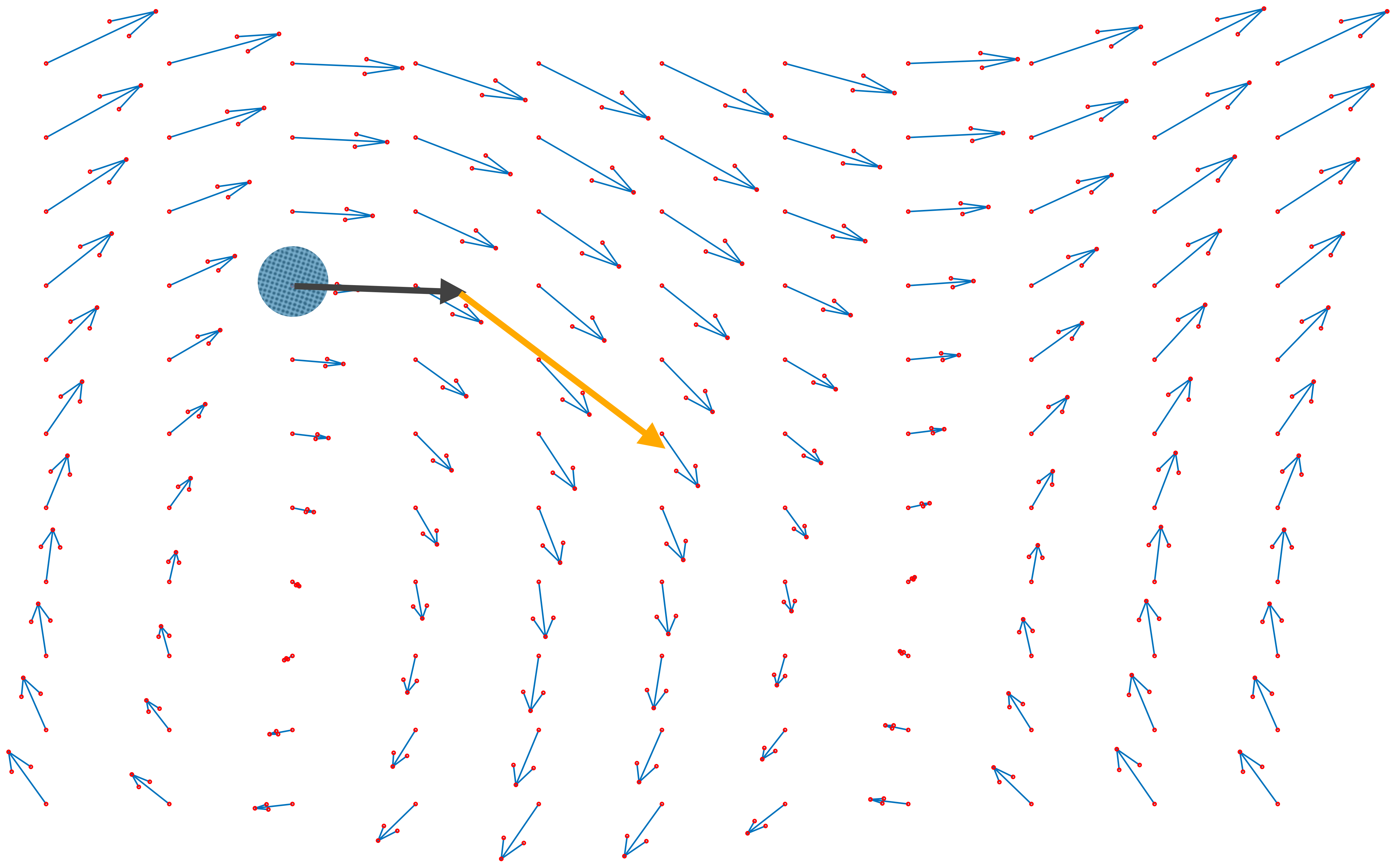
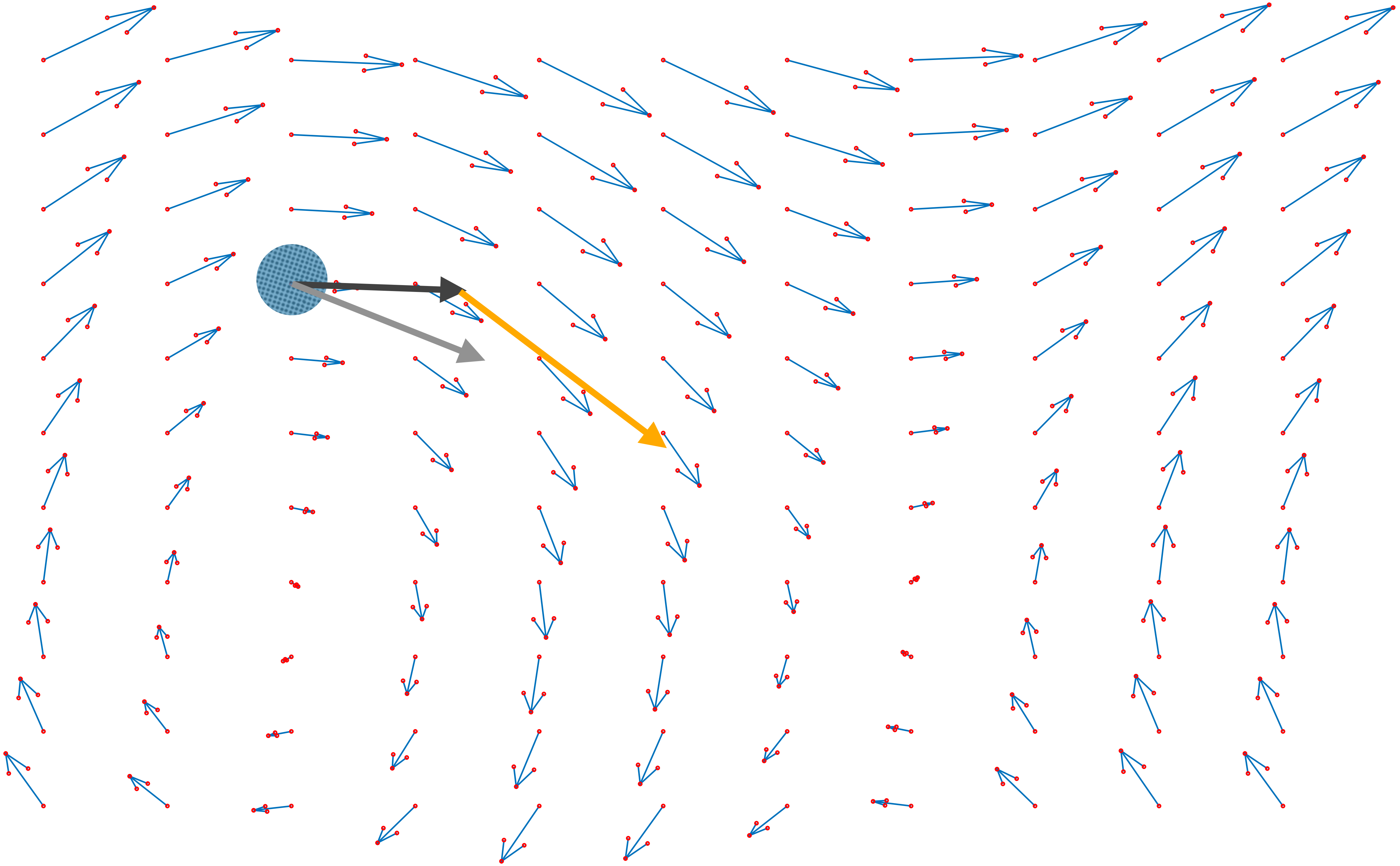
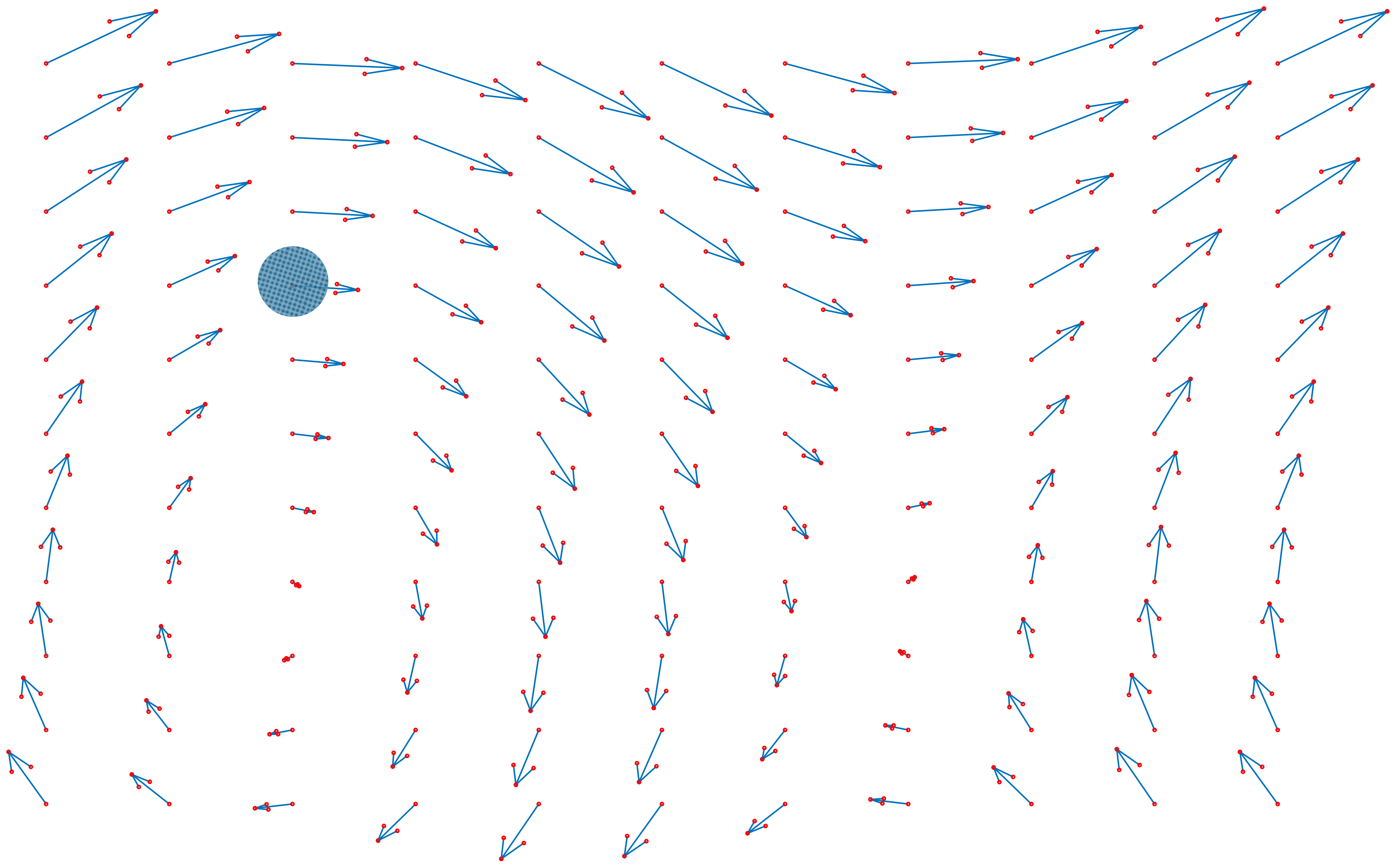
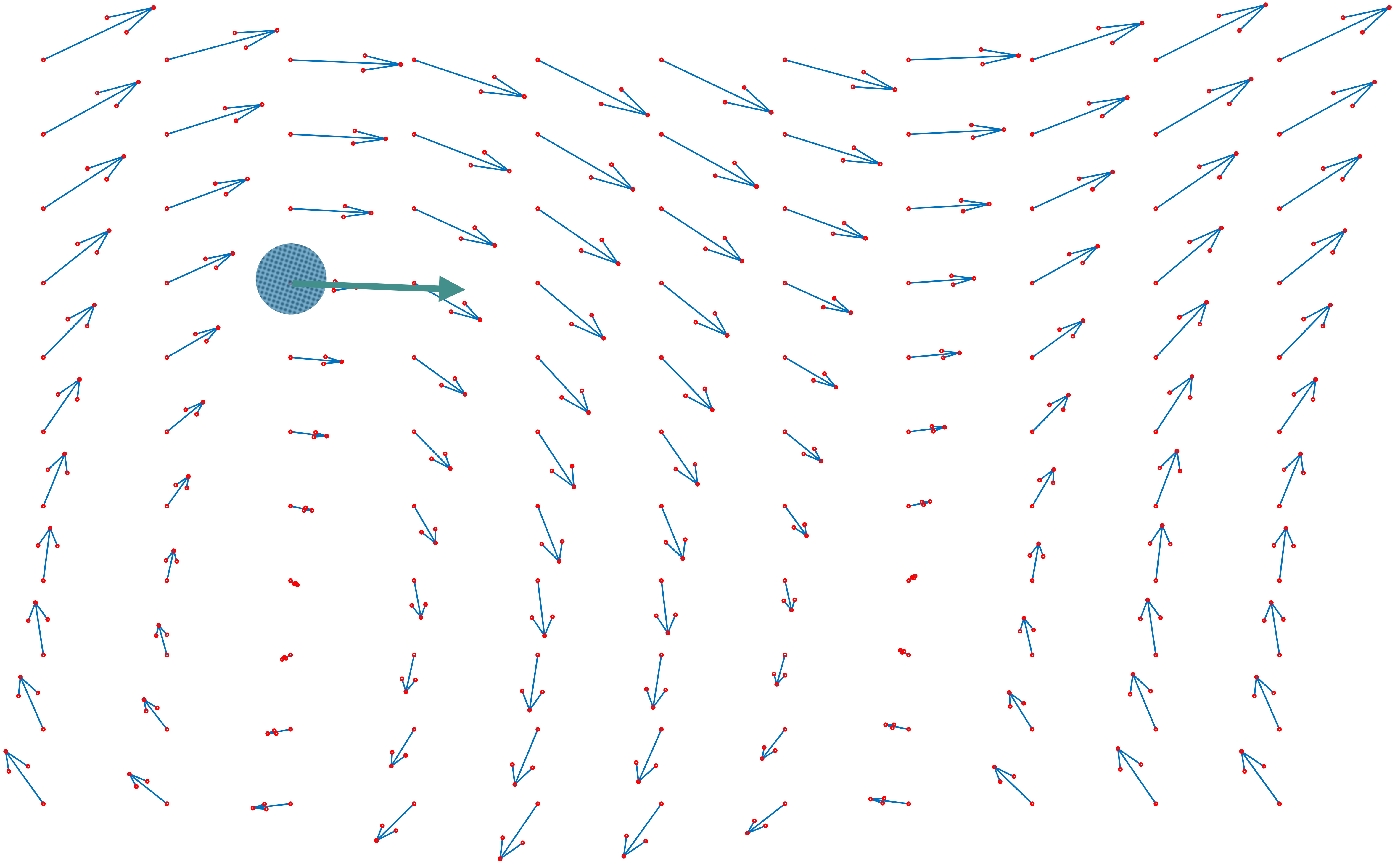


