Fluids in Games

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Introductory Bits

- General summary with some details
- Not a fluids expert
- Theory and examples

What is a Fluid?

- Deformable
- Flowing
- Examples
  - Smoke
  - Fire
  - Water

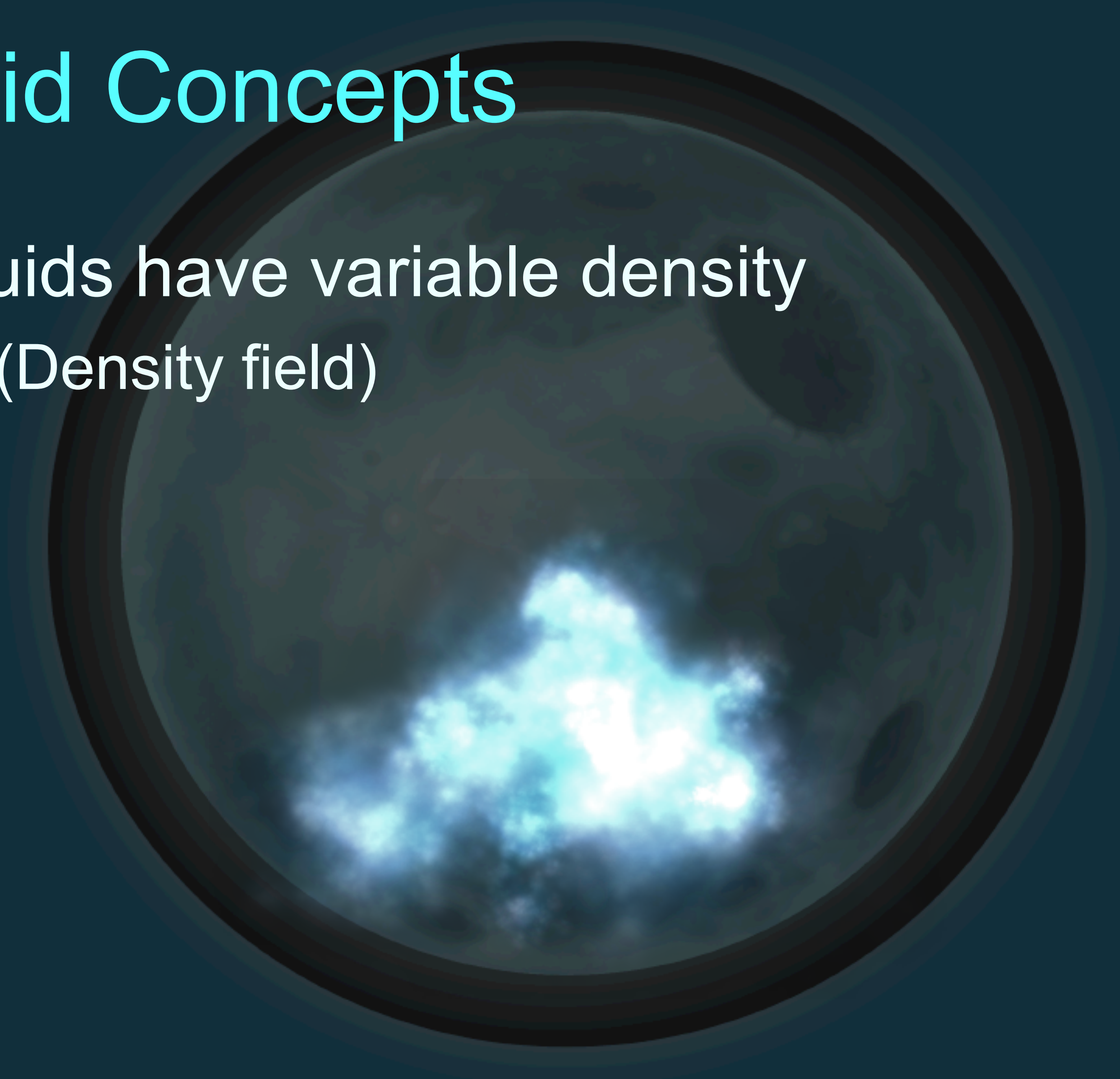
What is a Fluid?

What is a Fluid?

What is a Fluid?