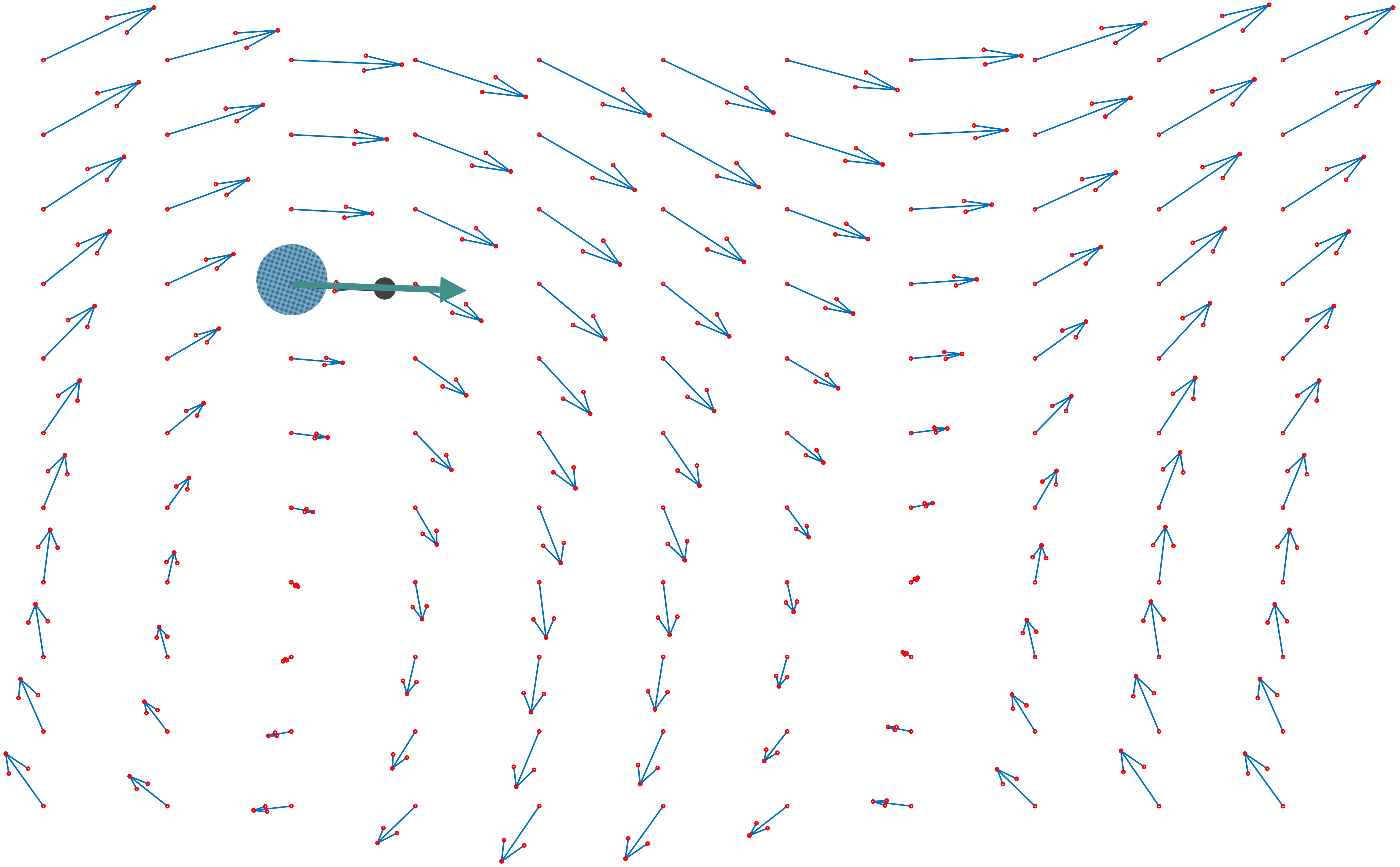
Average

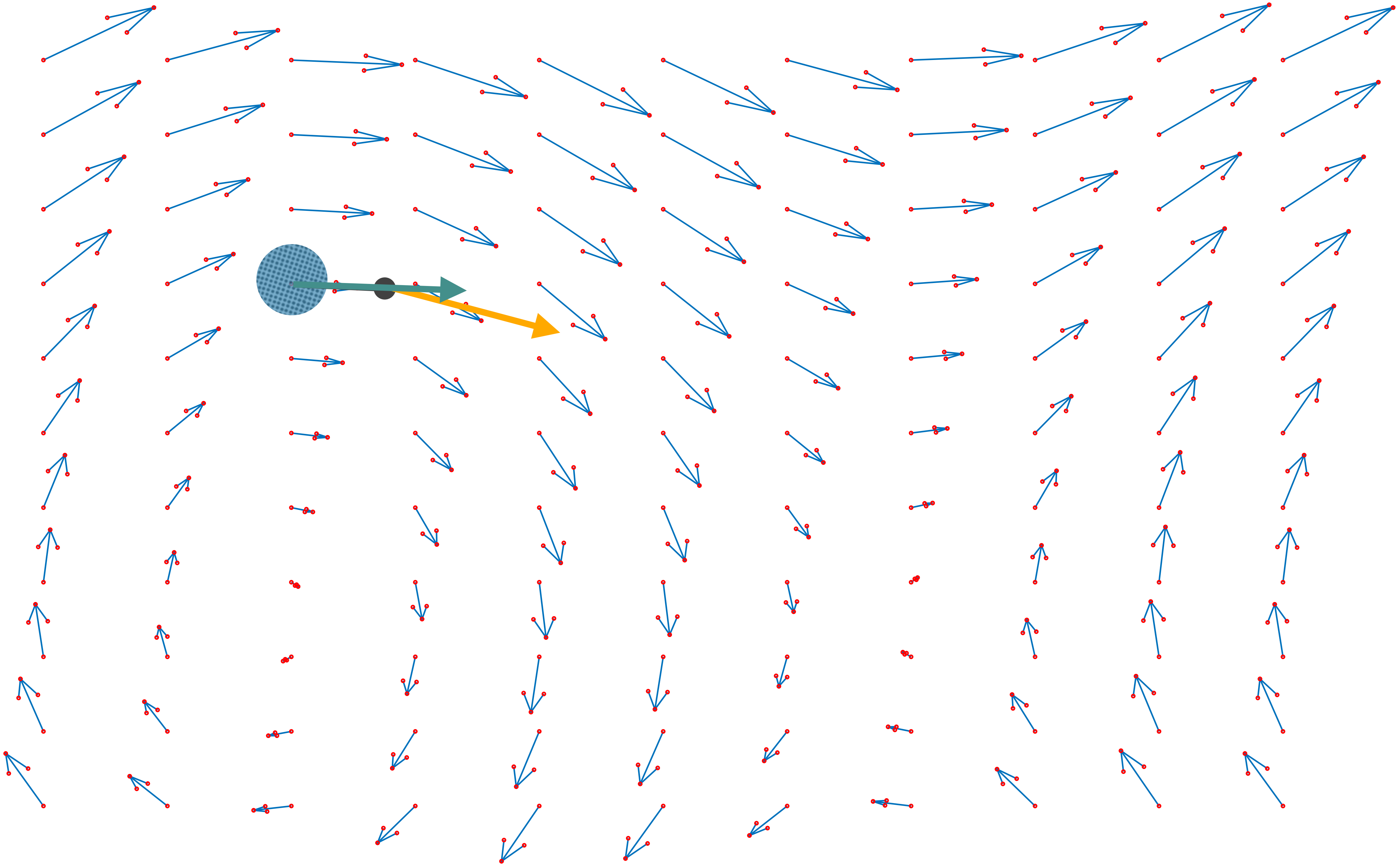


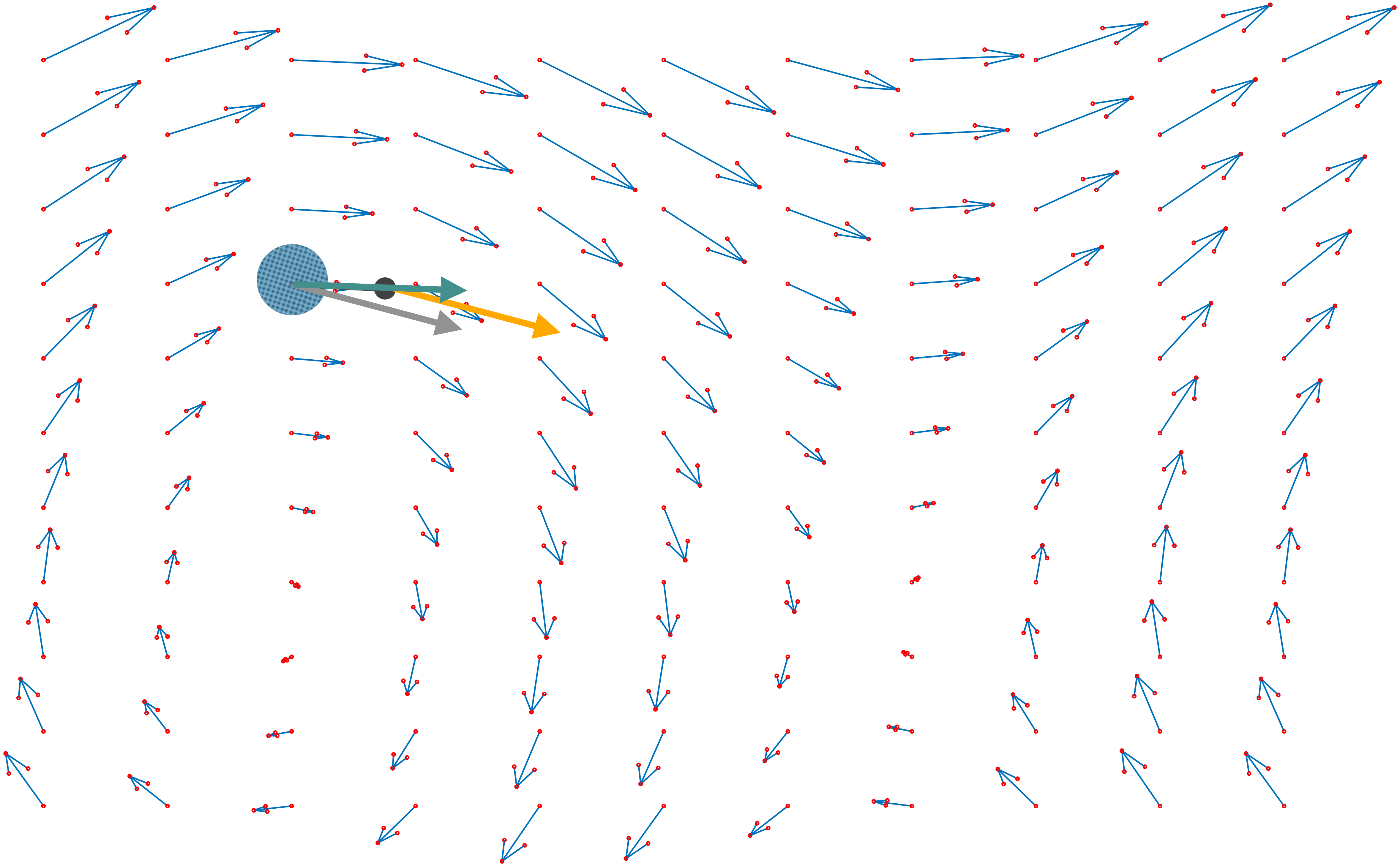
Midpoint Method











Trapezoidal Rule vs. Midpoint Method

- Both second-order Runge-Kutta methods (same accuracy)
- Very different behavior
  - Trapezoidal rule is smoother, more damped looking
  - Midpoint Method keeps more energy, but can be noisy / aliased

Position Updates for

$$\frac{d^2\mathbf{x}_p(t)}{dt^2} = \frac{\mathbf{f}(\mathbf{x}_p, t)}{m_p}$$

Three Position Updates

$$\mathbf{x}_p(t+\Delta t) = \mathbf{x}_p(t) + dt \cdot \mathbf{v}_p(t)$$

$$\mathbf{x}_p(t+\Delta t) = \mathbf{x}_p(t) + \frac{dt}{2} \cdot (\mathbf{v}_p(t) + \mathbf{v}_p(t+\Delta t))$$

$$\mathbf{x}_p(t+\Delta t) = \mathbf{x}_p(t) + dt \cdot \mathbf{v}_p(t+\Delta t)$$

“Stiff” Problems

Consider the IVP:

$$\mathbf{x}(0) = \mathbf{x}_0 \qquad \mathbf{v}(0) = 0 \qquad \mathbf{f} = -k\mathbf{x}$$

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After one time step:

$$\mathbf{x}(\Delta t) = \left(1 - \frac{\Delta t^2 k}{m}\right)\mathbf{x}_0$$

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After one time step:

$$\mathbf{x}(\Delta t) = \left(1 - \frac{\Delta t^2 k}{m}\right)\mathbf{x}_0$$

If $\Delta t > \sqrt{\frac{2m}{k}}$

the spring will be more extended then when we started

If We Want to Take Bigger Timesteps

Implicit Integration

Replace:

$$\mathbf{v}(t + \Delta t) = \mathbf{v}(t) + \Delta t \cdot \mathbf{M}^{-1}\mathbf{f}(\mathbf{x}(t), t)$$

$$\mathbf{x}(t + \Delta t) = \mathbf{x}(t) + \Delta t \cdot \mathbf{v}(t + \Delta t)$$

With:

$$\mathbf{v}(t + \Delta t) = \mathbf{v}(t) + \Delta t \cdot \mathbf{M}^{-1}\mathbf{f}(\mathbf{x}(t + \Delta t), t + \Delta t)$$

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Applied to Soft Bodies

$$\mathbf{K}(\mathbf{x} - \mathbf{x}_0) + \mathbf{D}(\mathbf{v}) + \mathbf{M}\mathbf{a} = \mathbf{f}_{ext}$$

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Linearize

Applied to Soft Bodies

$$\mathbf{K}(\mathbf{x} - \mathbf{x}_0) + \mathbf{D}(\mathbf{v}) + \mathbf{M}\mathbf{a} = \mathbf{f}_{ext}$$

Linearize

$$\mathbf{K}\mathbf{x} - \mathbf{K}\mathbf{x}_0 + \mathbf{D}\mathbf{v} + \mathbf{M}\mathbf{a} = \mathbf{f}_{ext}$$

Applied to Soft Bodies

$$\mathbf{K}(\mathbf{x} - \mathbf{x}_0) + \mathbf{D}(\mathbf{v}) + \mathbf{M}\mathbf{a} = \mathbf{f}_{ext}$$

Linearize

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$$+$$

$$\mathbf{x}(t + \Delta t) = \mathbf{x}(t) + \Delta t \cdot \mathbf{v}(t + \Delta t)$$

Applied to Soft Bodies

$$\mathbf{K}(\mathbf{x} - \mathbf{x}_0) + \mathbf{D}(\mathbf{v}) + \mathbf{Ma} = \mathbf{f}_{ext}$$

Linearize

$$\mathbf{Kx} - \mathbf{Kx}_0 + \mathbf{Dv} + \mathbf{Ma} = \mathbf{f}_{ext}$$

$$+$$

$$\mathbf{x}(t + \Delta t) = \mathbf{x}(t) + \Delta t \cdot \mathbf{v}(t + \Delta t)$$

substitute into

$$\mathbf{v}(t + \Delta t) = \mathbf{v}(t) + \Delta t \cdot \mathbf{M}^{-1}\mathbf{f}(\mathbf{x}(t + \Delta t), t + \Delta t)$$

Applied to Soft Bodies

$$\mathbf{K}(\mathbf{x} - \mathbf{x}_0) + \mathbf{D}(\mathbf{v}) + \mathbf{M}\mathbf{a} = \mathbf{f}_{ext}$$

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re-arrange

Applied to Soft Bodies

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substitute into

$$\mathbf{v}(t + \Delta t) = \mathbf{v}(t) + \Delta t \cdot \mathbf{M}^{-1}\mathbf{f}(\mathbf{x}(t + \Delta t), t + \Delta t)$$

re-arrange

$$\left(\mathbf{M} + \Delta t^2 \mathbf{K} + \Delta t \mathbf{D}\right) \mathbf{v}(t + \Delta t) = \mathbf{M}\mathbf{v}(t) + \Delta t \left(-\mathbf{K}\left(\mathbf{x}(t) - \mathbf{x}_0\right) + \mathbf{f}_{ext}\right)$$

$$\left(\mathbf{M} + \Delta t^2 \mathbf{K} + \Delta t \mathbf{D}\right) \mathbf{v}(t + \Delta t) = \mathbf{M}\mathbf{v}(t) + \Delta t \left(-\mathbf{K} \left(\mathbf{x}(t) - \mathbf{x}_0\right) + \mathbf{f}_{ext}\right)$$

$$\underbrace{\left(\mathbf{M} + \Delta t^2 \mathbf{K} + \Delta t \mathbf{D}\right)}_{} \mathbf{v}(t + \Delta t) = \mathbf{M}\mathbf{v}(t) + \Delta t \left(-\mathbf{K}\left(\mathbf{x}(t) - \mathbf{x}_0\right) + \mathbf{f}_{ext}\right)$$

Linear System

Sparse, Symmetric

$$\underbrace{\left(\mathbf{M} + \Delta t^2\mathbf{K} + \Delta t\mathbf{D}\right)}_{\text{Linear System, Sparse, Symmetric}} \mathbf{v}(t + \Delta t) = \underbrace{\mathbf{M}\mathbf{v}(t)}_{\text{Momentum}} + \Delta t \left(-\mathbf{K}\left(\mathbf{x}(t) - \mathbf{x}_0\right) + \mathbf{f}_{ext}\right)$$

Linear System
Sparse, Symmetric

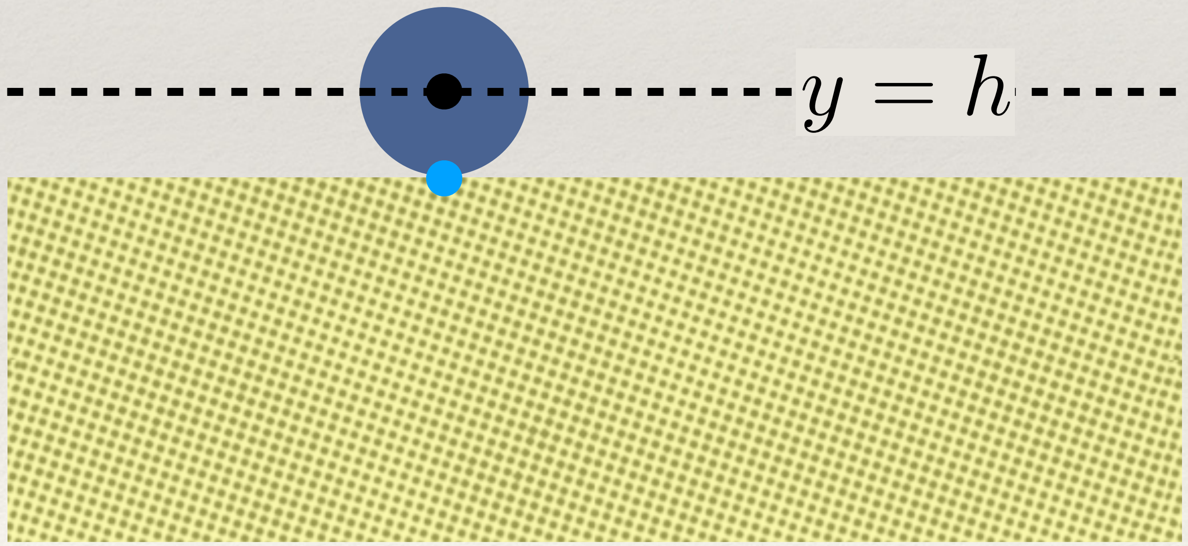
Momentum

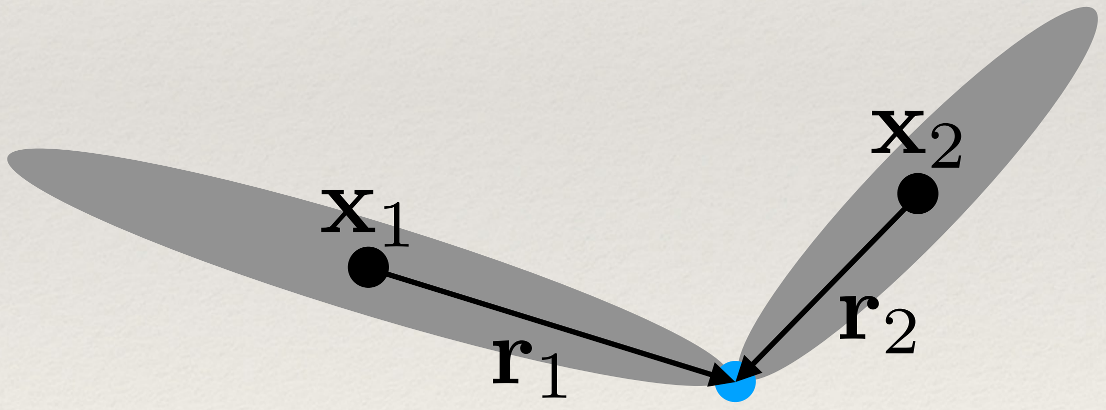
$$\underbrace{\left(\mathbf{M} + \Delta t^2 \mathbf{K} + \Delta t \mathbf{D}\right)}_{\text{Linear System Sparse, Symmetric}} \mathbf{v}(t + \Delta t) = \underbrace{\mathbf{M}\mathbf{v}(t)}_{\text{Momentum}} + \overbrace{\Delta t \left(-\mathbf{K}\left(\mathbf{x}(t) - \mathbf{x}_0\right) + \mathbf{f}_{ext}\right)}^{\text{Euler step of elastic and external forces}}$$

V. Constraints

Constraints

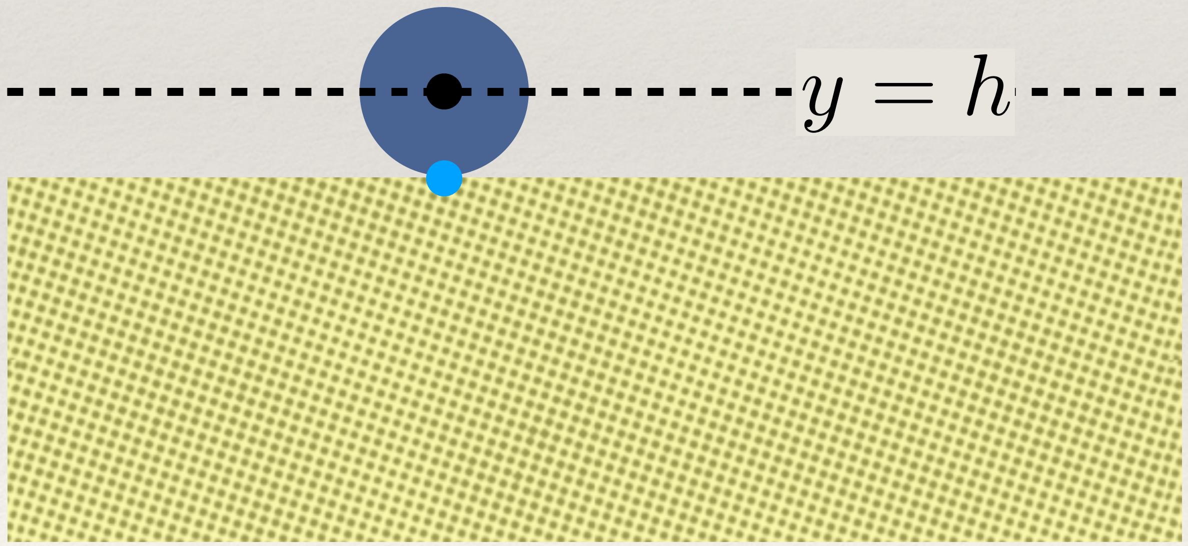
- Geometric relationships that must be satisfied

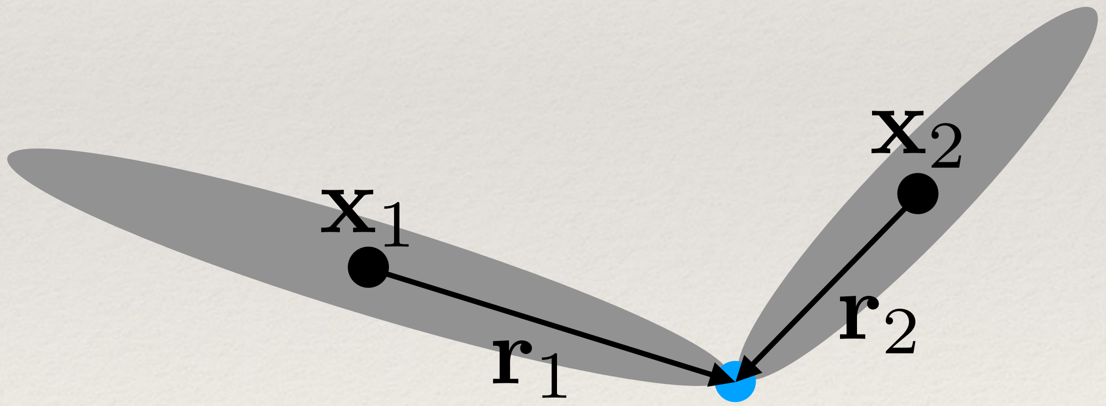




Constraints

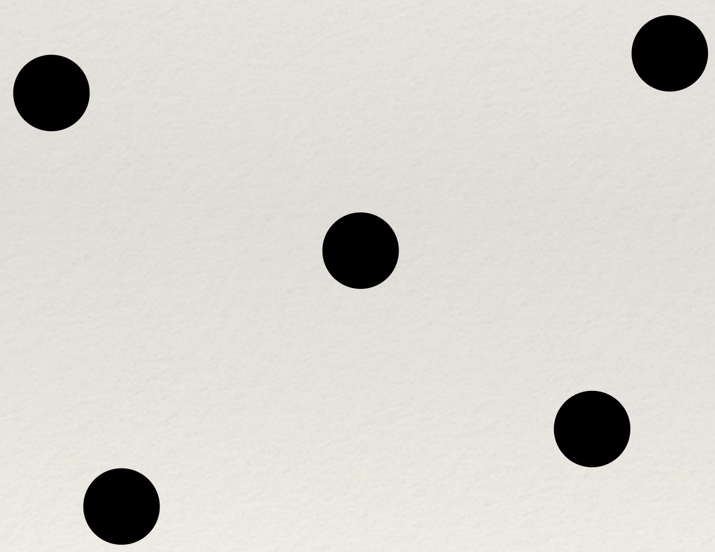
- Constraint forces arises in response to other forces to maintain the constraint





Degrees of Freedom (DOF)