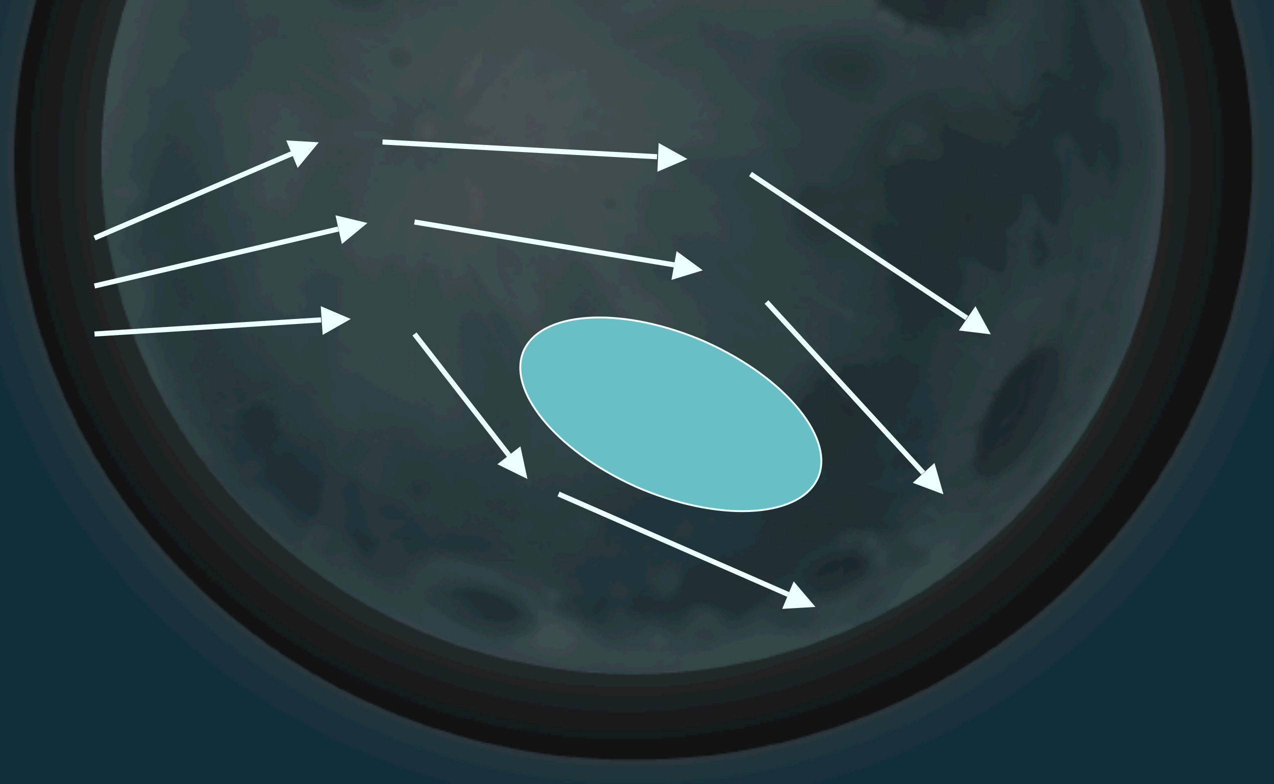
Fluid Concepts

- Fluids have variable density
  – (Density field)



Fluid Concepts

- Fluids “flow”
  - (Vector field)



Fluid Concepts

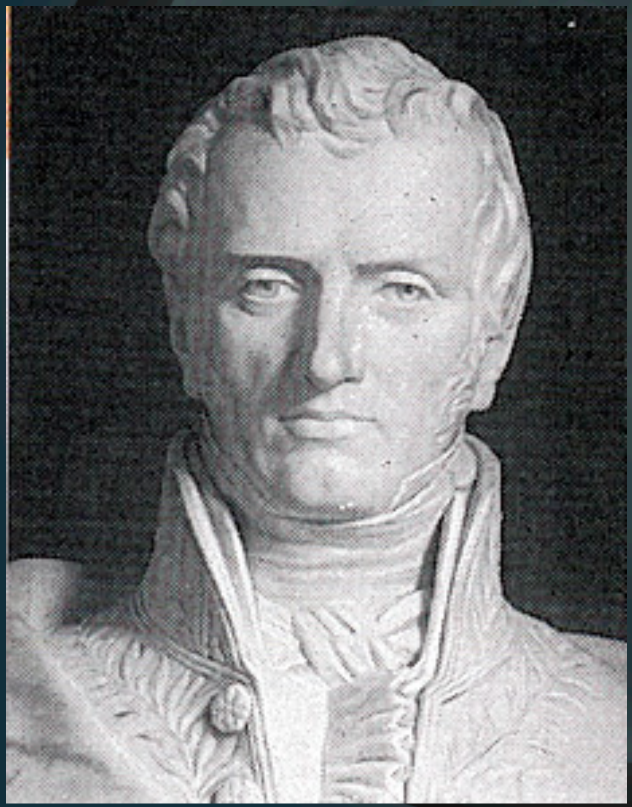
- Need way to represent
  - Density ($\mathbf{x}$)
  - Velocity ($\mathbf{u}$)
  - Sometimes temperature

Fluid Concepts

- Our heroes:

Fluid Concepts

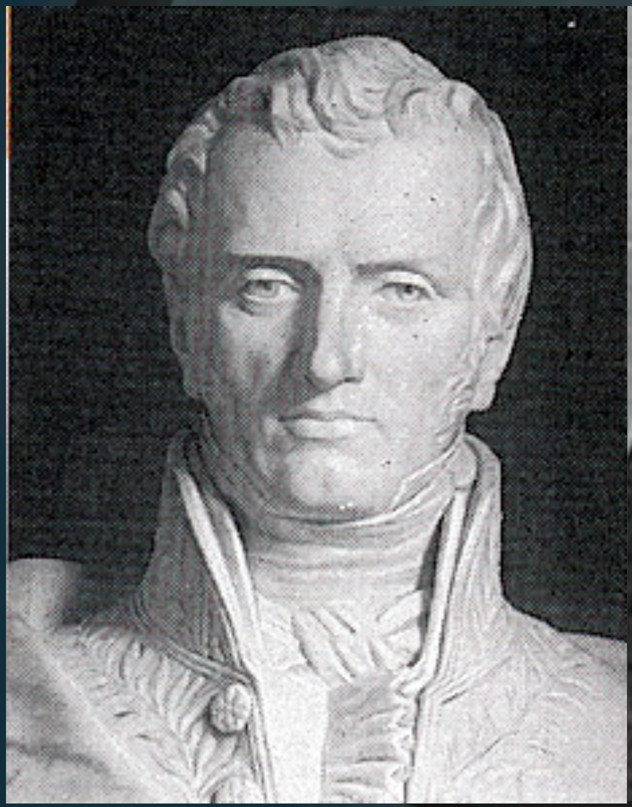
- Our heroes:



Navier

Fluid Concepts

- Our heroes:

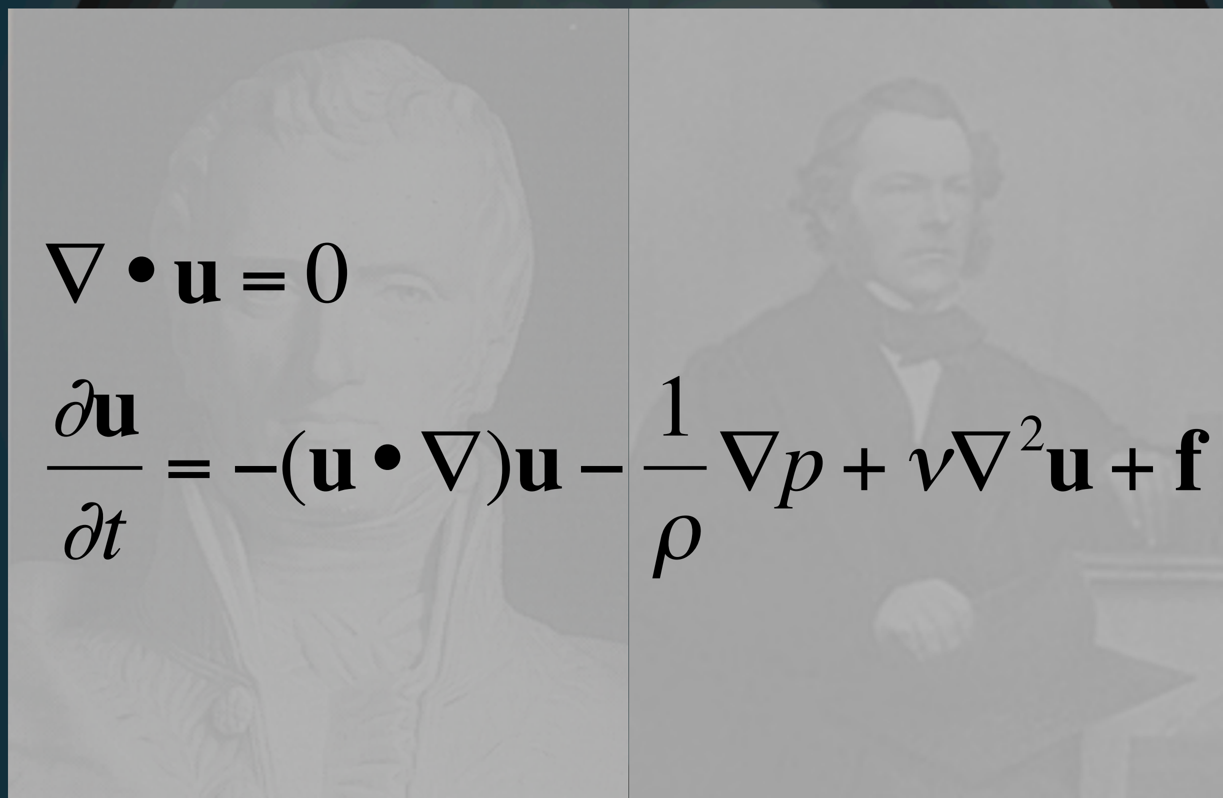


Navier

Stokes

Fluid Concepts

- Their creation:

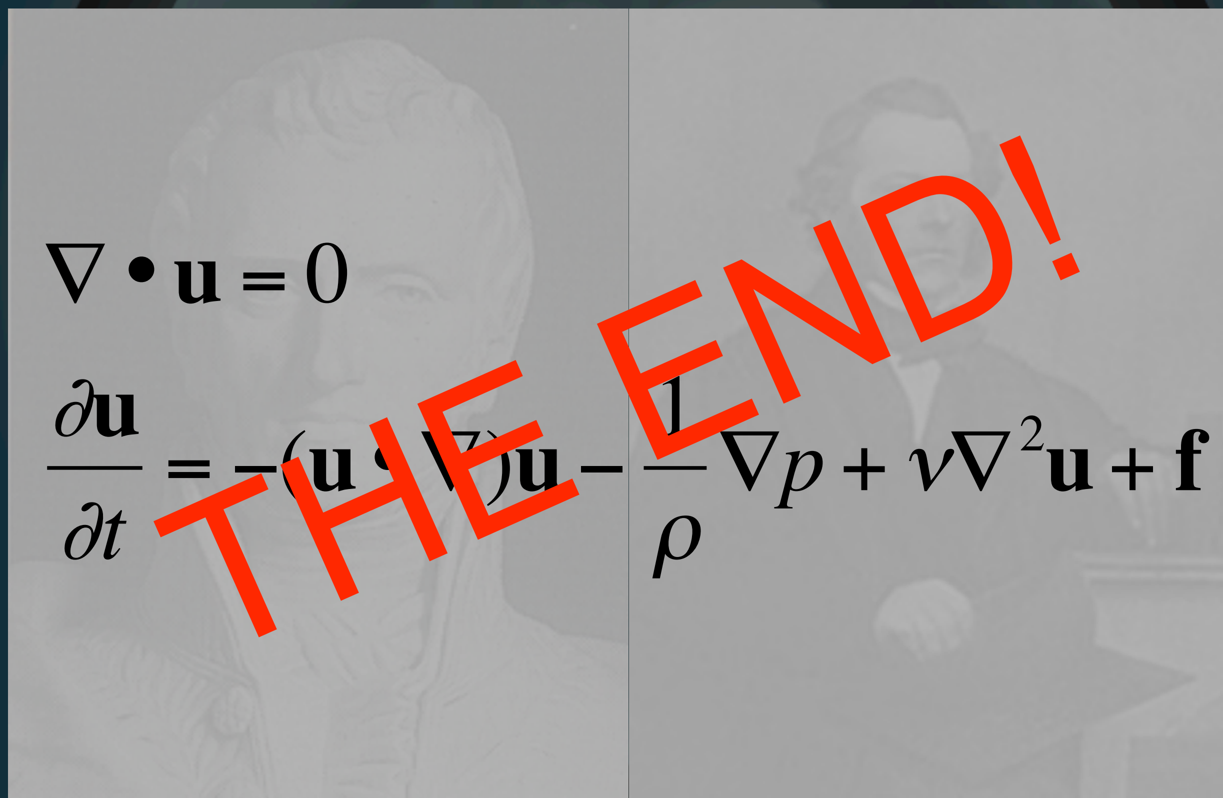


$$\nabla \bullet \mathbf{u} = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u} \bullet \nabla)\mathbf{u} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}$$

Fluid Concepts

- Their creation:



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Fluid Concepts

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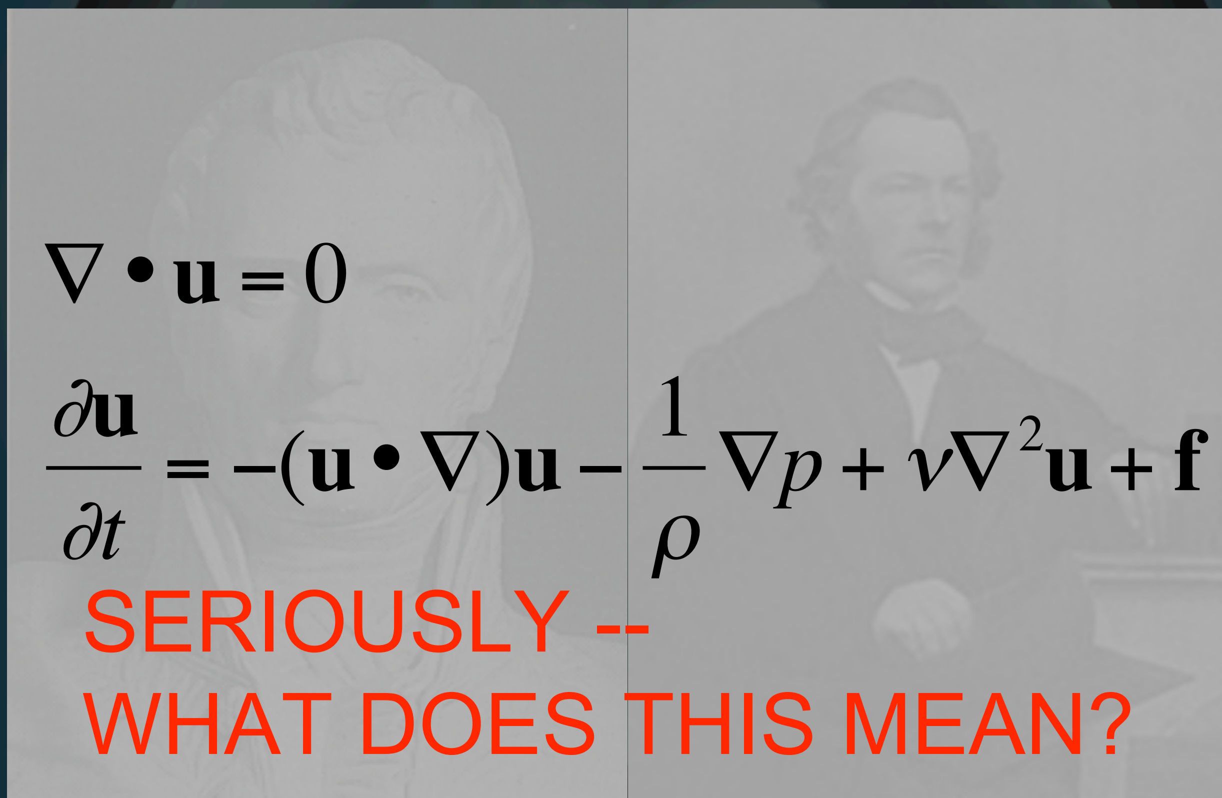

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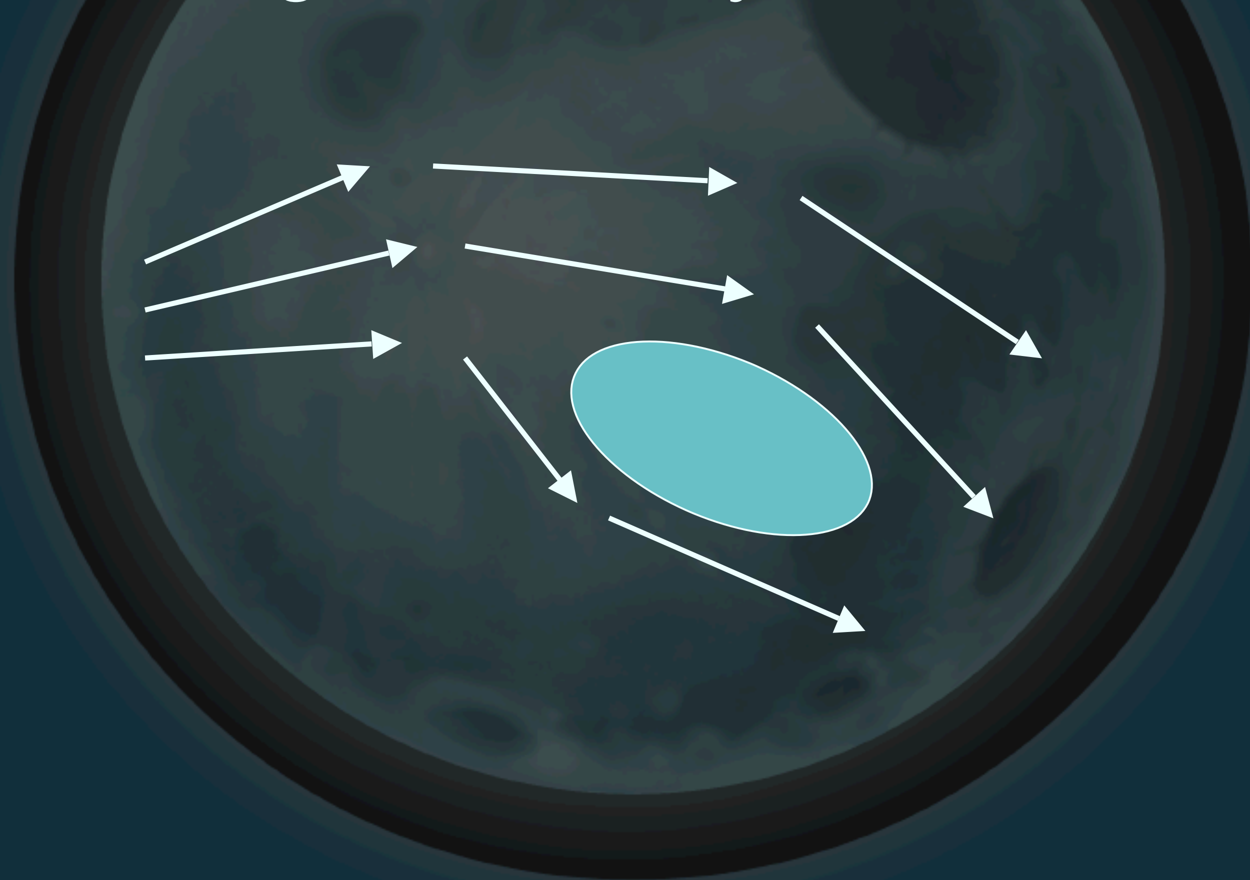
SERIOUSLY --

WHAT DOES THIS MEAN?

Fluid Concepts

- Want change in velocity field



Fluid Concepts

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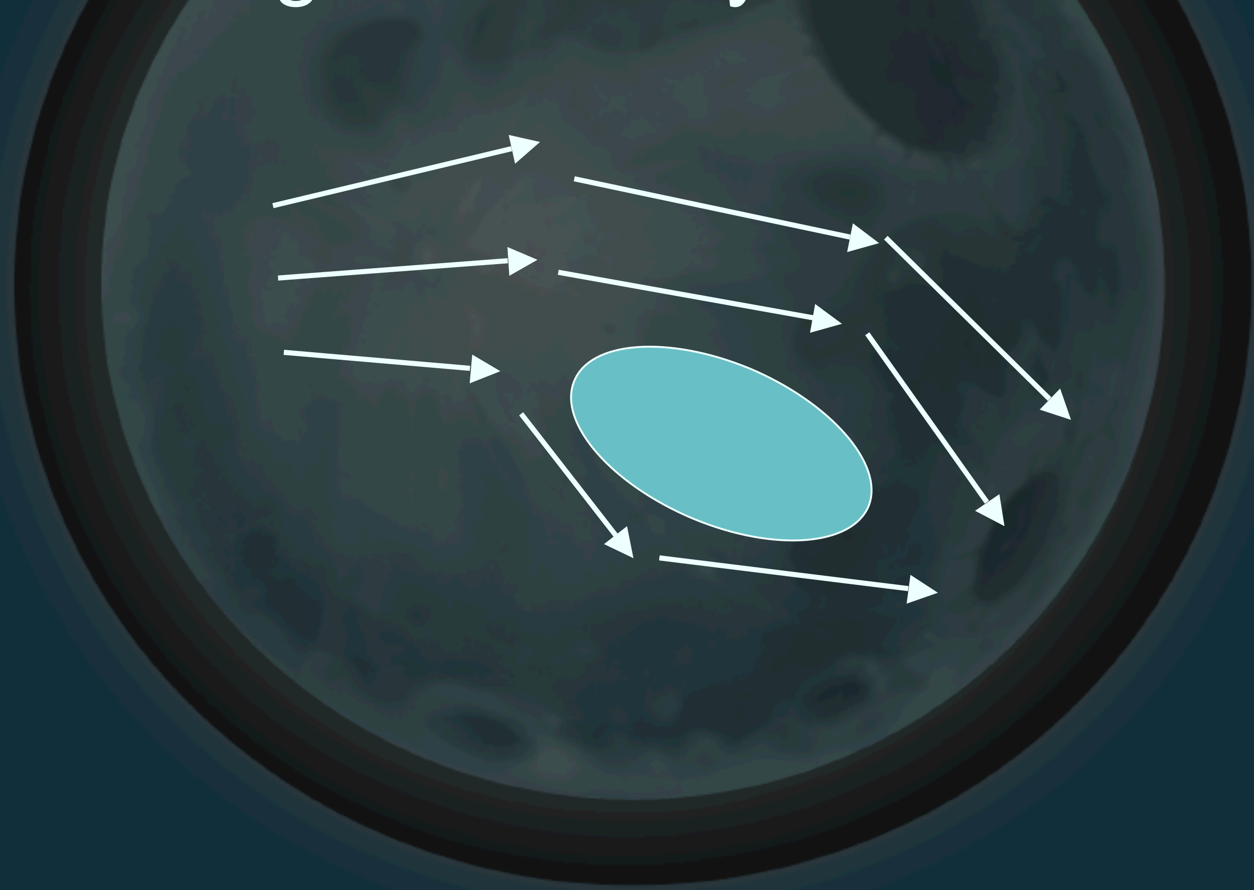

Fluid Concepts

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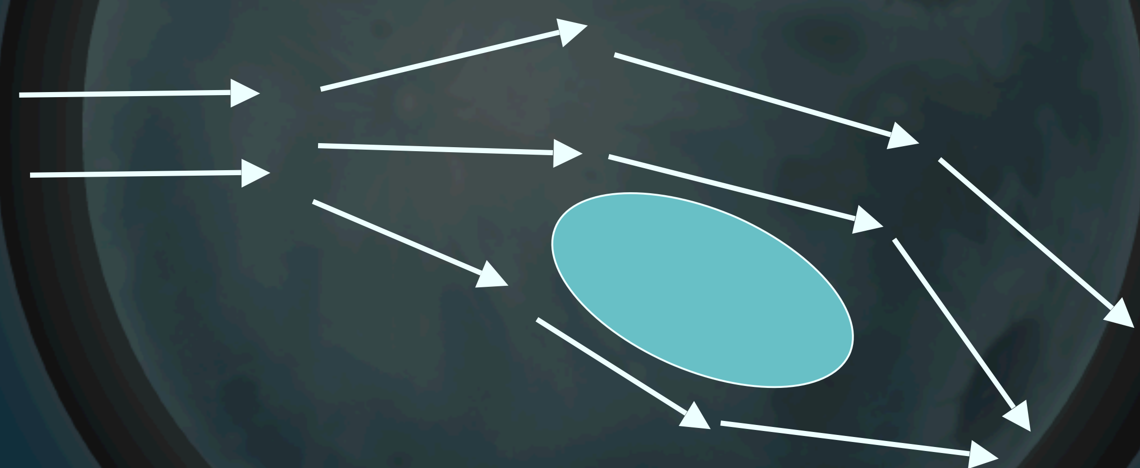