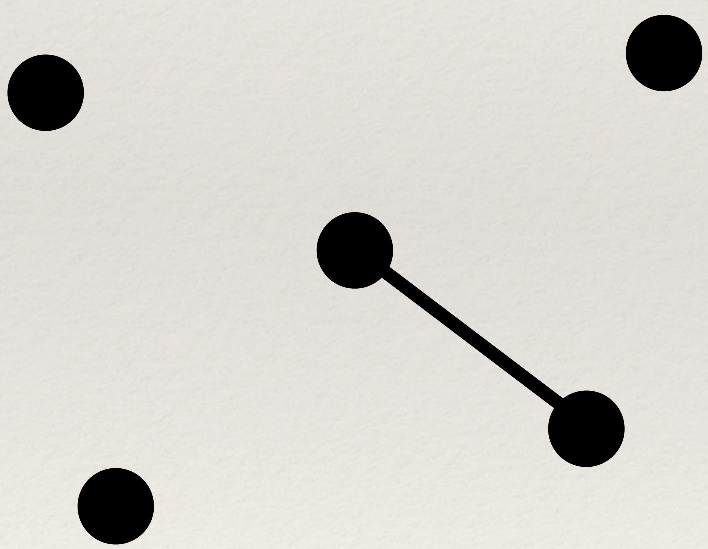
- Number of independent parameters describing configuration



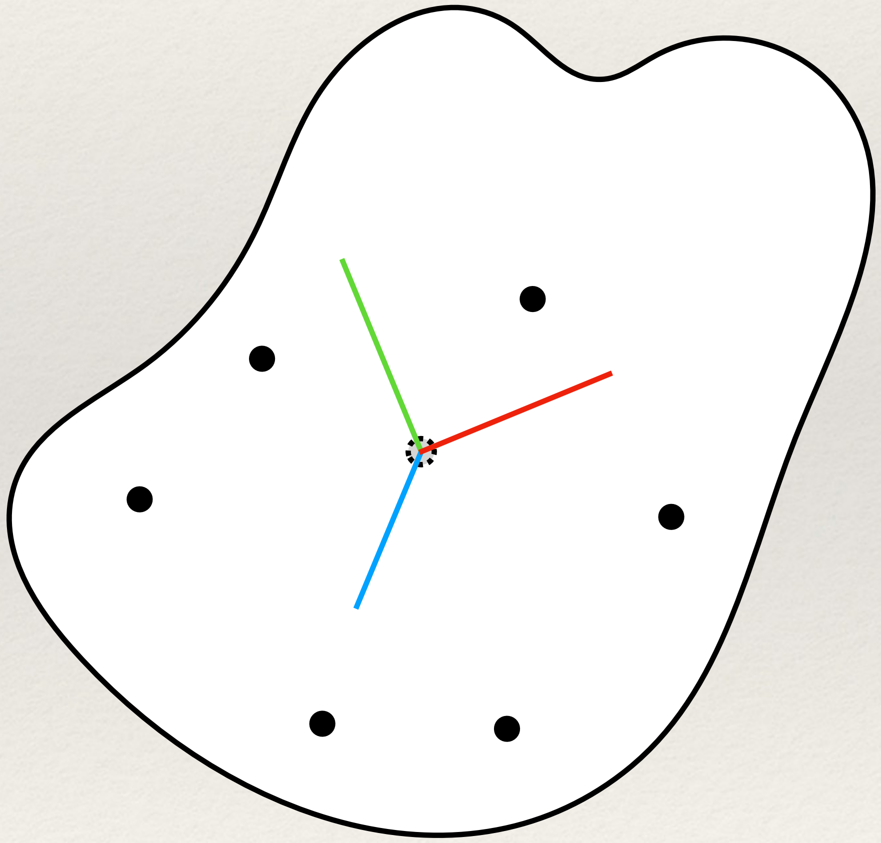
$3n$

Degrees of Freedom (DOF)

- number of independent parameters describing configuration



$3n - 1$

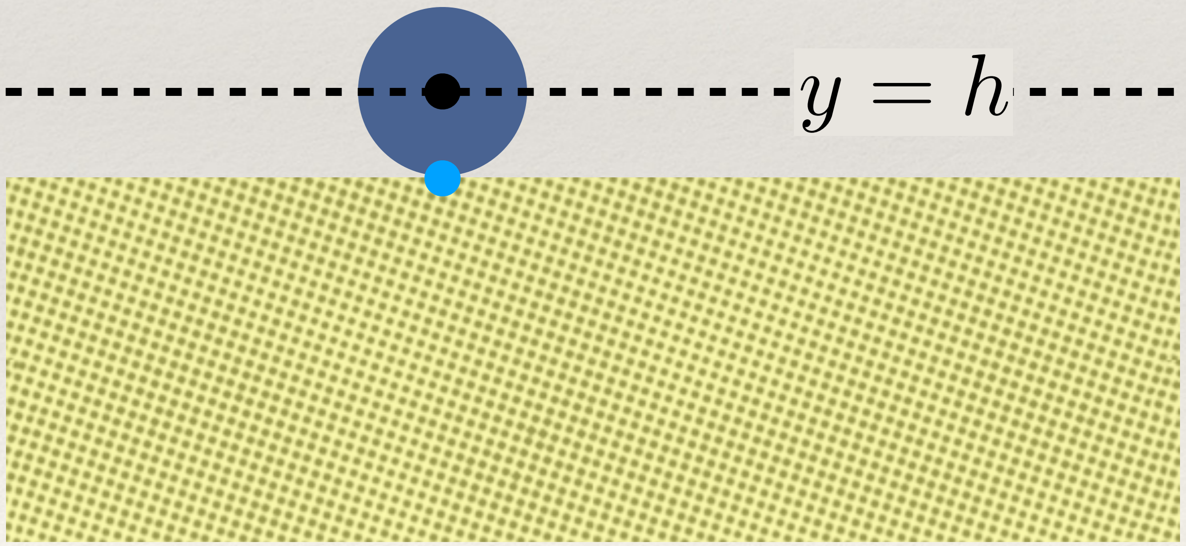


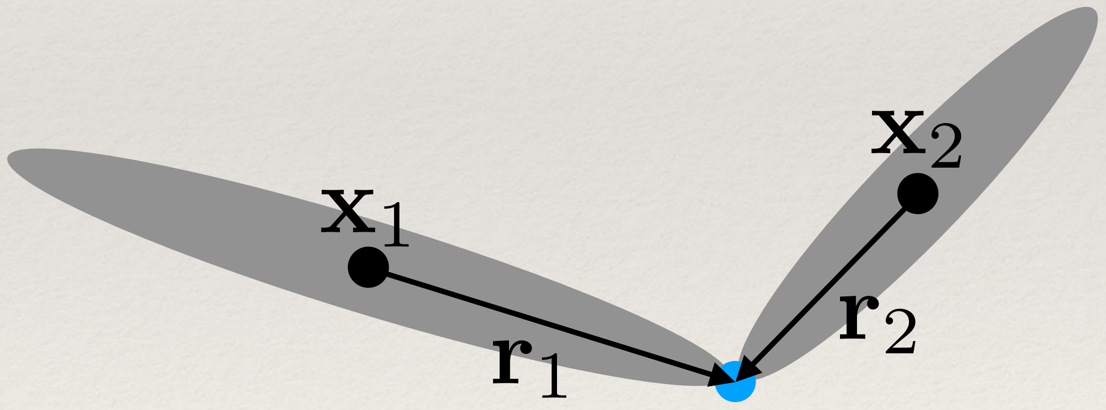
6

Unilateral/Bilateral Constraints

$$\mathbf{g}(\mathbf{x}, t) \geq \mathbf{0}$$

$$\mathbf{g}(\mathbf{x}, t) = \mathbf{0}$$





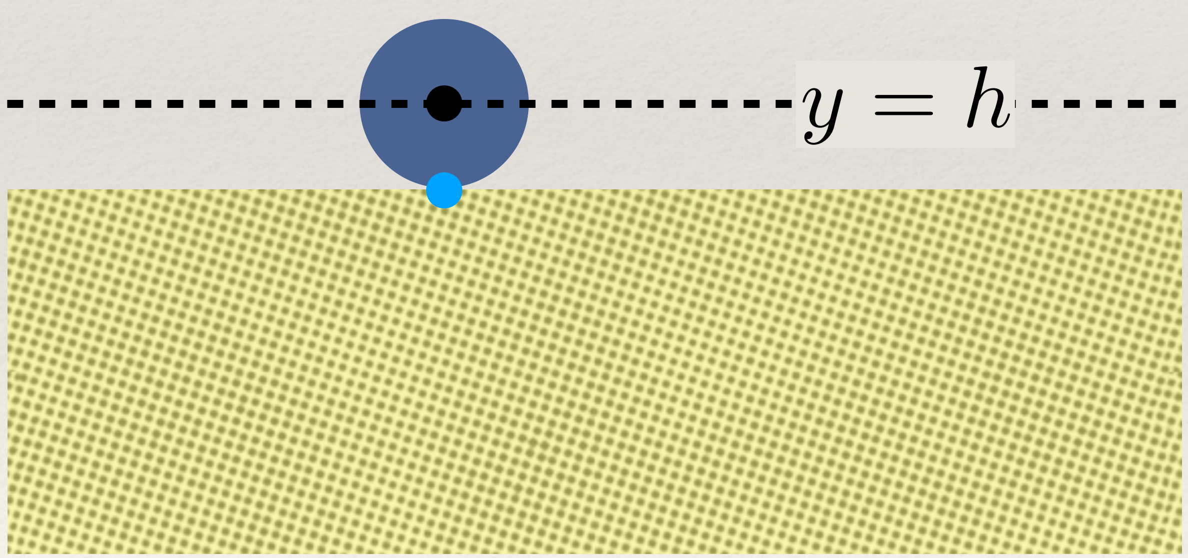
Unilateral/Bilateral Constraints

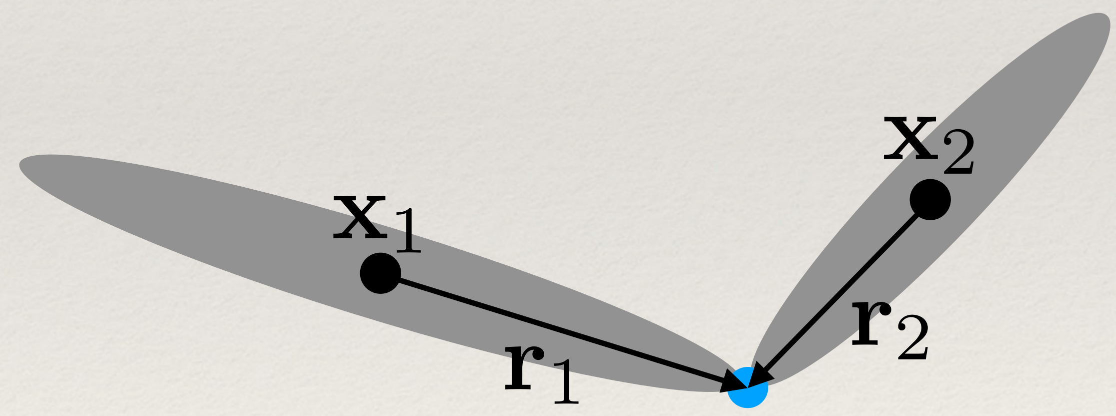
$$\mathbf{g}(\mathbf{x}, t) \geq \mathbf{0}$$

$$\mathbf{g}(\mathbf{x}, t) = \mathbf{0}$$

$$y_1 - h \geq 0$$

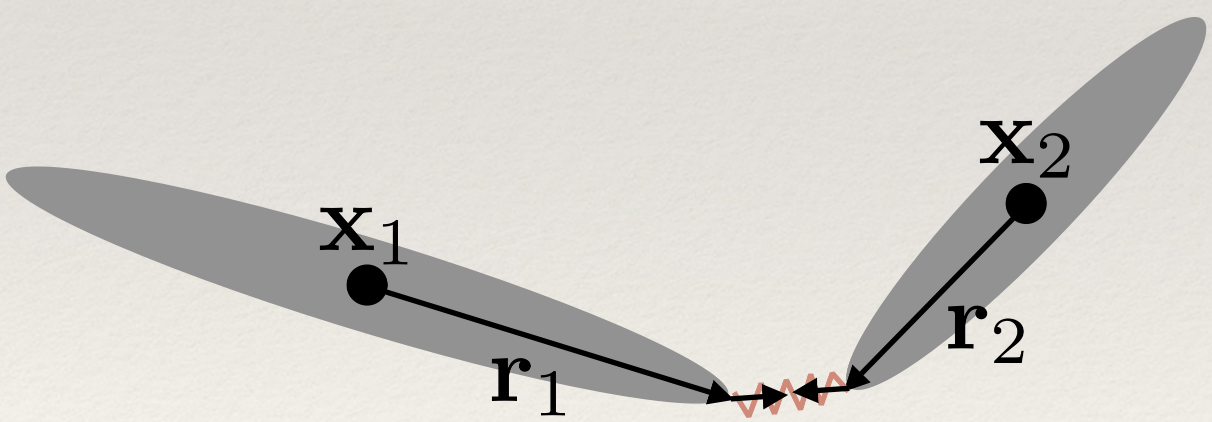
$$(\mathbf{x}_1 + \mathbf{r}_1) - (\mathbf{x}_2 + \mathbf{r}_2) = \mathbf{0}$$

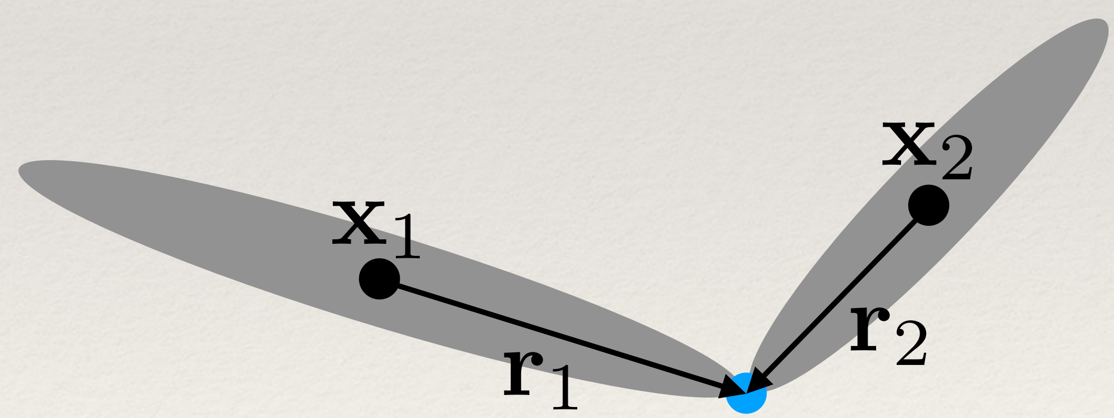




Soft vs. Hard Constraints

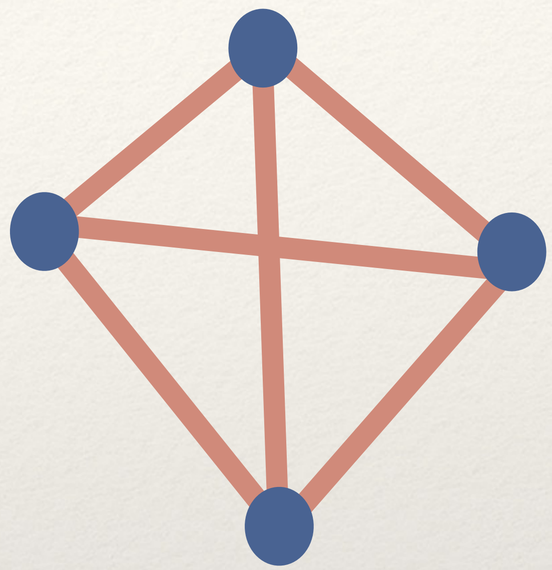
- **Soft constraint**: force competes with other forces in the system
- **Hard constraint**: force as strong as necessary to maintain constraint



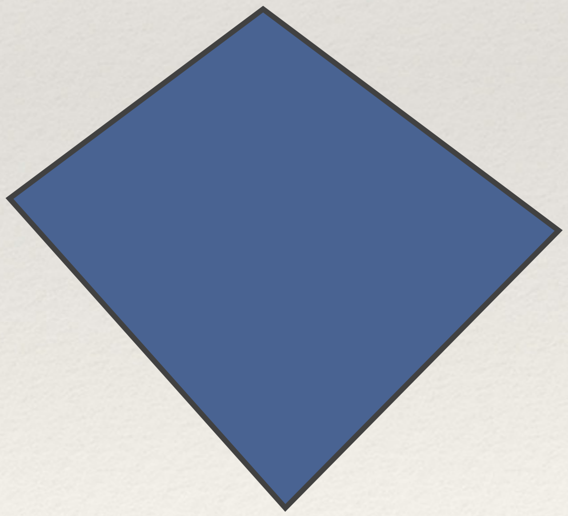


Constraints: Solution Methods

- Maximal coordinates + auxiliary conditions
  - Include forces to maintain constraint



- Generalized coordinates (a.k.a., reduced coordinates, minimal coordinates)
  - Parameterize true DOF, respecting constraints



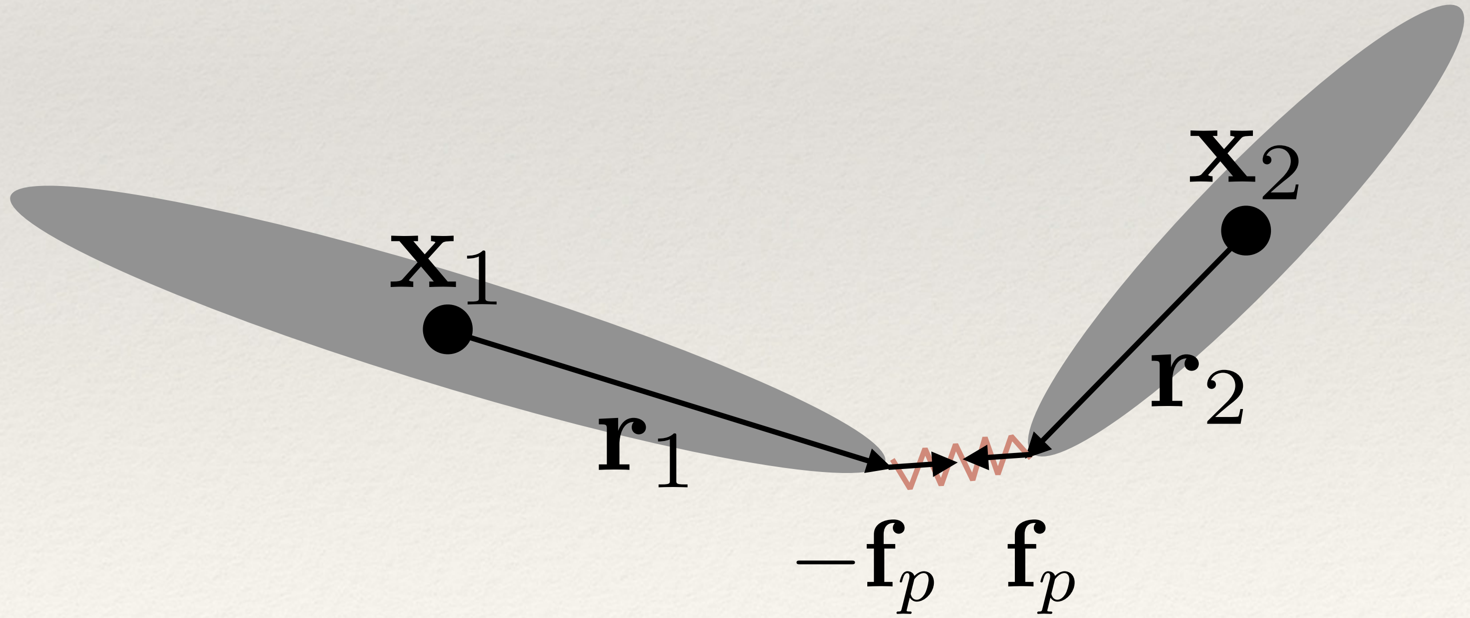
Penalty Methods

- Restoring force that acts to drive system to valid state

constraint: $$(\mathbf{x}_1 + \mathbf{r}_1) - (\mathbf{x}_2 + \mathbf{r}_2) = \mathbf{0}$$

penalty force: $$\mathbf{f}_p = -k((\mathbf{x}_2 + \mathbf{r}_2) - (\mathbf{x}_1 + \mathbf{r}_1))$$

$$m\mathbf{a} = \mathbf{f} + \mathbf{f}_p$$



Penalty Methods

- ✓ Simple to add to solver
- — Must tune parameters (k)
- — Introduce stiff forces -> smaller time step or implicit integration
- — Constraint violation, oscillations

Lagrange Multiplier Methods

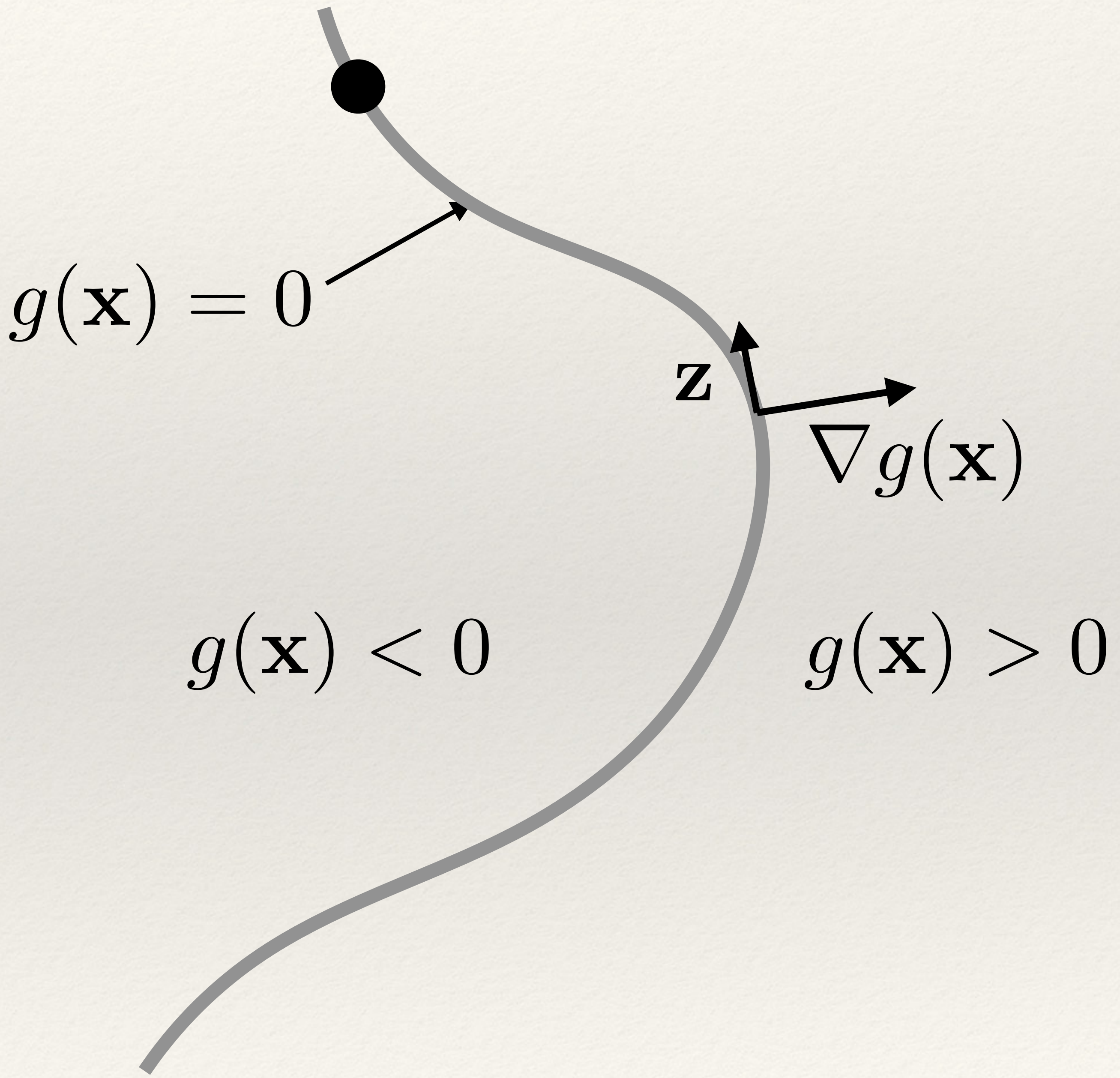
- Constraint force arises in response to other forces in the system
- Add unknowns to equations that represent strength of constraint force
- Add (differentiated) constraint equations

Constraint Implicit Surface

$$\mathbf{x} = (x_1, x_2, \ldots, x_n)$$

- Gradient

$$\nabla g(\mathbf{x}) = \begin{pmatrix} \frac{\partial g}{\partial x_1}(\mathbf{x}) \\ \frac{\partial g}{\partial x_2}(\mathbf{x}) \\ \vdots \\ \frac{\partial g}{\partial x_n}(\mathbf{x}) \end{pmatrix}$$



Constraint Force

- Constraint force

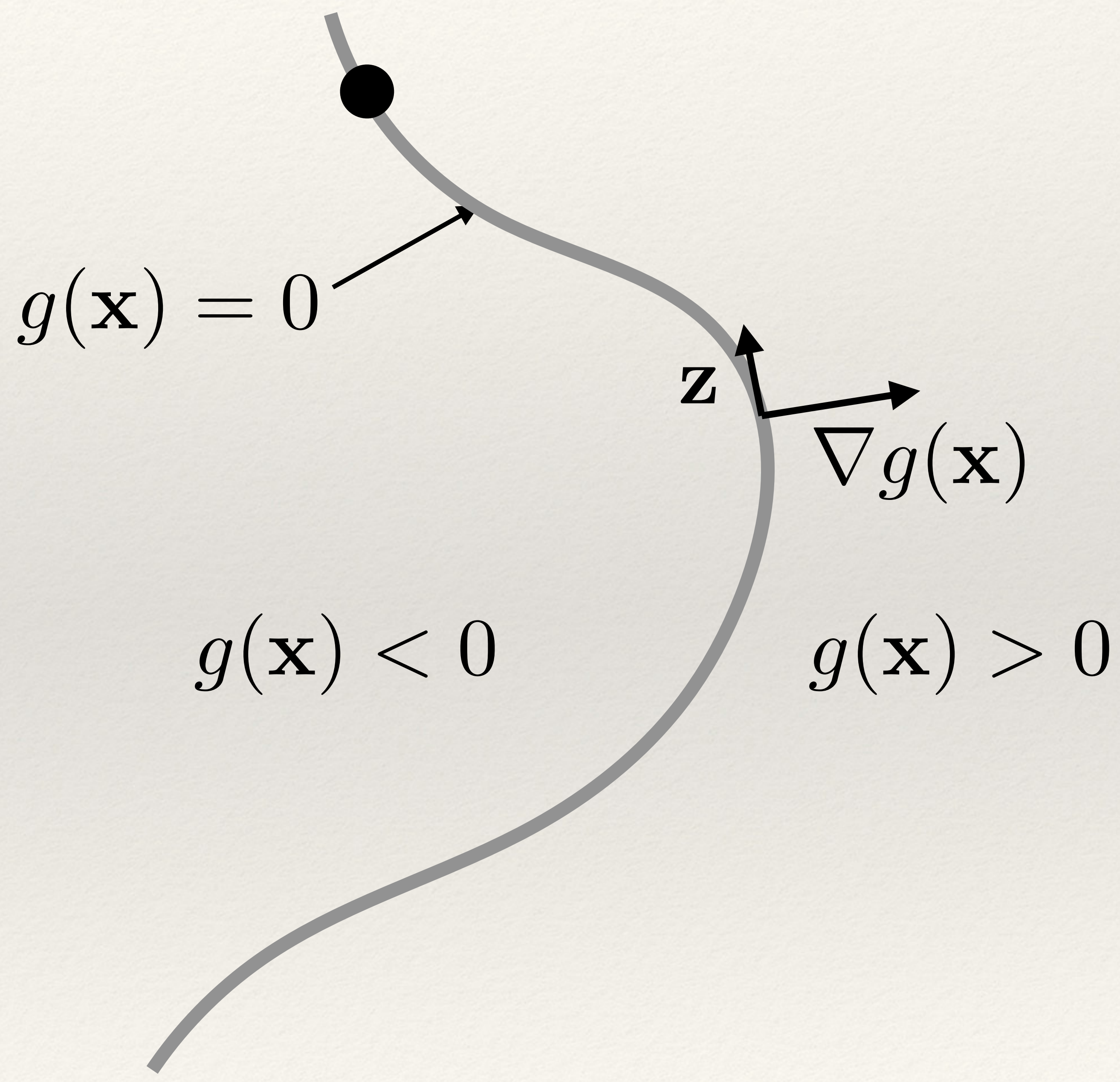
$$\mathbf{F}_c$$

- **Workless**

$$\mathbf{F}_c \cdot \delta \mathbf{x} = 0$$

$$\Rightarrow \mathbf{F}_c = \lambda \nabla g(\mathbf{x})$$

Lagrange multiplier



Equations of Motion

- m constraints

$$\mathbf{g}(\mathbf{x}) = \begin{pmatrix} g_1(\mathbf{x}) \\ g_2(\mathbf{x}) \\ \vdots \\ g_m(\mathbf{x}) \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix} = \mathbf{0}$$

- Constraint force

$$\mathbf{F}_c = J^T \lambda = \begin{pmatrix} \nabla g_1 & \nabla g_2 & \dots & \nabla g_m \end{pmatrix} \begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_m \end{pmatrix}$$

- Equations of motion

$$M\mathbf{a} = \mathbf{F} + \mathbf{F}_c = \mathbf{F} + J^T \lambda$$

How to find λ

- Constraint tells us valid positions

$$\mathbf{g}(\mathbf{x}) = \mathbf{0}$$

- Differentiate to get valid velocities

$$\dot{\mathbf{g}}(\mathbf{x}) = J(\mathbf{x})\mathbf{v} = \mathbf{0}$$

- Differentiate again to get valid accelerations

$$\ddot{\mathbf{g}}(\mathbf{x}) = \dot{J}\mathbf{v} + J\mathbf{a} = \mathbf{0}$$

How to find λ

- Equations of motion

$$M\mathbf{a} = \mathbf{F} + \mathbf{F}_c = \mathbf{F} + J^T\lambda$$

$$\mathbf{a} = M^{-1}(\mathbf{F} + J^T\lambda)$$

How to find λ

- Equations of motion

$$M\mathbf{a} = \mathbf{F} + \mathbf{F}_c = \mathbf{F} + J^T\lambda$$

$$\mathbf{a} = M^{-1}(\mathbf{F} + J^T\lambda)$$

- Plug into expression for valid **a**

$$\ddot{\mathbf{g}}(\mathbf{x}) = \dot{J}\mathbf{v} + J\mathbf{a} = \mathbf{0}$$

How to find λ

- Equations of motion

$$M\mathbf{a} = \mathbf{F} + \mathbf{F}_c = \mathbf{F} + J^T\lambda$$

$$\mathbf{a} = M^{-1}(\mathbf{F} + J^T\lambda)$$

- Plug into expression for valid **a**

$$\ddot{\mathbf{g}}(\mathbf{x}) = \dot{J}\mathbf{v} + J\mathbf{a} = \mathbf{0}$$

- Rearrange

$$(JM^{-1}J^T)\lambda = -JM^{-1}\mathbf{F} - \dot{J}\mathbf{v}$$

How to find λ

- Rearrange

$$(JM^{-1}J^T)\lambda = \underbrace{-JM^{-1}\mathbf{F} - \dot{J}\mathbf{v}}_{\mathbf{b}}$$

- KKT System

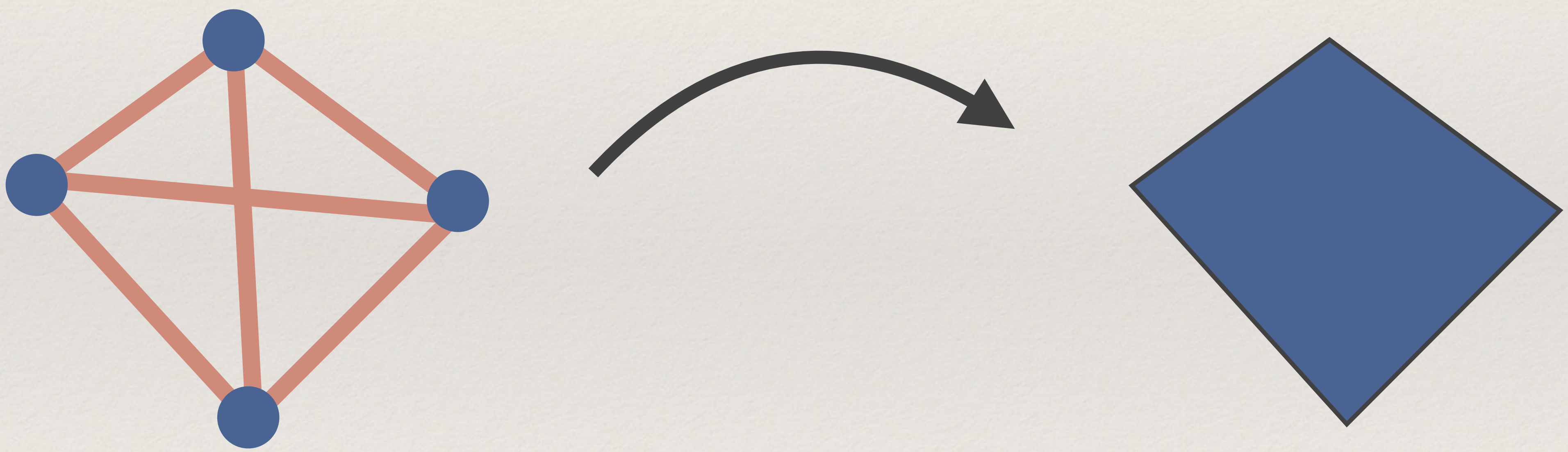
$$\begin{pmatrix} M & -J^T \\ -J & 0 \end{pmatrix} \begin{pmatrix} \mathbf{y} \\ \lambda \end{pmatrix} = \begin{pmatrix} \mathbf{0} \\ -\mathbf{b} \end{pmatrix}$$

Generalized Coordinates

- Instead of maximal coordinates $x_1, x_2, \ldots, x_n$ along with auxiliary conditions and forces
- Generalized coordinates $q_1, q_2, \ldots, q_N$ with $N < n$ that take constraints into account

Generalized Coordinates

- Example: rigid body



$\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, \mathbf{x}_4$

+ constraints

$\mathbf{x}, R$

Transformation Equations

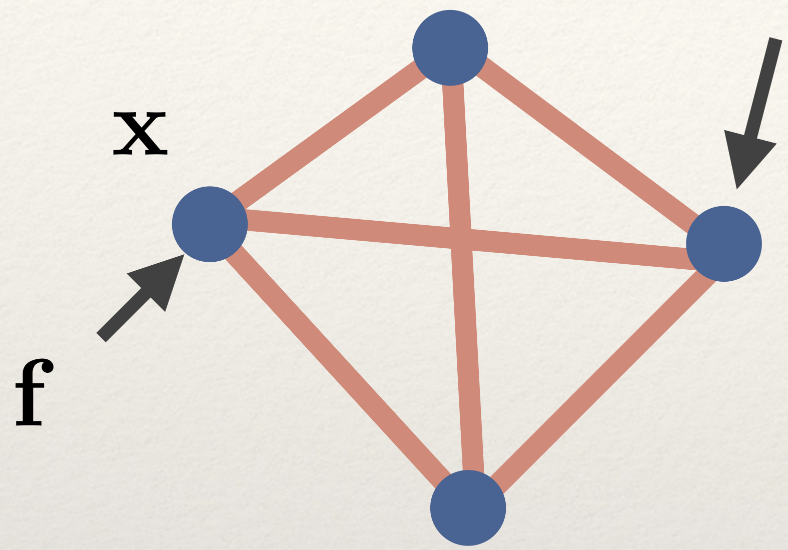
- Relate maximal and generalized coordinates

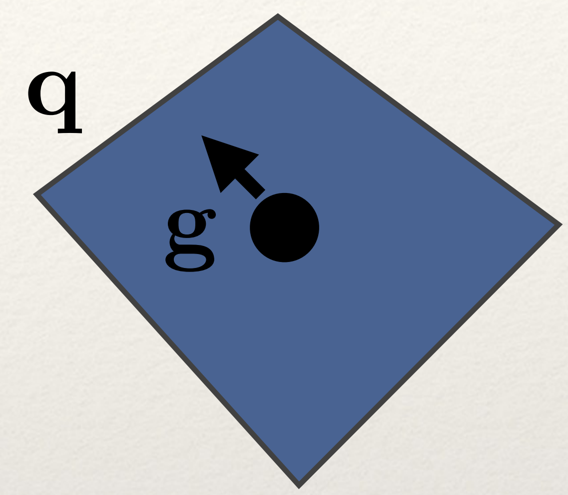
$$
\begin{aligned}
x_1 &= x_1(q_1, q_2, \ldots, q_N) \\
x_2 &= x_2(q_1, q_2, \ldots, q_N) \\
&\vdots \\
x_n &= x_n(q_1, q_2, \ldots, q_N)
\end{aligned}
\qquad \mathbf{x} = \mathbf{x}(\mathbf{q})
$$

- Jacobian

$$J(\mathbf{q}) = \frac{\partial \mathbf{x}}{\partial \mathbf{q}}$$

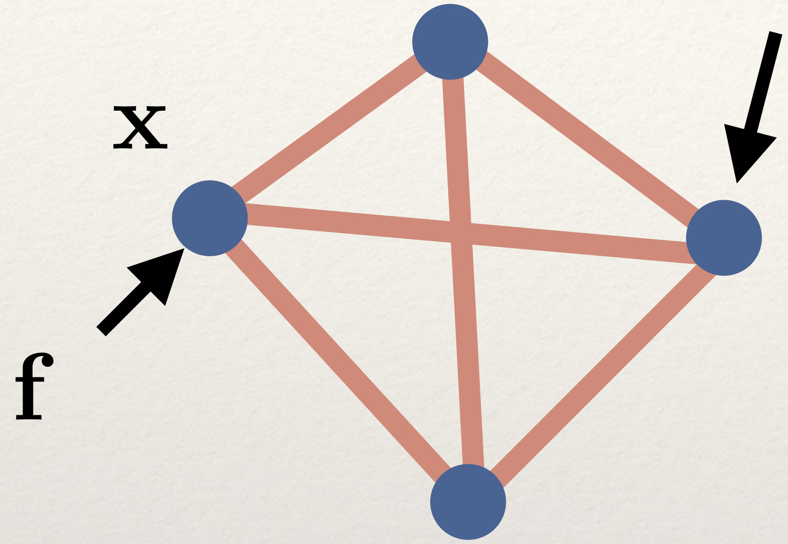
Generalized Forces

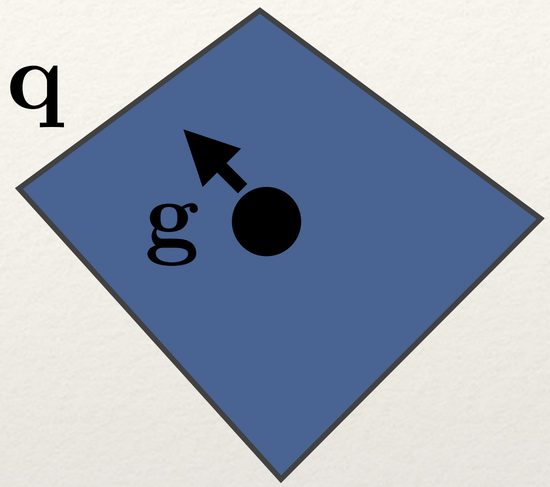




$$\begin{matrix} x_1 & f_1 \\ \vdots & \vdots \\ x_n & f_n \end{matrix} \qquad \begin{matrix} q_1 & g_1 \\ \vdots & \vdots \; ? \\ q_N & g_N \end{matrix}$$

Generalized Forces





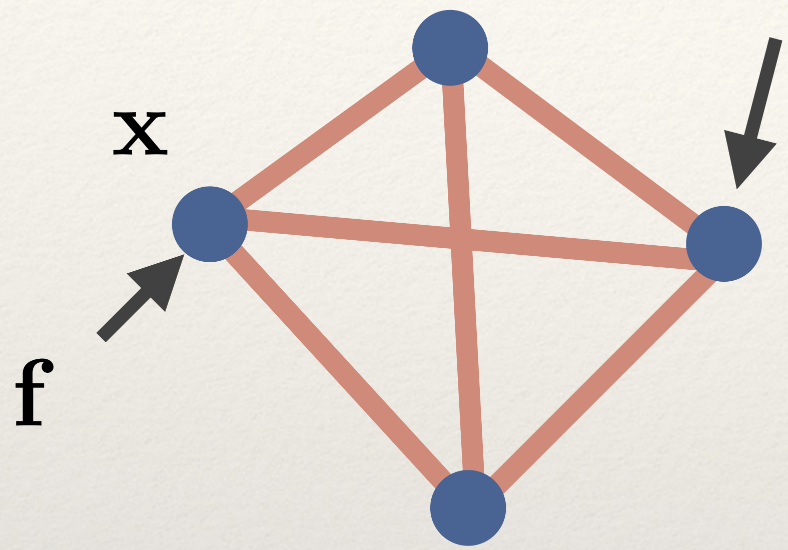
- Two sets of forces are dynamically equivalent if they do the same "virtual work"

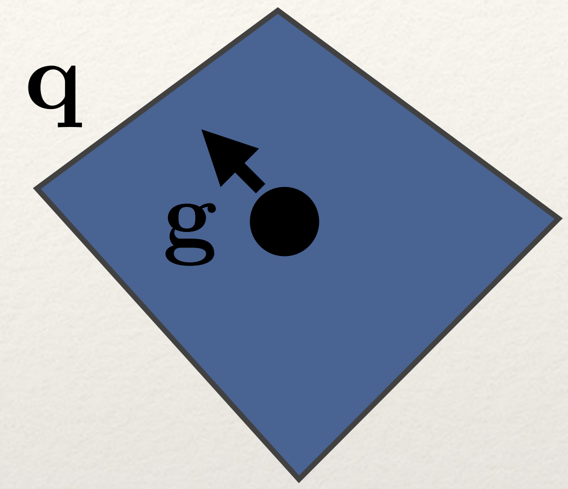
$$\mathbf{f} \cdot \delta\mathbf{x} = \mathbf{g} \cdot \delta\mathbf{q}$$

$$\mathbf{f} \cdot J\delta\mathbf{q} = \mathbf{g} \cdot \delta\mathbf{q}$$

$$\mathbf{g} = J^T\mathbf{f}$$

Generalized Forces: Rigid Body





Jacobian $$\dot{\mathbf{x}} = \mathbf{v} + \omega \times \mathbf{r} = \underbrace{\begin{pmatrix} I & \mathbf{r}^{\star T} \end{pmatrix}}_{J} \begin{pmatrix} \mathbf{v} \\ \omega \end{pmatrix}$$

generalized force $$\mathbf{g} = J^T \mathbf{f} = \begin{pmatrix} I \\ \mathbf{r}^{*} \end{pmatrix} \mathbf{f} = \begin{pmatrix} \mathbf{f} \\ \mathbf{r} \times \mathbf{f} \end{pmatrix}$$