Fluid Concepts

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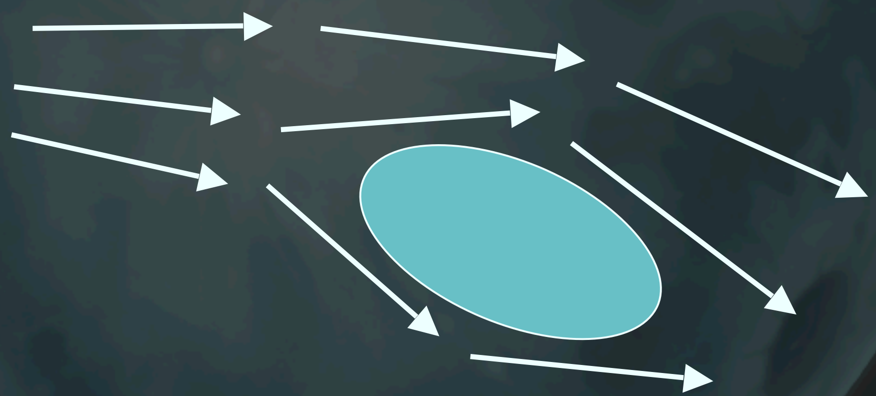
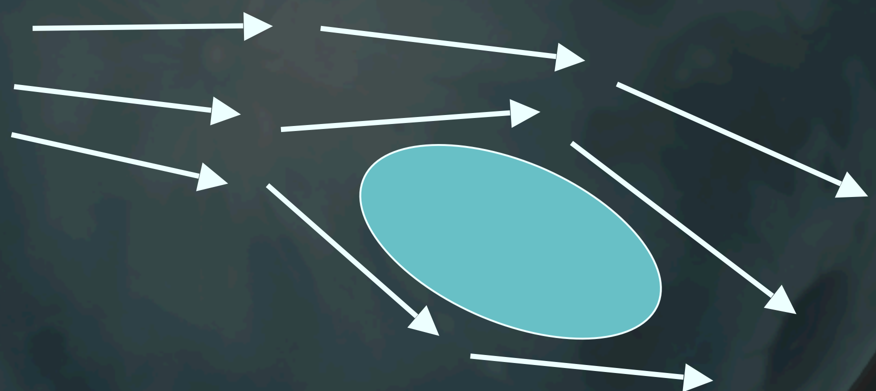


Fluid Concepts

- What affects it?



Fluid Concepts

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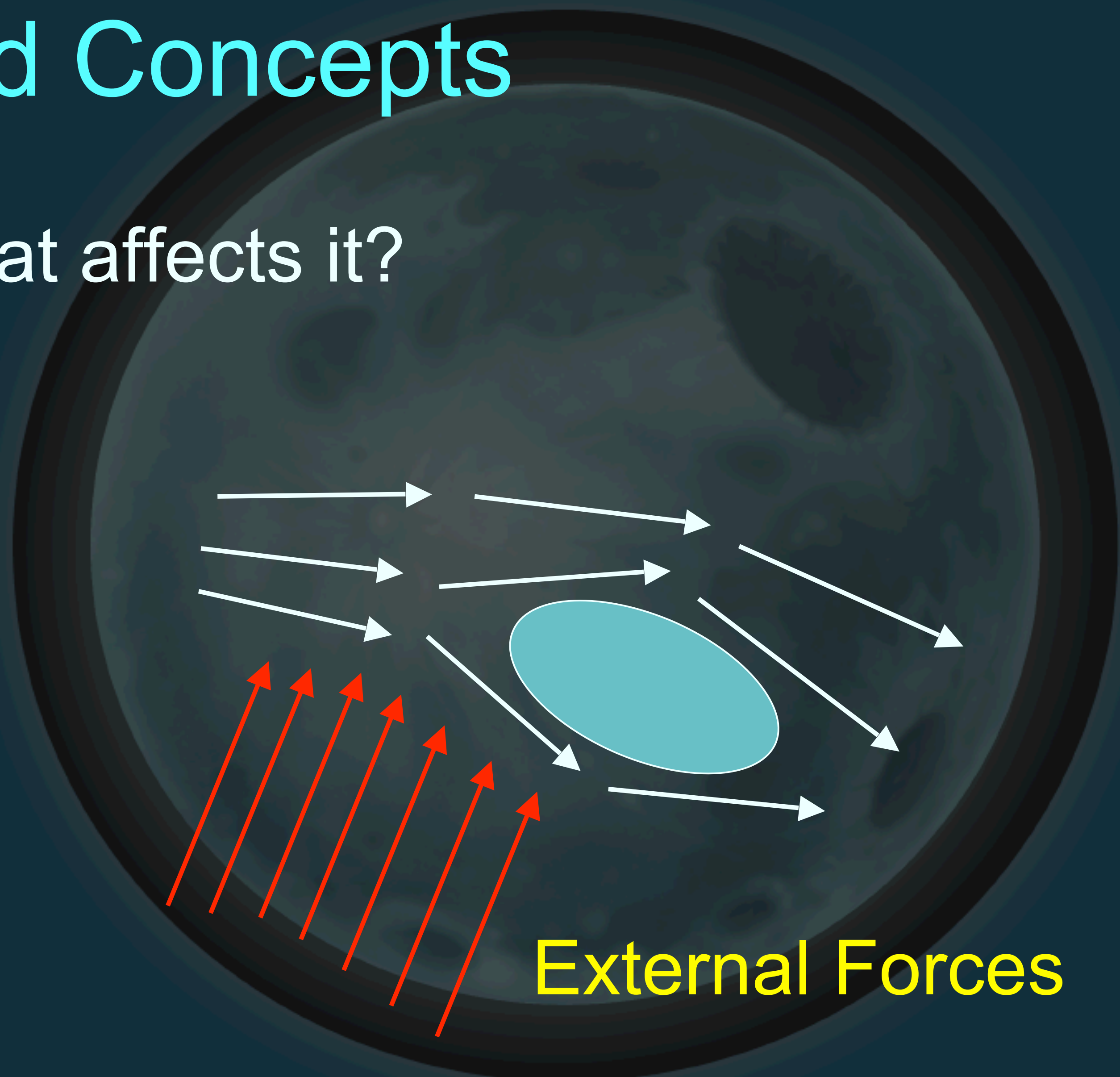