Equations of Motion

- Lagrange equations of motion

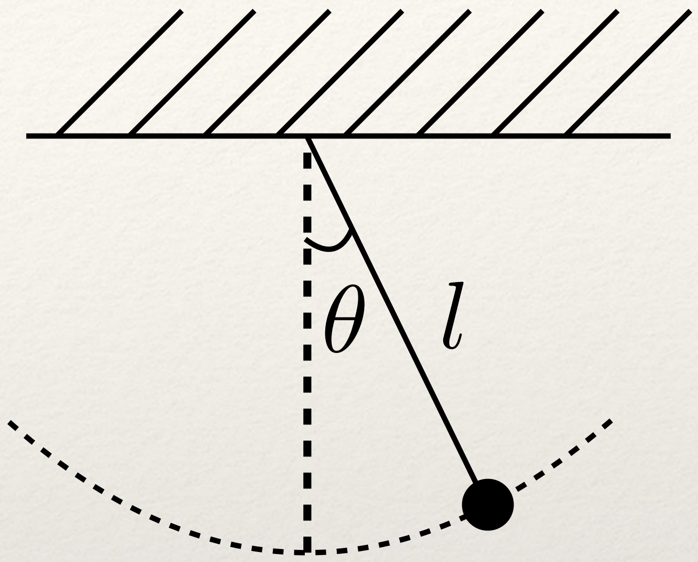
$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\mathbf{q}}}\right) = \mathbf{g} \qquad \left(\frac{d}{dt}(m\mathbf{v}) = \mathbf{f}\right)$$

$$T = \frac{1}{2}\dot{\mathbf{x}}^T M \dot{\mathbf{x}} = \frac{1}{2}(J\dot{\mathbf{q}})^T M J\dot{\mathbf{q}} = \frac{1}{2}\dot{\mathbf{q}}^T J^T M J \dot{\mathbf{q}}$$

- Euler-Lagrange equations of motion, defining Lagrangian $L = T - V$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\mathbf{q}}}\right) - \frac{\partial L}{\partial \mathbf{q}} = \mathbf{0}$$

Example: Pendulum



- Transformation equations

$$x(\theta) = l\sin\theta$$
$$y(\theta) = -l\cos\theta$$

- Velocity

$$\begin{pmatrix}\dot{x}(\theta)\\ \dot{y}(\theta)\end{pmatrix} = \begin{pmatrix} l\cos\theta\dot{\theta}\\ l\sin\theta\dot{\theta}\end{pmatrix} = J\dot{\theta}$$

- Lagrangian

$$L = \frac{1}{2}ml^2\dot{\theta}^2 - mgl\cos\theta$$

- Equations of motion

$$\ddot{\theta} + \frac{g}{l}\sin\theta = 0$$

Constrained Rigid Body Systems

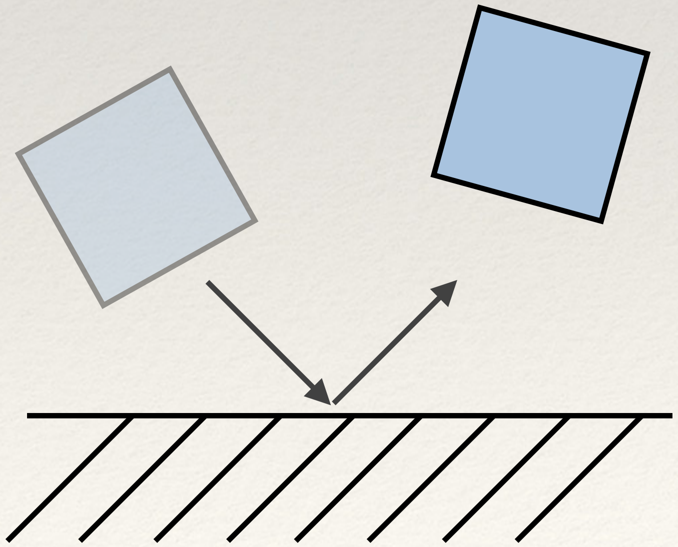
- Types of constraints
  - Articulation (joints)
  - Collisions
  - Resting and sliding contact

Impulse-Momentum Equations

- Acceleration-level formulation doesn't work well with discontinuous velocities, frictional contact
- Instead, integrate f = ma to get **impulse-momentum** formulation

$$\int_{t_1}^{t_2} m\mathbf{a}\, dt = \int_{t_1}^{t_2} \mathbf{f}\, dt,$$

$$\Rightarrow m(\mathbf{v}(t_2) - \mathbf{v}(t_1)) = \mathbf{j}$$



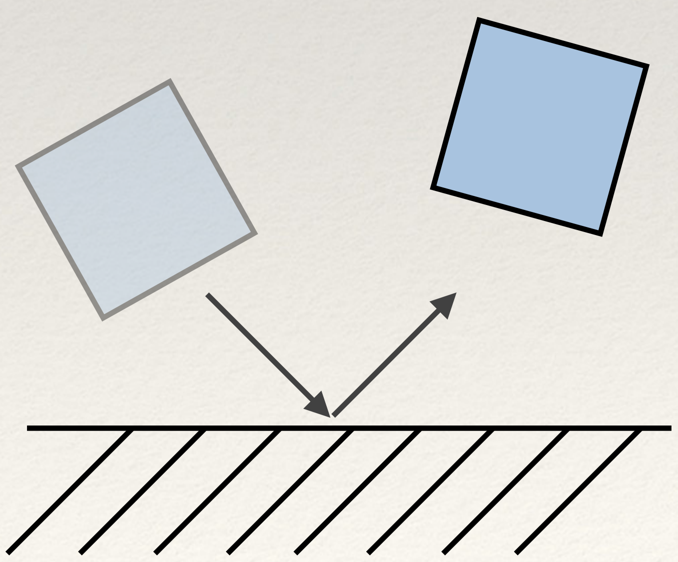
Impulse-Momentum Equations

- Integrated, semi-discrete equations

$$M\mathbf{V}^{n+1} = M\mathbf{V}^n + \Delta t\mathbf{F} + J^T\lambda^{n+1}$$

- Combine with velocity-level constraint equation $J\mathbf{V} = \mathbf{0}$

$$\begin{pmatrix} M & -J^T \\ -J & 0 \end{pmatrix} \begin{pmatrix} \mathbf{V}^{n+1} \\ \mu^{n+1} \end{pmatrix} = \begin{pmatrix} M\mathbf{V}^n + \Delta t\mathbf{F} \\ \mathbf{0} \end{pmatrix}$$



$$\Rightarrow JM^{-1}J^T\mu^{n+1} = -J\mathbf{V}^n - \Delta t JM^{-1}\mathbf{F}$$

Impulse-Momentum Equations

- Instead of solving global, coupled system, common to split

update with non-constraint forces

$$M\mathbf{V}^{\star} = M\mathbf{V}^{n} + \Delta t\mathbf{F}$$

add constraint impulses

$$M\mathbf{V}^{n+1} = M\mathbf{V}^{\star} + J^{T}\mu^{n+1}$$

Impulse-Momentum Equations

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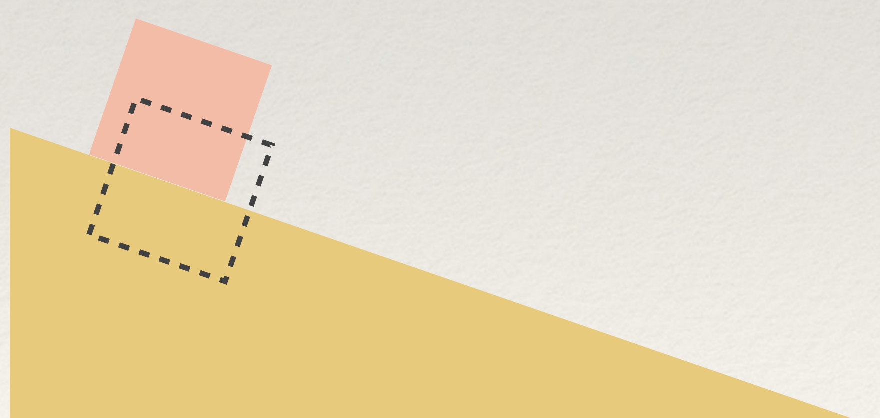

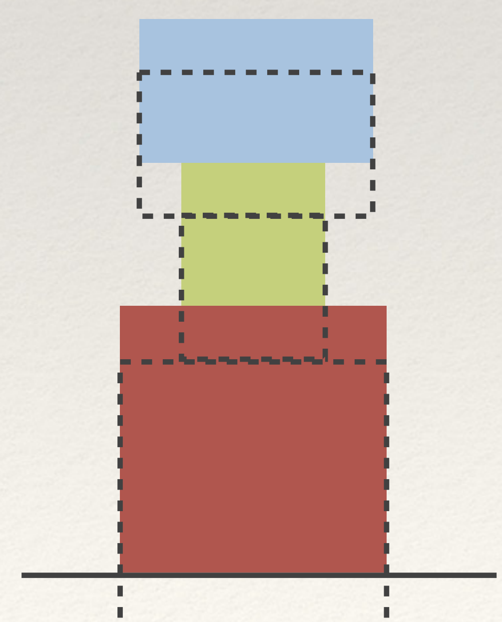

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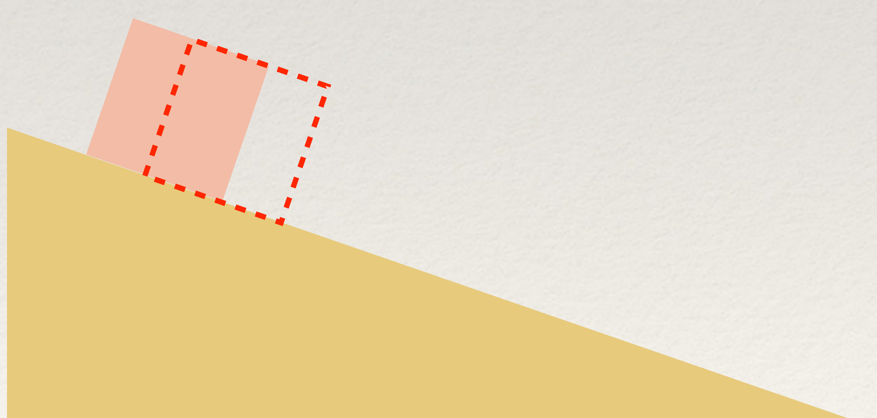

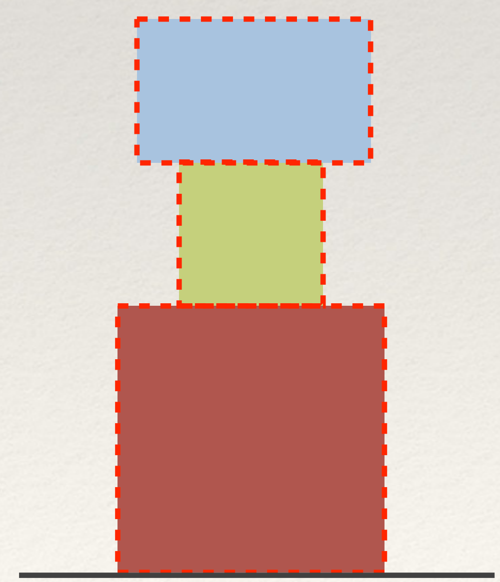

global impulse solve

Impulse-Momentum Equations

- Instead of solving global, coupled system, common to split

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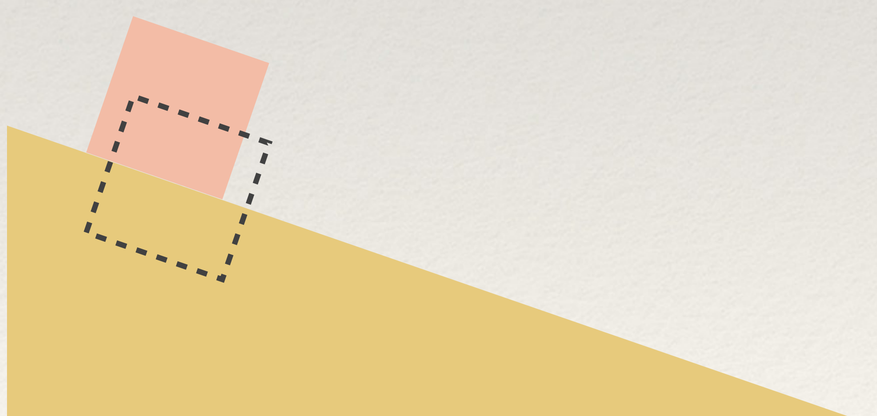

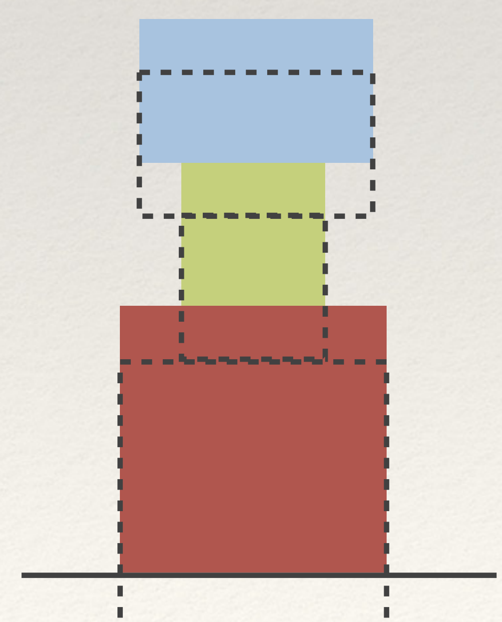

iterative impulse solve

Impulse-Momentum Equations

- Instead of solving global, coupled system, common to split

update with non-constraint forces

$$M\mathbf{V}^{\star} = M\mathbf{V}^{n} + \Delta t\mathbf{F}$$

add constraint impulses

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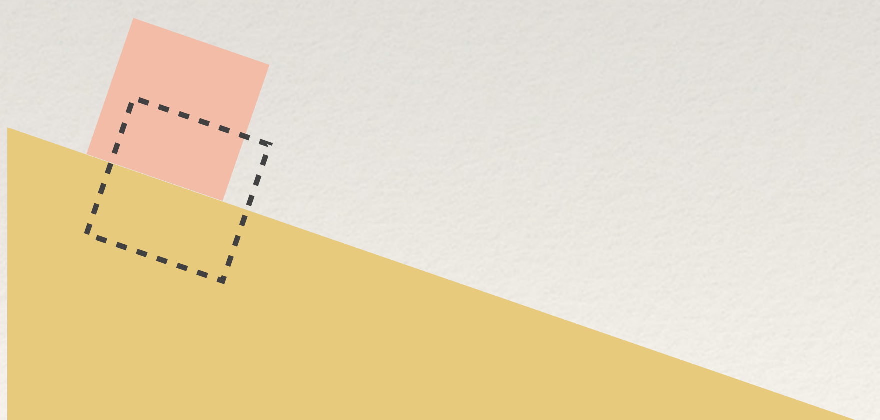

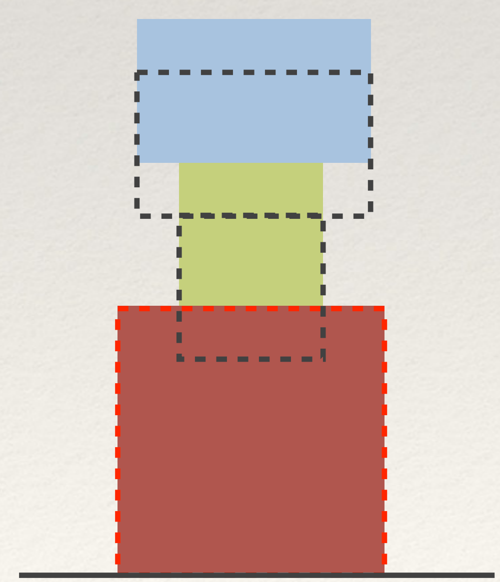

iterative impulse solve

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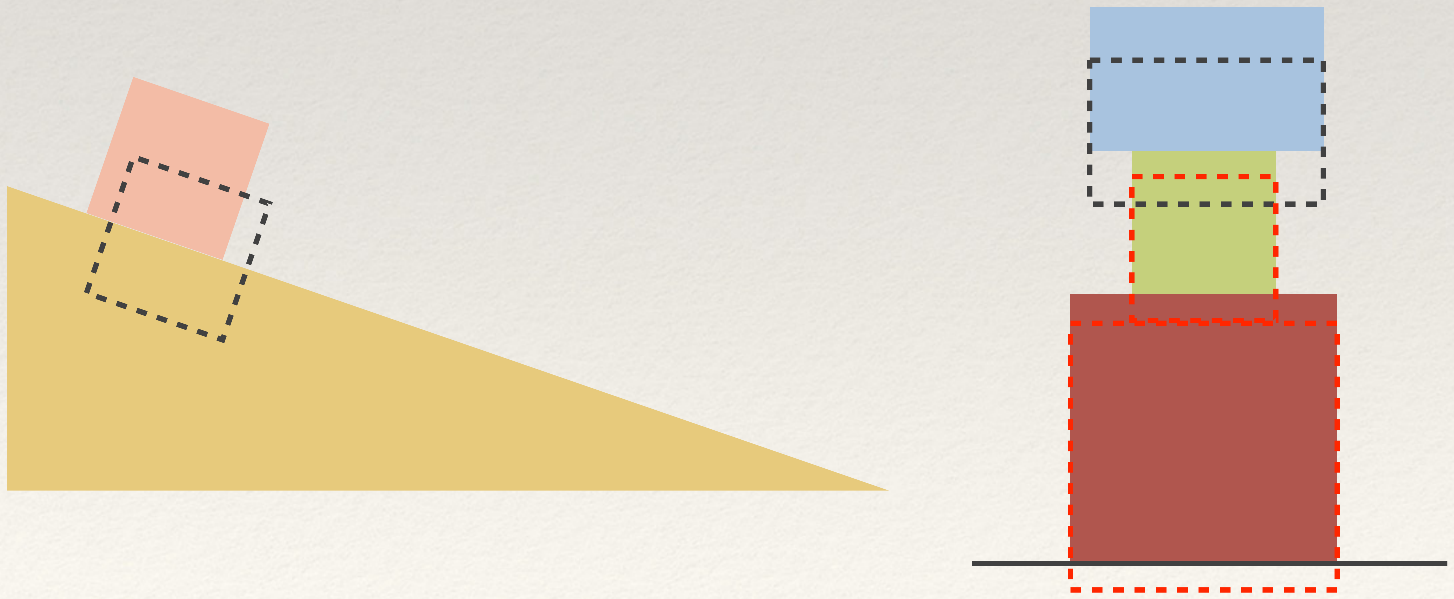

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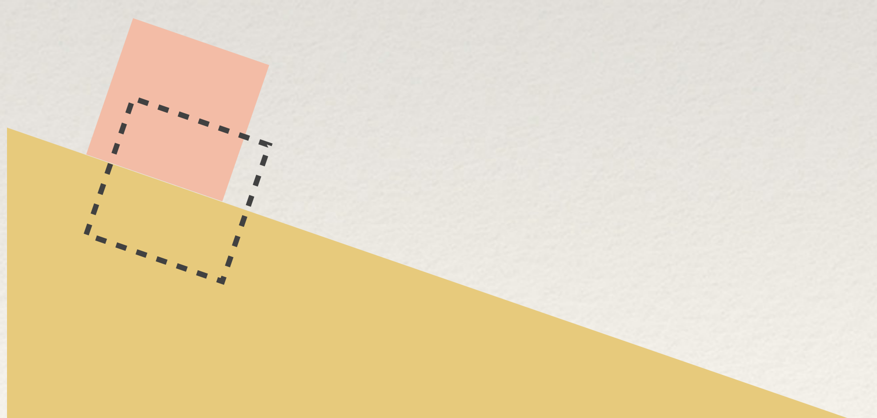

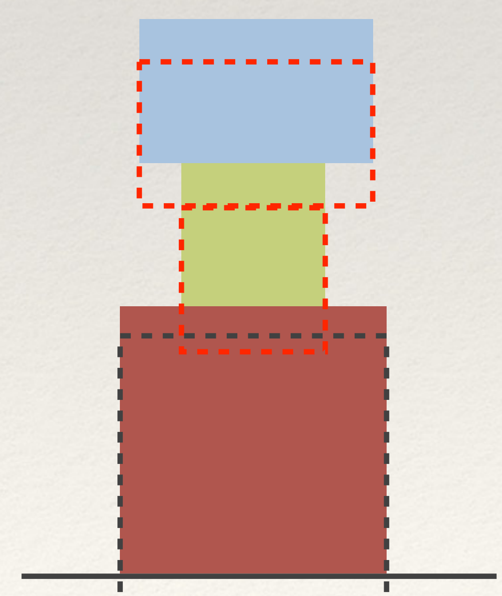

iterative impulse solve

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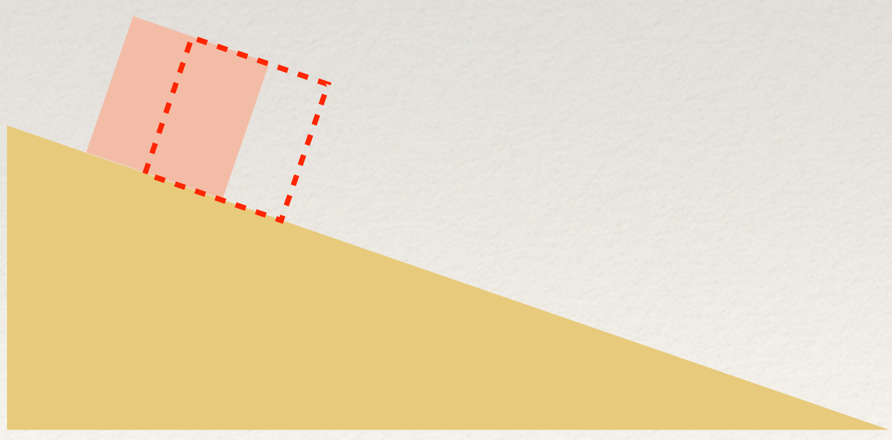

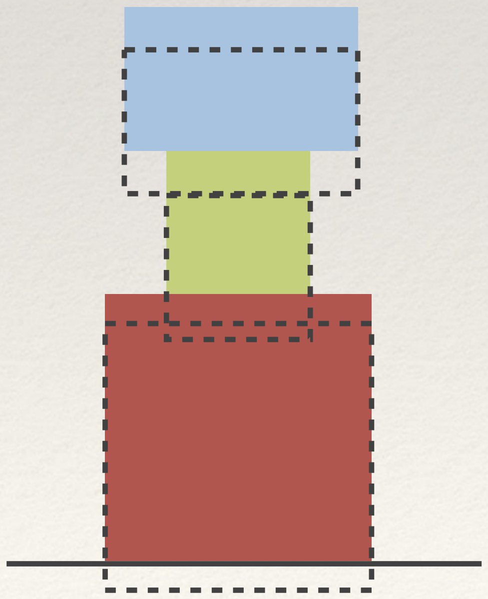

iterative impulse solve

Impulse-Momentum Equations

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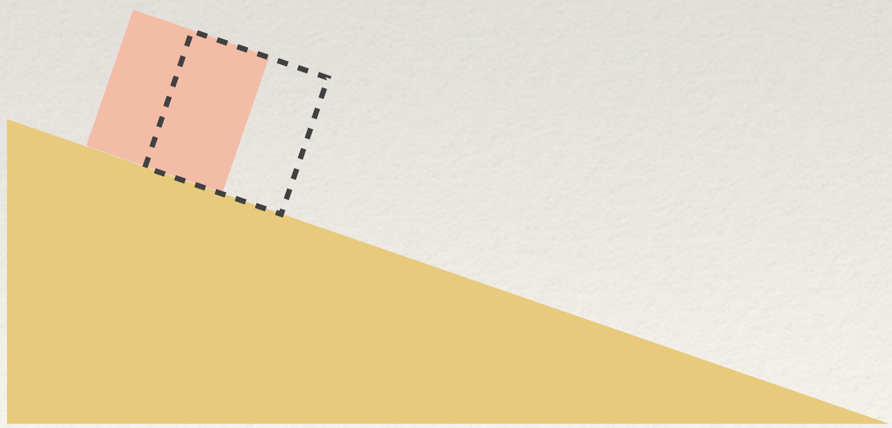

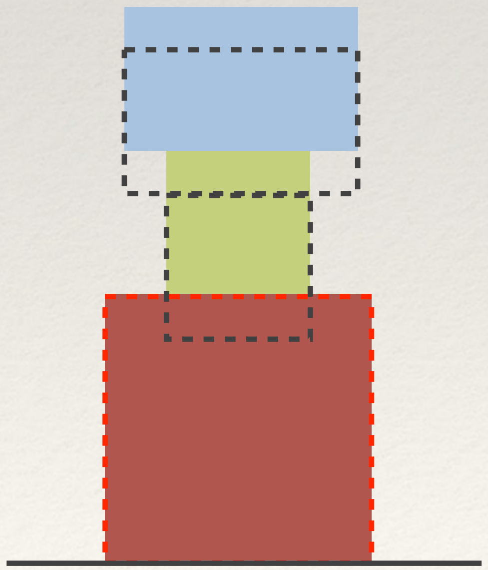

iterative impulse solve

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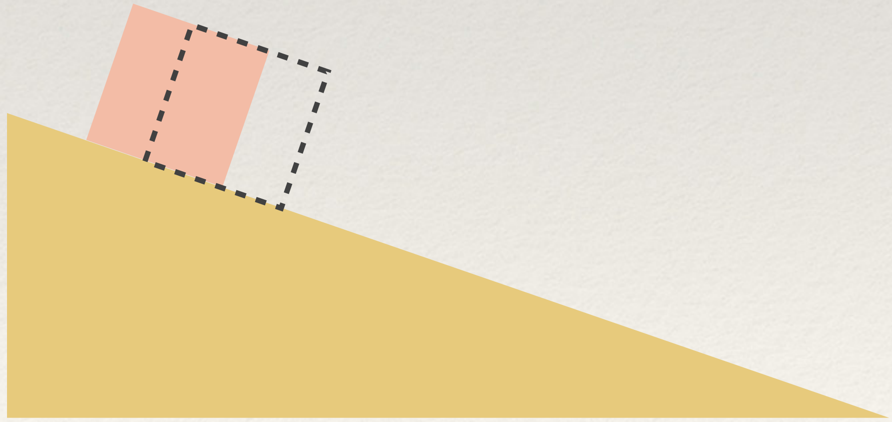

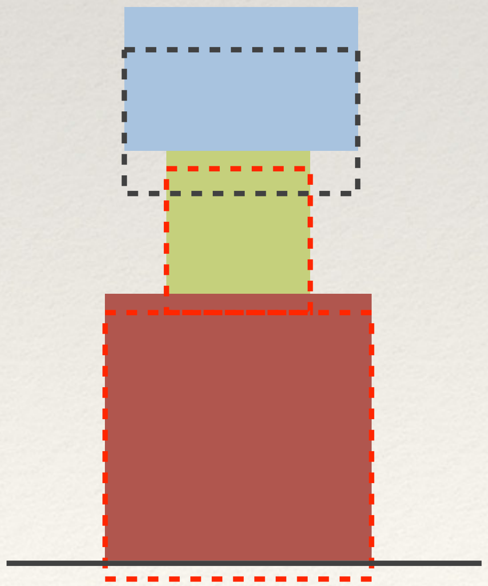

iterative impulse solve

Impulse-Momentum Equations

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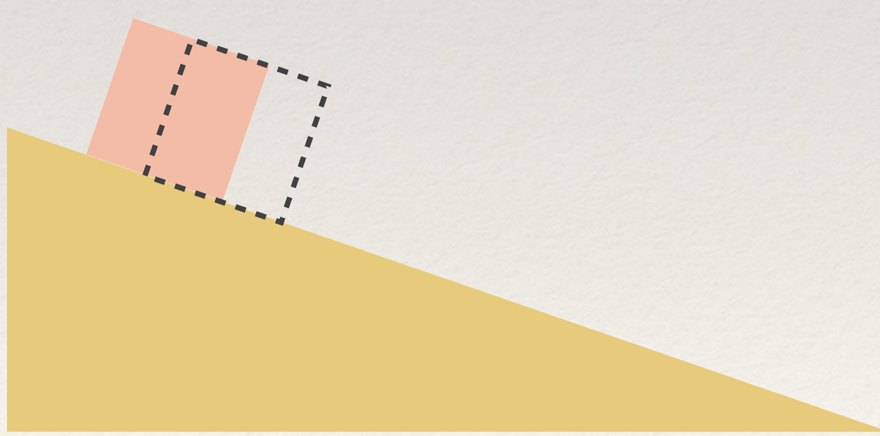

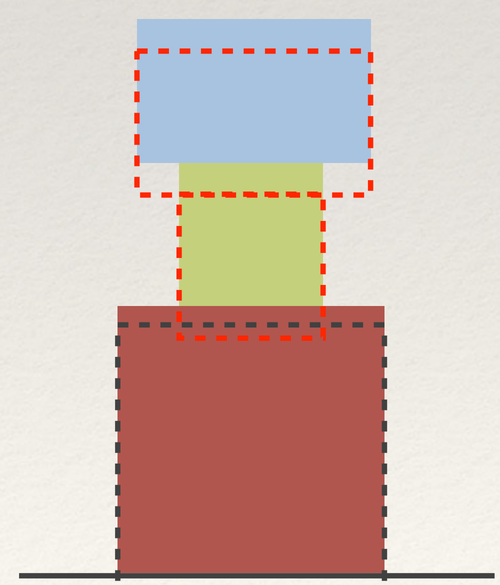

iterative impulse solve

Impulse-Momentum Equations

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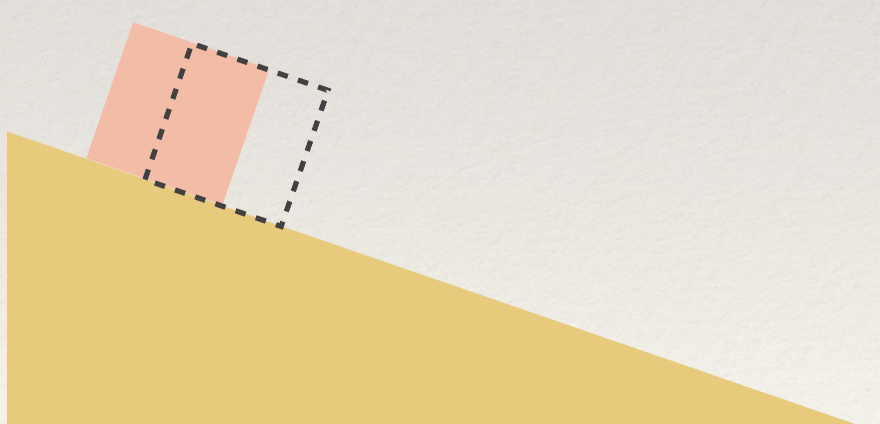
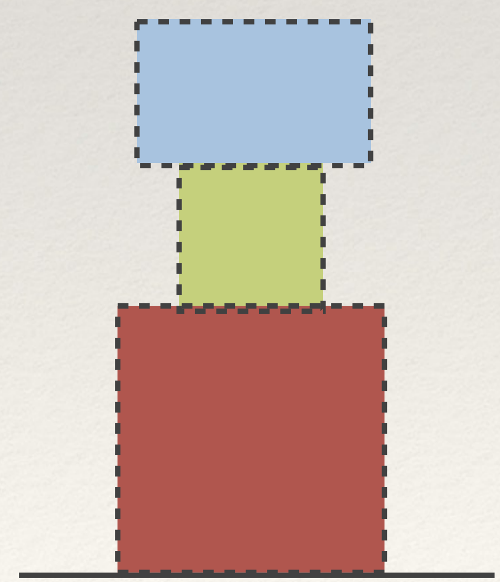


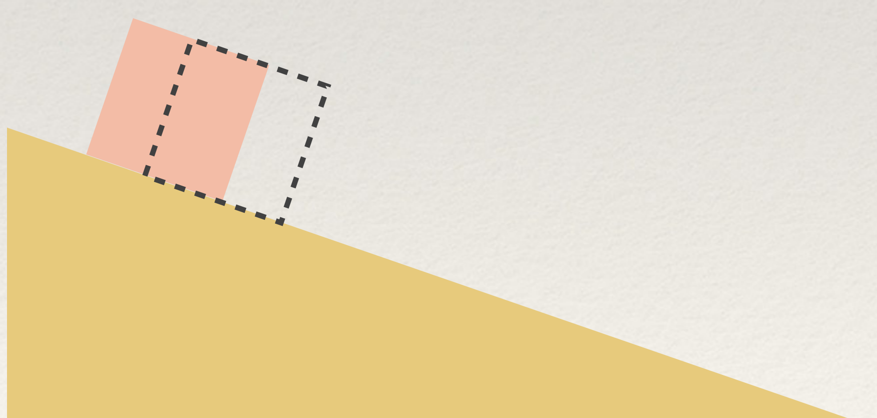


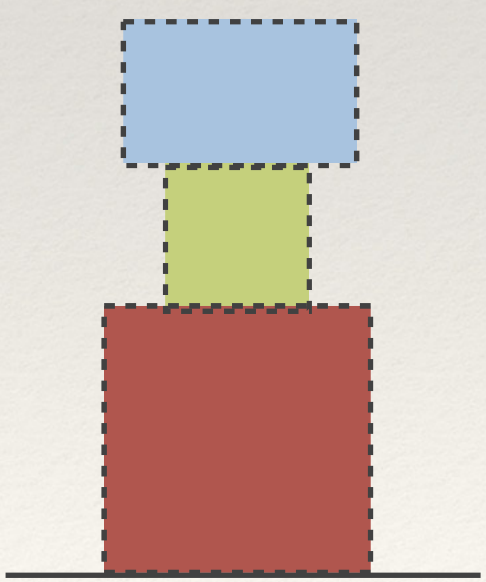
iterative impulse solve

repeat fixed number of times or until tolerance met

Global vs. Iterative Solve

- Global
  - need to solve larger linear system
  - LCP for inequality constraints
- Iterative
  - may be slow to converge
  - simple to do inequality constraints





Handling Drift With Stabilization

- Approach was based on velocity-level constraints lead to drift in positions

$$\begin{pmatrix} M & -J^T \\ -J & 0 \end{pmatrix} \begin{pmatrix} \mathbf{V}^{n+1} \\ \mu^{n+1} \end{pmatrix} = \begin{pmatrix} M\mathbf{V}^n + \Delta t \mathbf{F} \\ \mathbf{0} \end{pmatrix}$$

- Correct drift with stabilization
  - E.g., Baumgarte stabilization $\dot{\mathbf{g}}(\mathbf{x}) + \gamma \mathbf{g}(\mathbf{x}) = 0$
  - Modify positions and velocities so they satisfy constraints

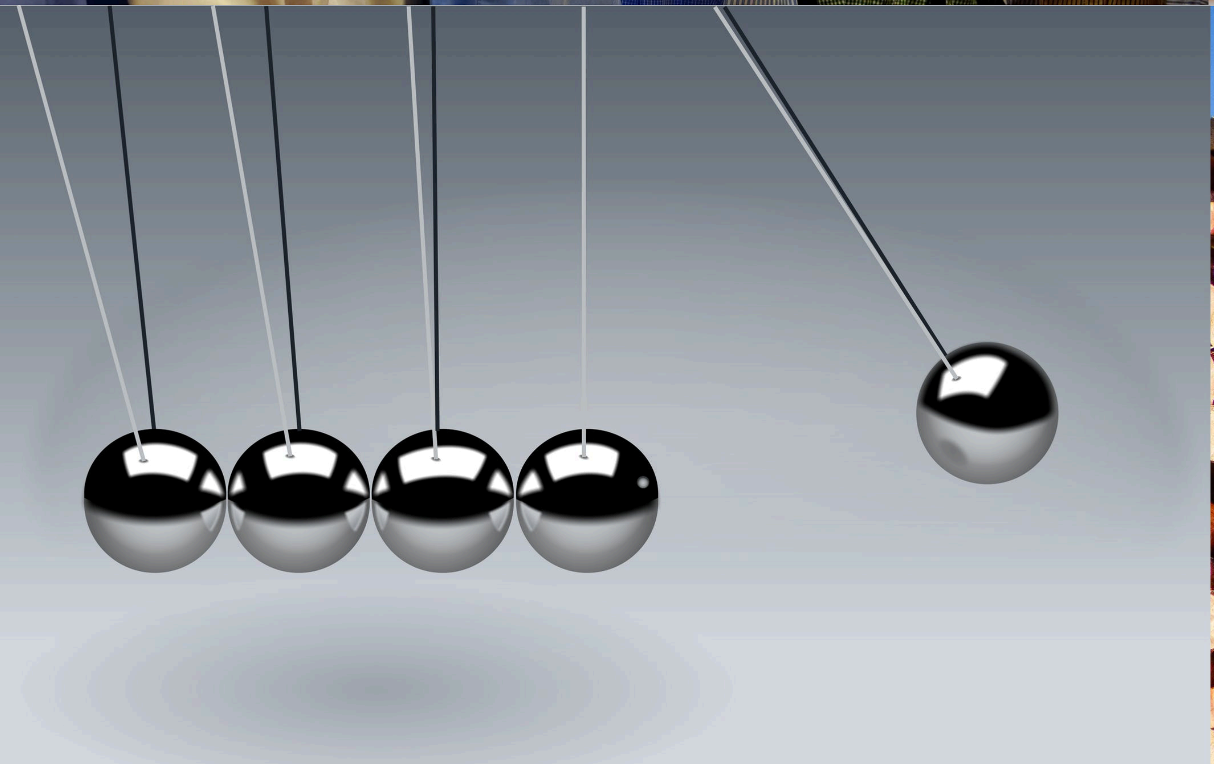
Softening Constraints

- Also common to soften constraints

$$\begin{pmatrix} M & -J^T \\ -J & \gamma I \end{pmatrix} \begin{pmatrix} \mathbf{V}^{n+1} \\ \mu^{n+1} \end{pmatrix} = \begin{pmatrix} M\mathbf{V}^n + \Delta t \mathbf{F} \\ -\frac{\beta}{\Delta t}\mathbf{g}(\mathbf{X}^n) \end{pmatrix}$$

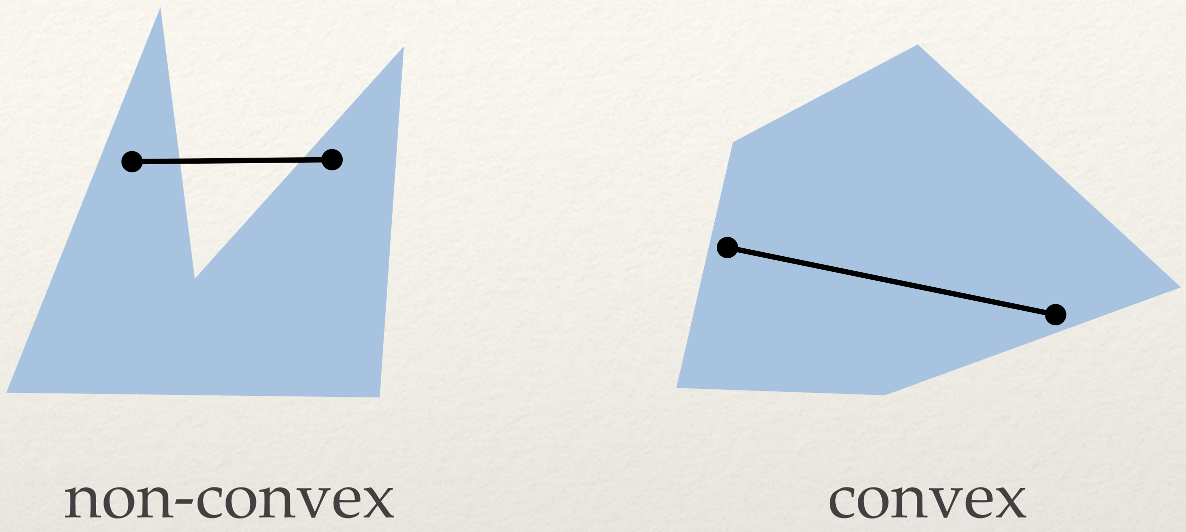
- Stabilizes constraints
- Regularizes system
  - Better numerical properties
  - Handle redundant constraints
- Adds some compliance to constraint