Fluid Concepts

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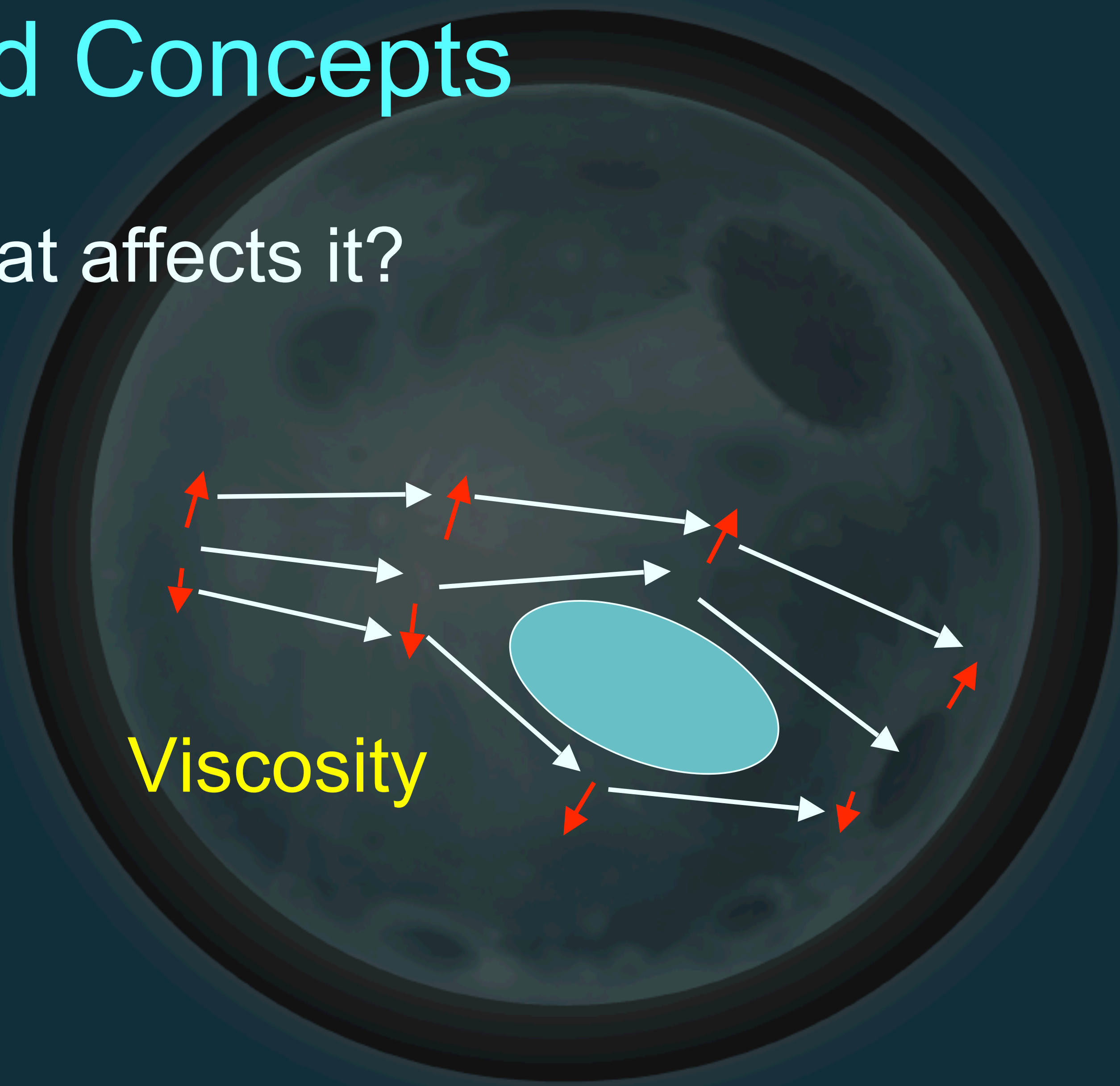