Collisions and Contact

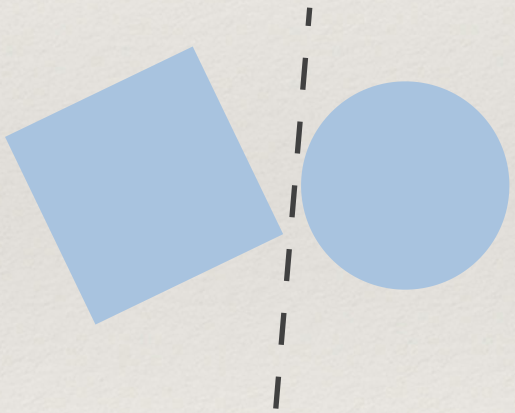


Collision Detection

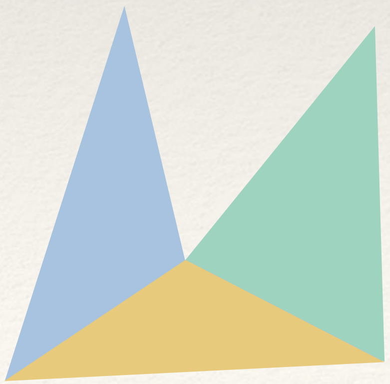
- Polygonal geometry



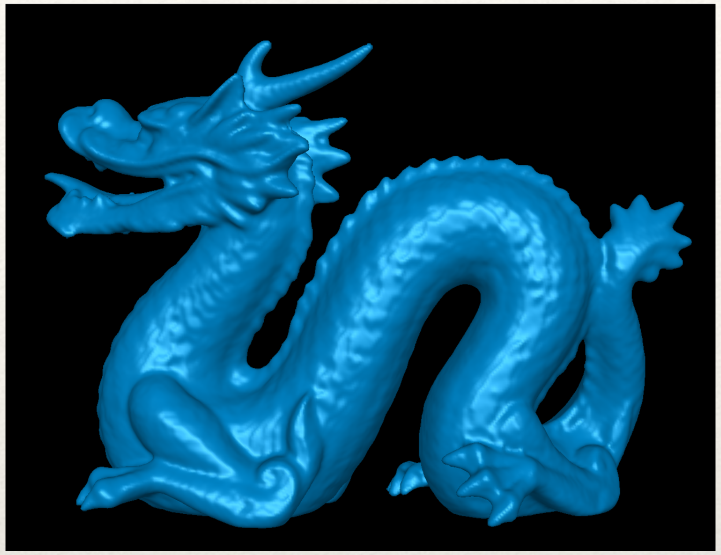
- Separating axis theorem



- Convex decomposition



Collision Detection



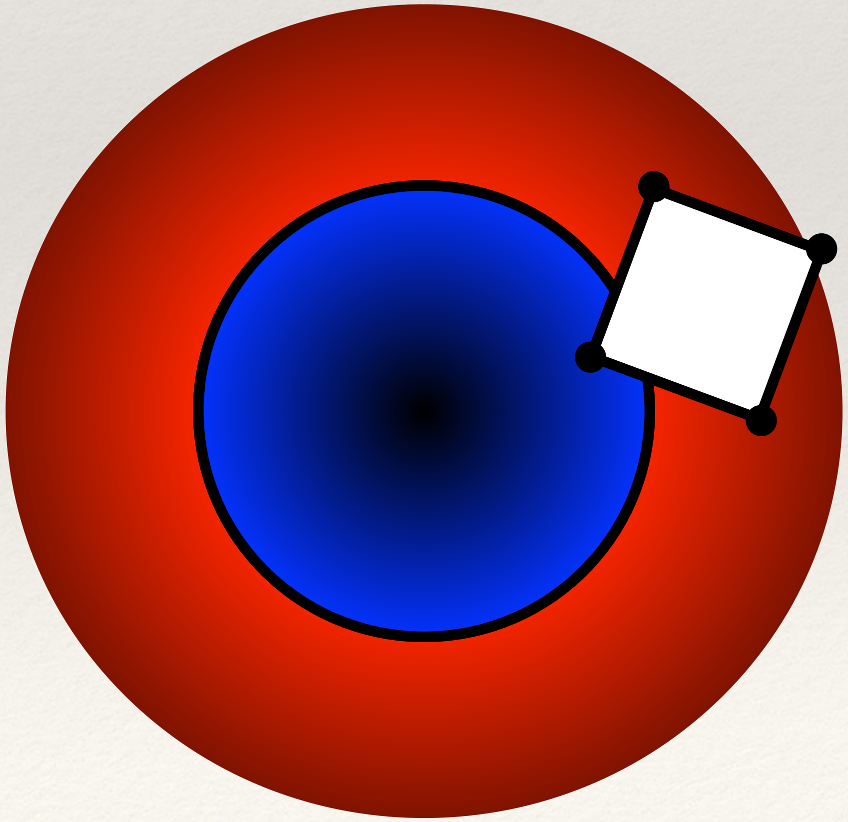
- Signed distance field

$$\phi(\mathbf{x})$$

- Zero level set

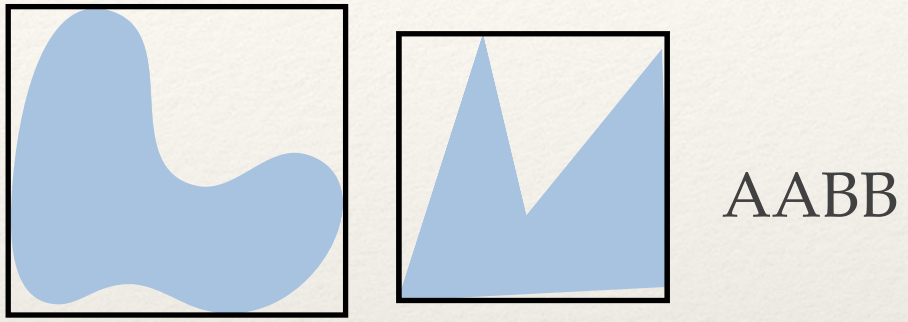
$$\phi(\mathbf{x}) = 0$$

- Fast inside/outside tests
- Penetration depth $\phi(\mathbf{x})$
- Normals $\nabla\phi(\mathbf{x})$

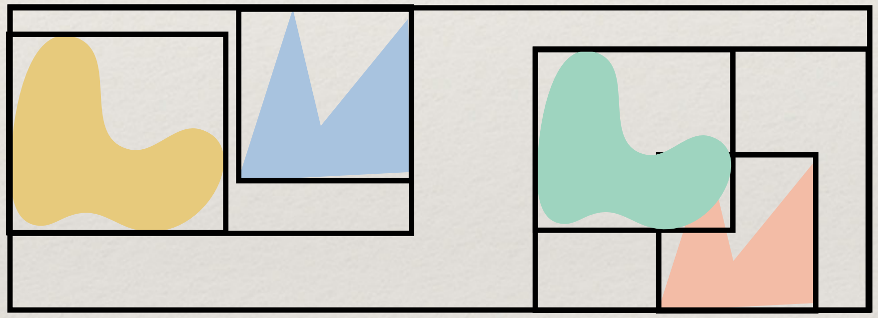


Accelerating Collision Detection

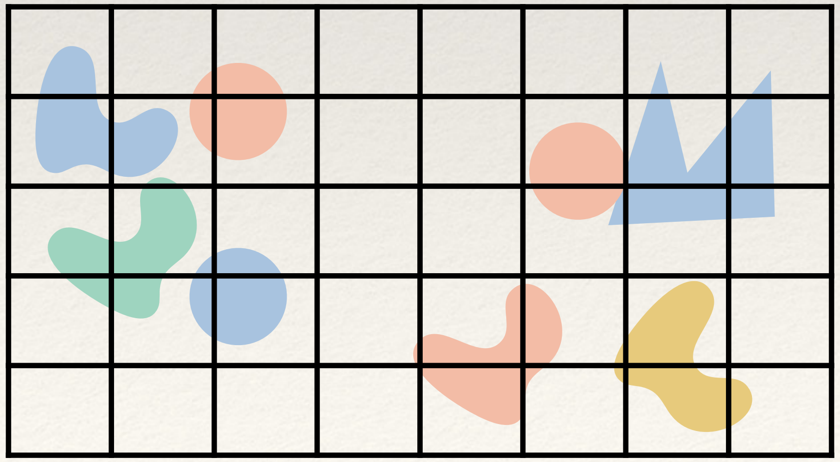
- Bounding volumes



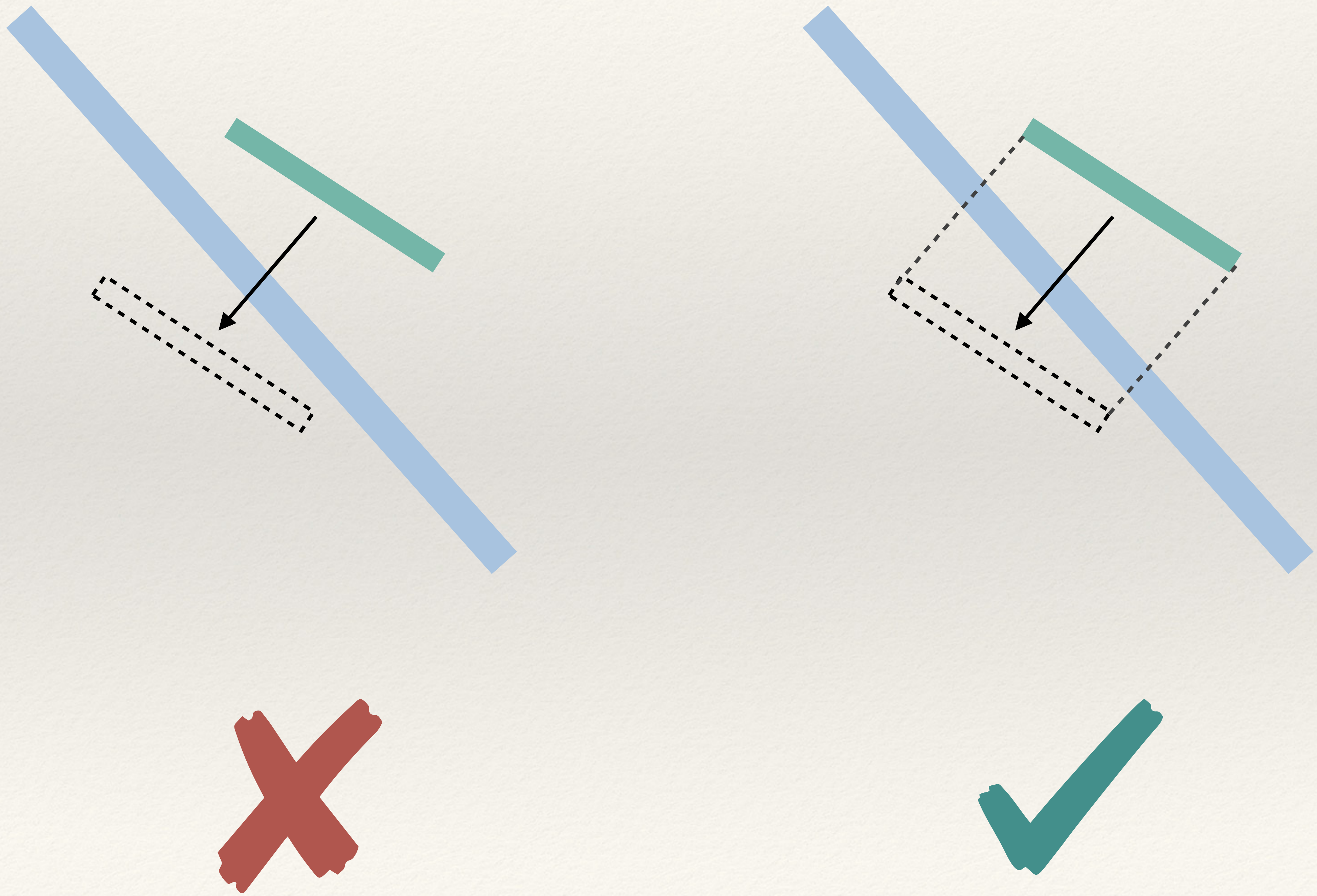
- Hierarchical bounding volumes



- Spatial partitions



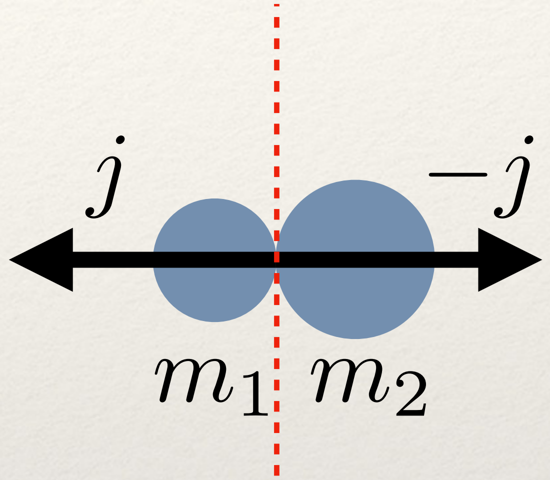
Discrete vs. Continuous Collision Detection



Collision Response: Inelastic

- Newton's third law (action/reaction)

$$m_1 v_1' = m_1 v_1 + j$$
$$m_2 v_2' = m_2 v_2 - j$$



- Assume inelastic (sticking)

$$v_1' = v_2'$$

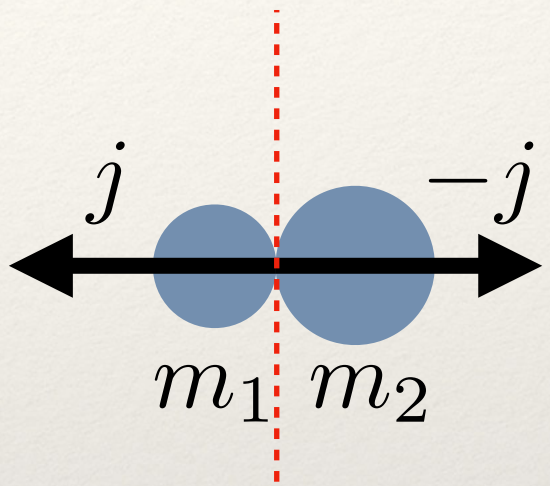
- Solve: $j = \left(\frac{1}{m_1} + \frac{1}{m_2}\right)^{-1} (v_2 - v_1)$

$$v_1' = v_2' = \left(\frac{m_1}{m_1 + m_2}\right) v_1 + \left(\frac{m_2}{m_1 + m_2}\right) v_2$$

Collision Response: Elastic

- Newton's third law (action/reaction)

$$m_1 v_1' = m_1 v_1 + j$$
$$m_2 v_2' = m_2 v_2 - j$$



- Assume elastic (bouncing)

$$(v_2' - v_1') = -\epsilon(v_2 - v_1)$$

coefficient of restitution

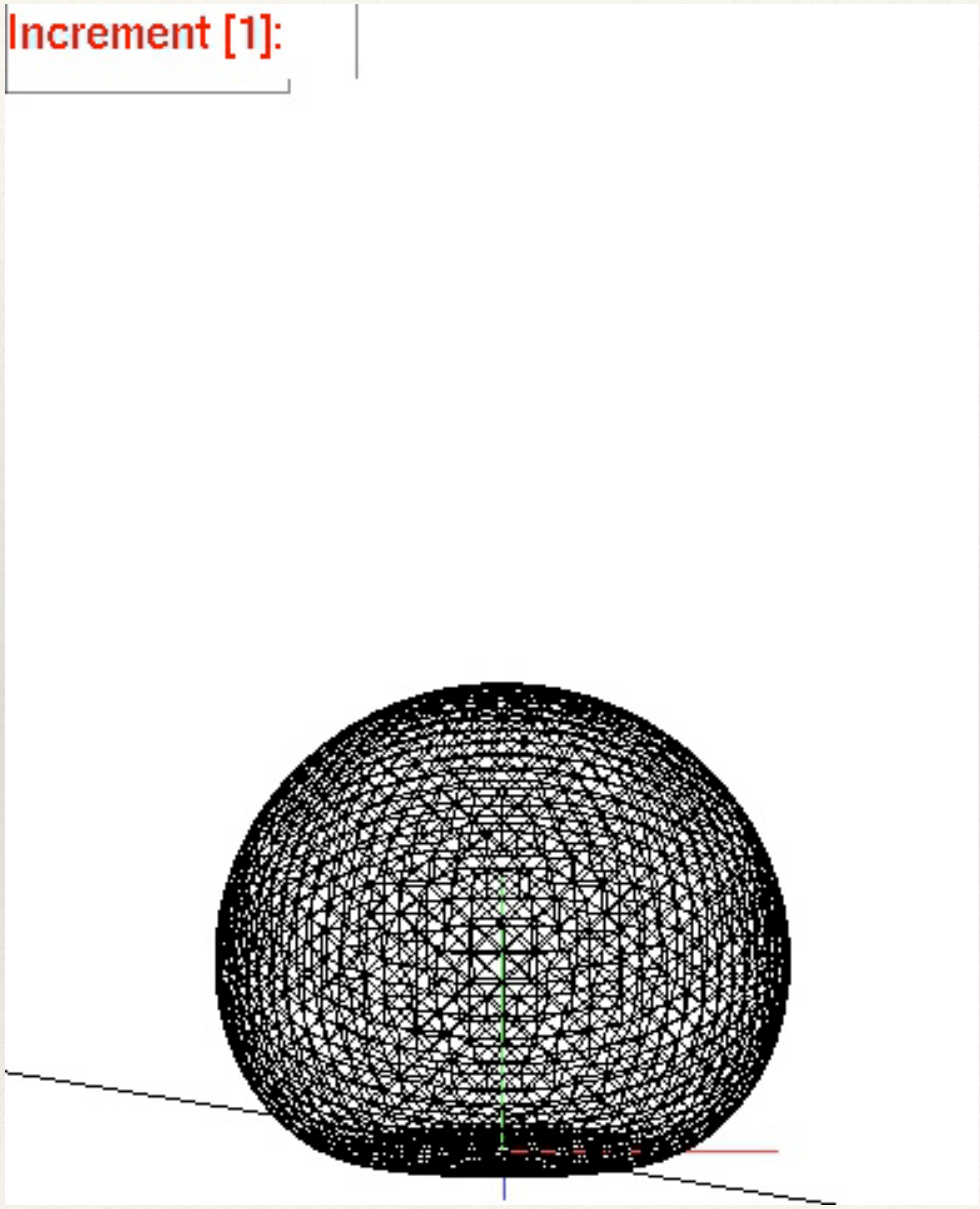
- Solve: $j = \left(\frac{1}{m_1} + \frac{1}{m_2}\right)^{-1} (1+\epsilon)(v_2 - v_1)$

$$v_1' = v_1 + \frac{1}{m_1} j, \quad v_2' = v_2 - \frac{1}{m_2} j$$

Deformable Object Collisions

- Body compresses, stores energy and bounces
- Inelastic collision between particles and ground

$$m_1\mathbf{v}_1' = m_1\mathbf{v}_1 + \mathbf{j}$$
$$m_2\mathbf{v}_2' = m_2\mathbf{v}_2 - \mathbf{j}$$
$$\mathbf{v}_2' = \mathbf{v}_1'$$



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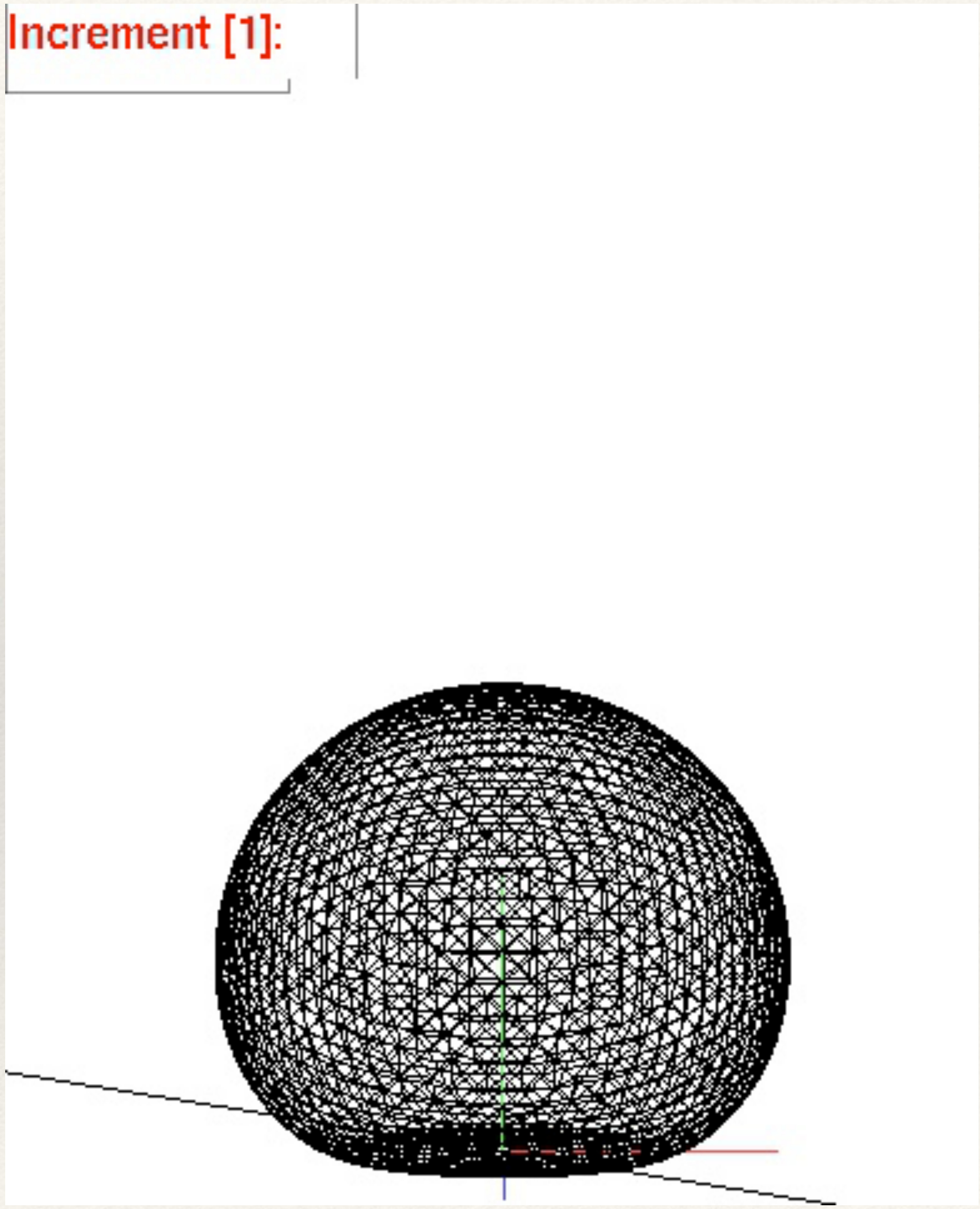
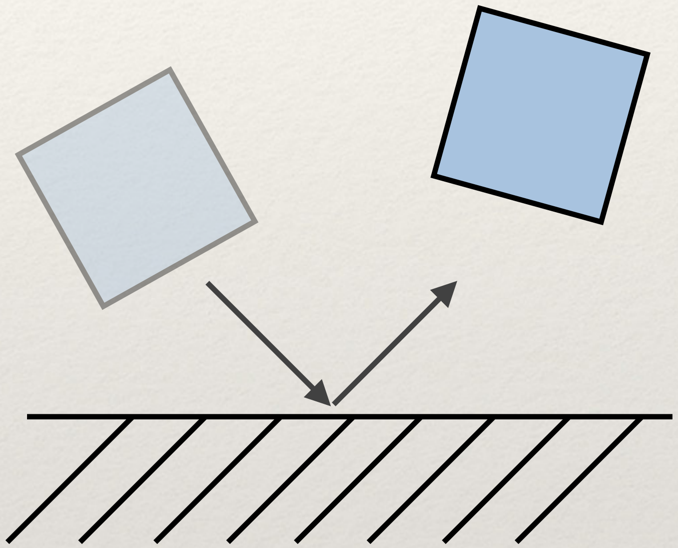


Rigid Body Collisions

- Physically, similar to deformable body collisions
- But rigid idealization precludes storing energy
- Instead, algebraic collision laws for before/after collision
- Cases:
  - Inelastic (sticking)
  - Elastic: frictionless, with friction



Rigid Body Inelastic Collision

- Linear momentum

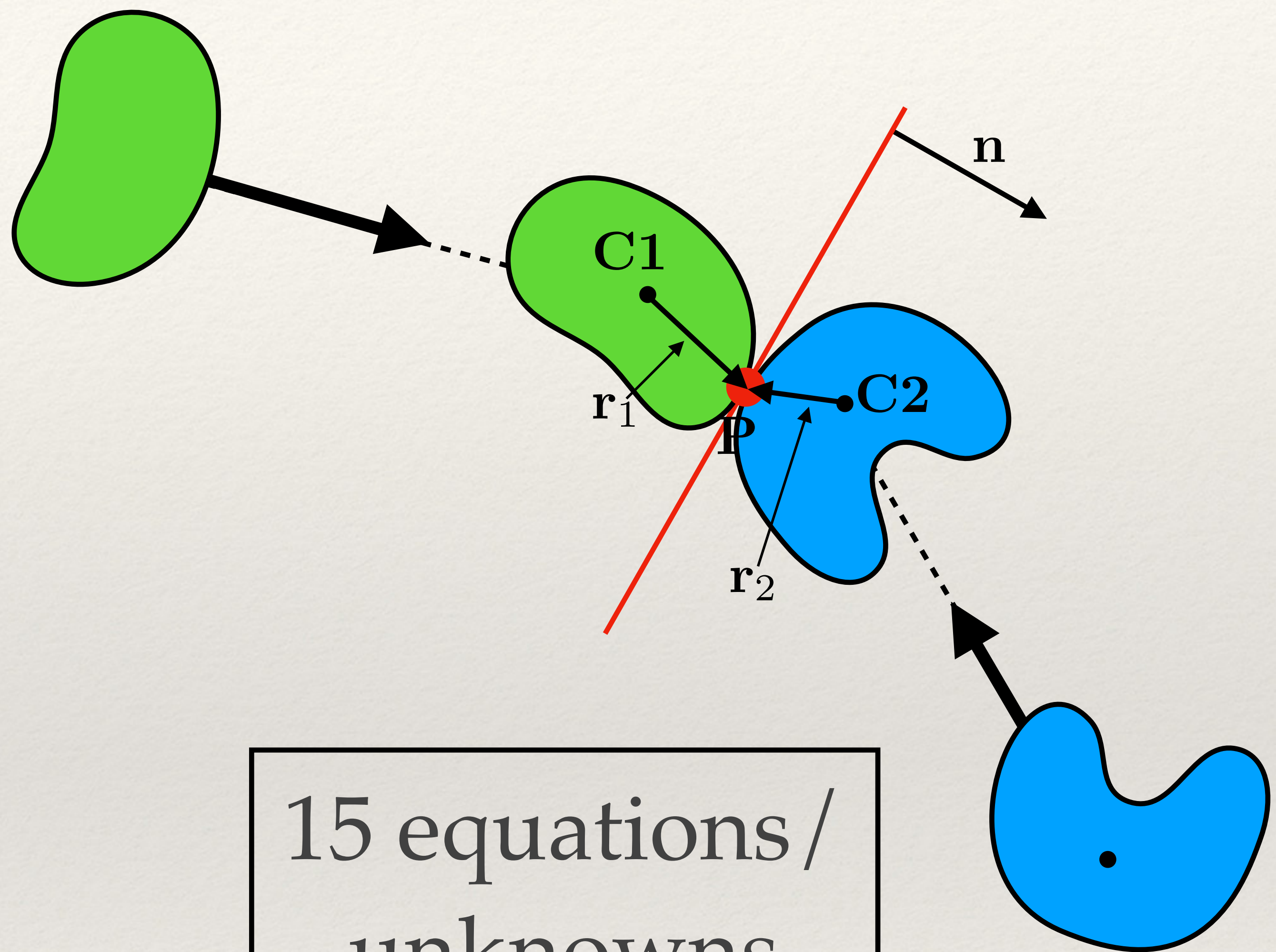
$$m_1\mathbf{v}'_{C1} = m_1\mathbf{v}_{C1} + \mathbf{j}$$
$$m_2\mathbf{v}'_{C2} = m_2\mathbf{v}_{C2} - \mathbf{j}$$

- Angular momentum

$$I_1\omega'_1 = I_1\omega_1 + \mathbf{r}_1 \times \mathbf{j}$$
$$I_2\omega'_2 = I_2\omega_1 - \mathbf{r}_2 \times \mathbf{j}$$

- Sticking

$$\mathbf{v}'_{P1} = \mathbf{v}'_{P2}$$

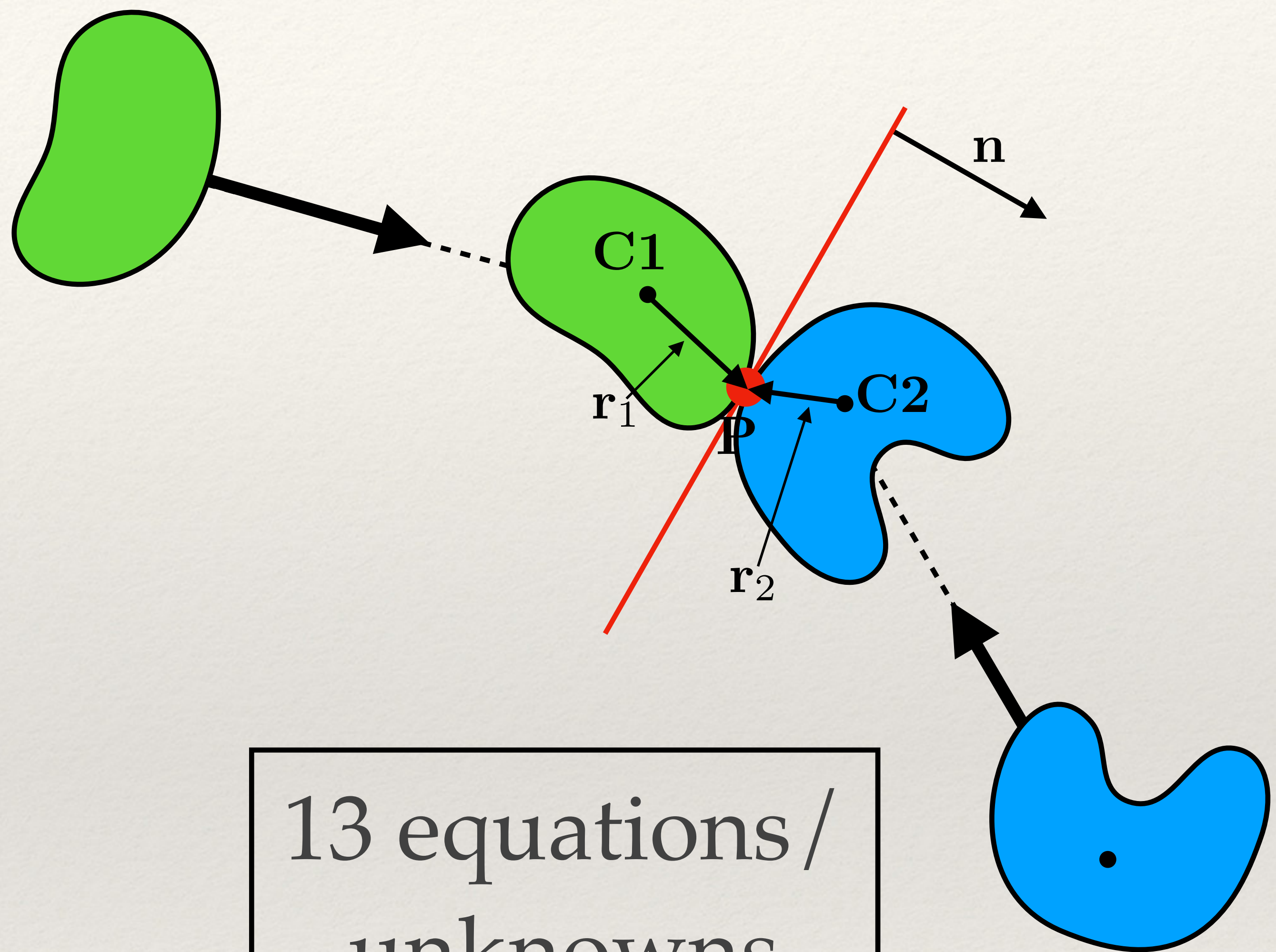


15 equations / unknowns

Rigid Body Frictionless Collision

- Linear momentum

$$m_1 \mathbf{v}'_{C1} = m_1 \mathbf{v}_{C1} + \mathbf{j}$$
$$m_2 \mathbf{v}'_{C2} = m_2 \mathbf{v}_{C2} - \mathbf{j}$$



- Angular momentum

$$I_1 \omega'_1 = I_1 \omega_1 + \mathbf{r}_1 \times \mathbf{j}$$
$$I_2 \omega'_2 = I_2 \omega_1 - \mathbf{r}_2 \times \mathbf{j}$$

13 equations / unknowns

- Elastic

$$\mathbf{j} = j\mathbf{n}$$

$$(\mathbf{v}'_{P2} - \mathbf{v}'_{P1}) \cdot \mathbf{n} = -\epsilon(\mathbf{v}_{P2} - \mathbf{v}_{P1}) \cdot \mathbf{n}$$

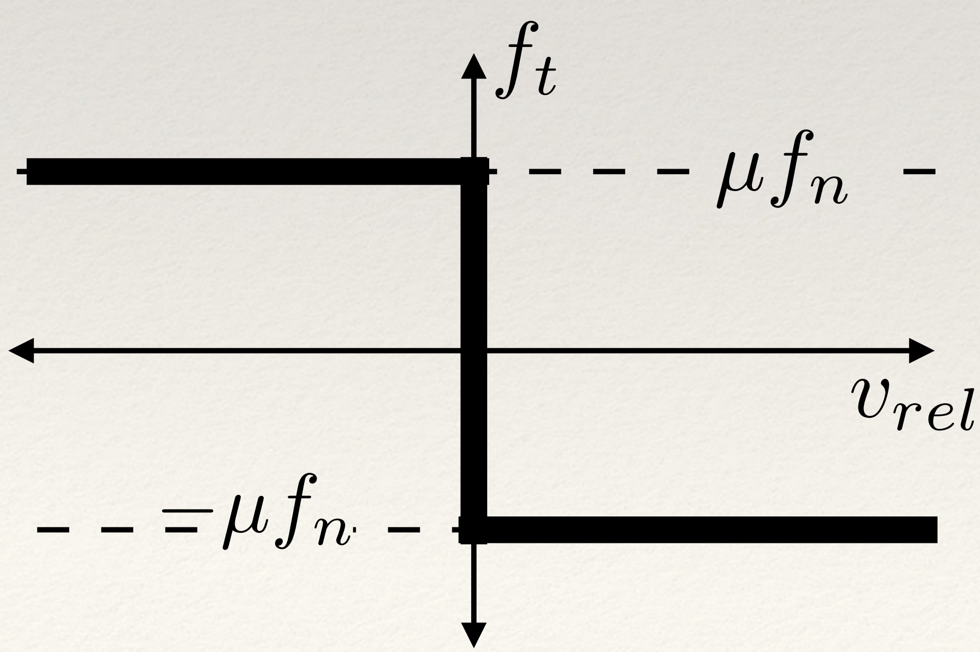
Rigid Body Frictional Collision

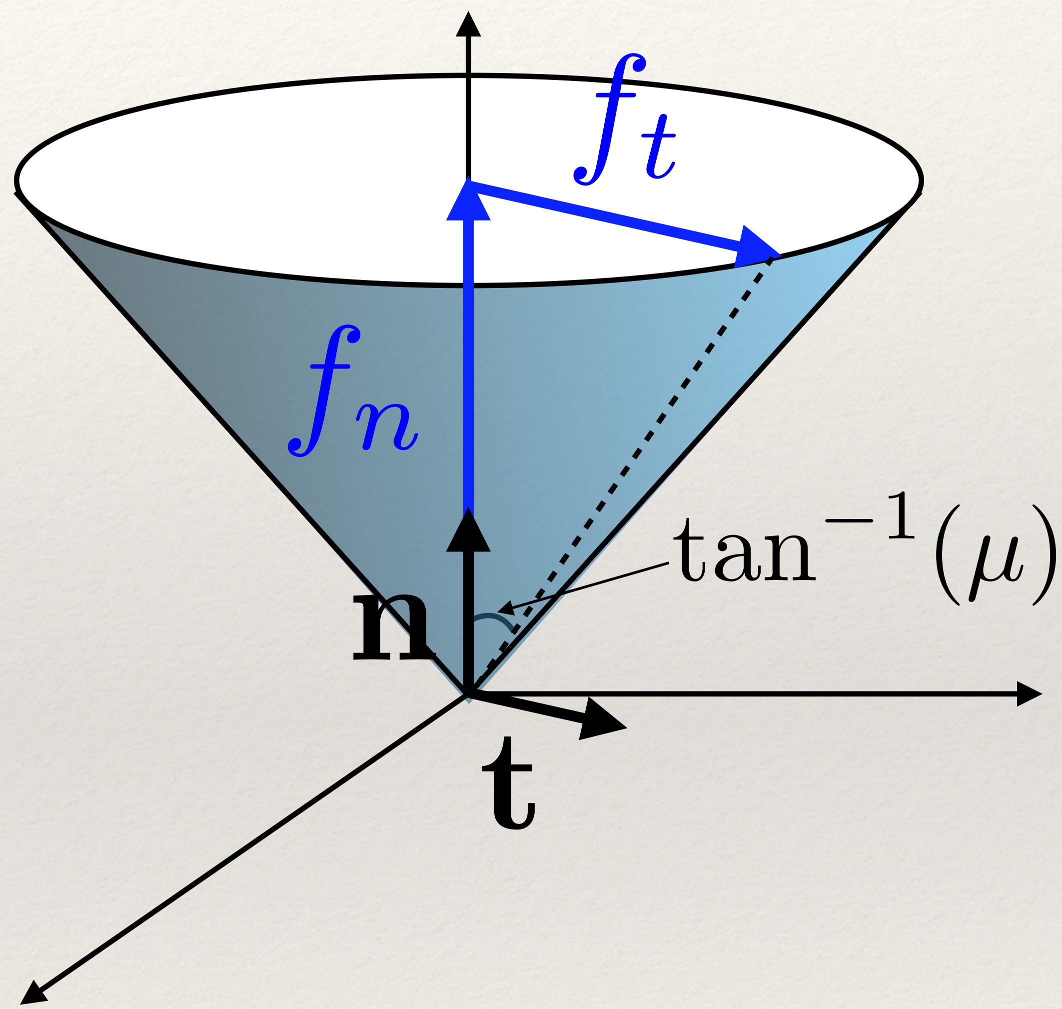
- Coulomb friction model

  μ **coefficient of friction**

- Static $\|\mathbf{f}_t\| \leq \mu\|\mathbf{f}_n\|$

- Sliding $\mathbf{f}_t = -\mu\|\mathbf{f}_n\|\mathbf{t}$

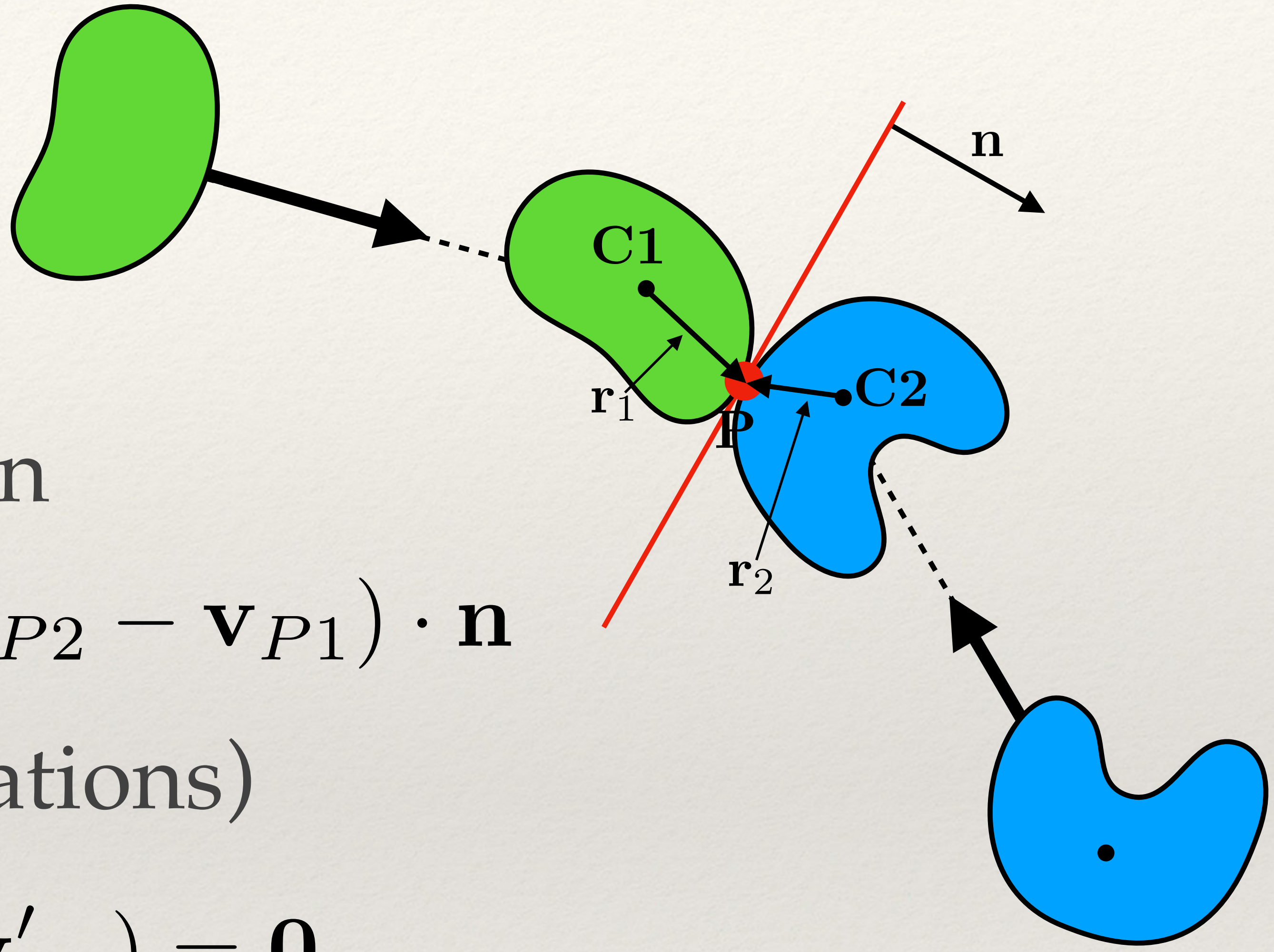




friction cone

Rigid Body Frictional Collision

- Example [Guendelman et al. 2003]



- Elastic in normal direction

$$(\mathbf{v}'_{P2} - \mathbf{v}'_{P1}) \cdot \mathbf{n} = -\epsilon(\mathbf{v}_{P2} - \mathbf{v}_{P1}) \cdot \mathbf{n}$$

- Assume sticking (+2 equations)

$$(I - \mathbf{n}\mathbf{n}^T)(\mathbf{v}'_{P2} - \mathbf{v}'_{P1}) = \mathbf{0}$$

- If not admissible, assume sliding (-2 unknowns)

$$\mathbf{j} = j_n\mathbf{n} - \mu j_n\mathbf{t}$$

Thanks!

For notes, slides, and source code visit:

https://cal.cs.umbc.edu/Courses/PhysicsBasedAnimation

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