Fluid Concepts

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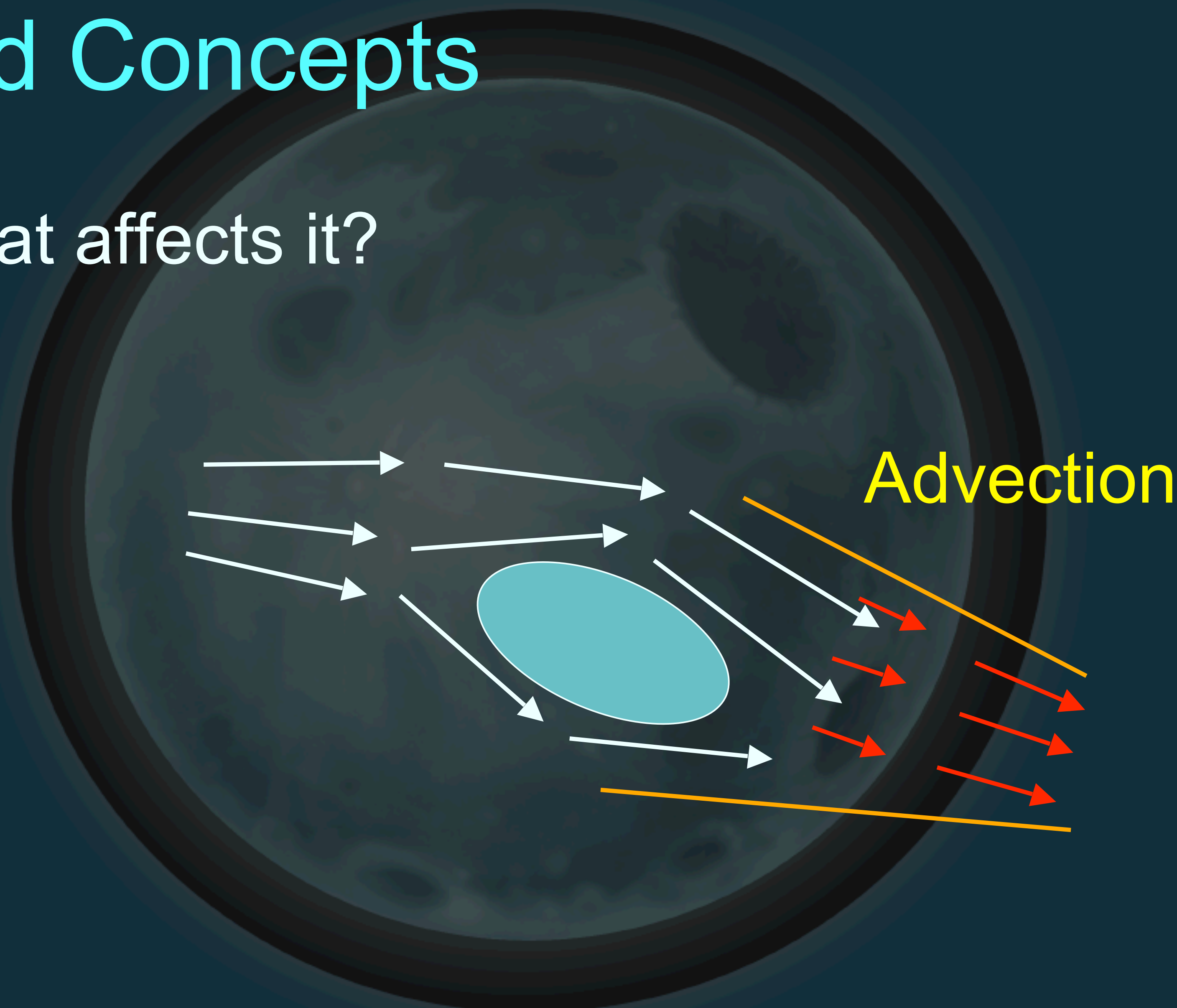
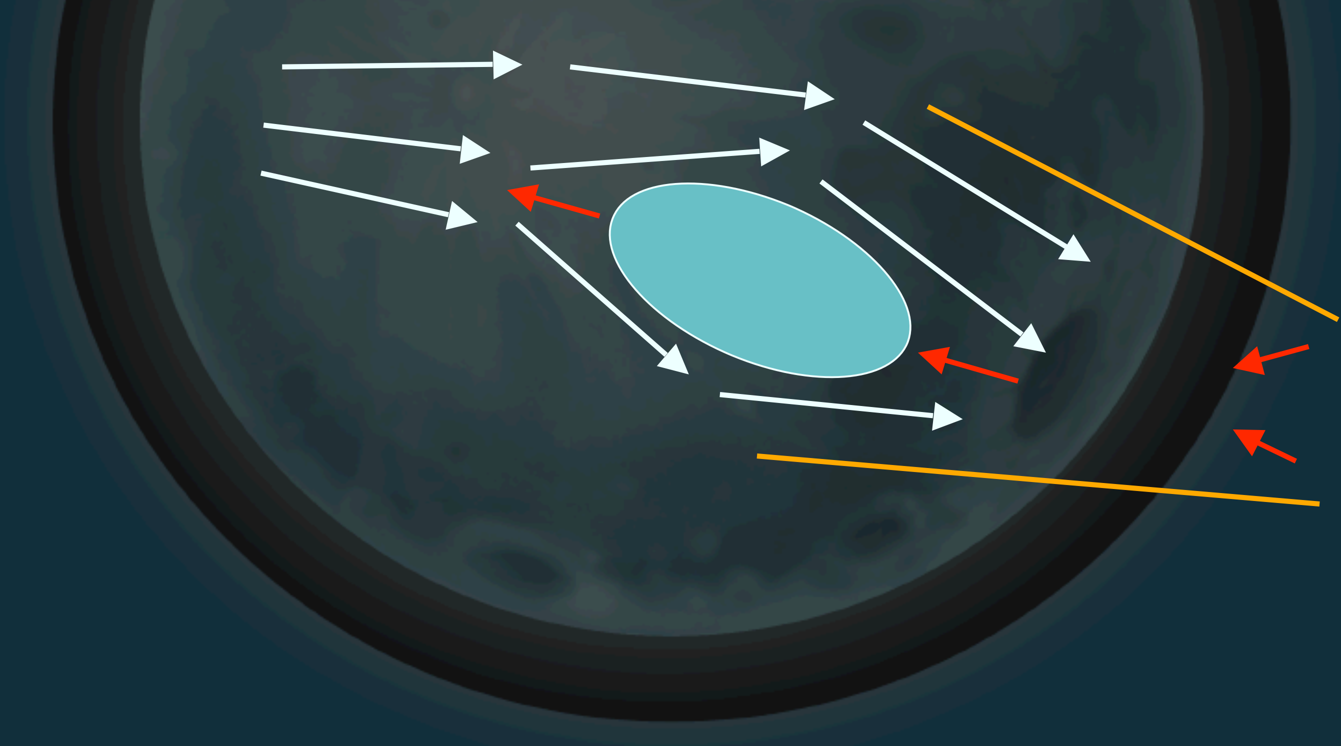


Fluid Concepts

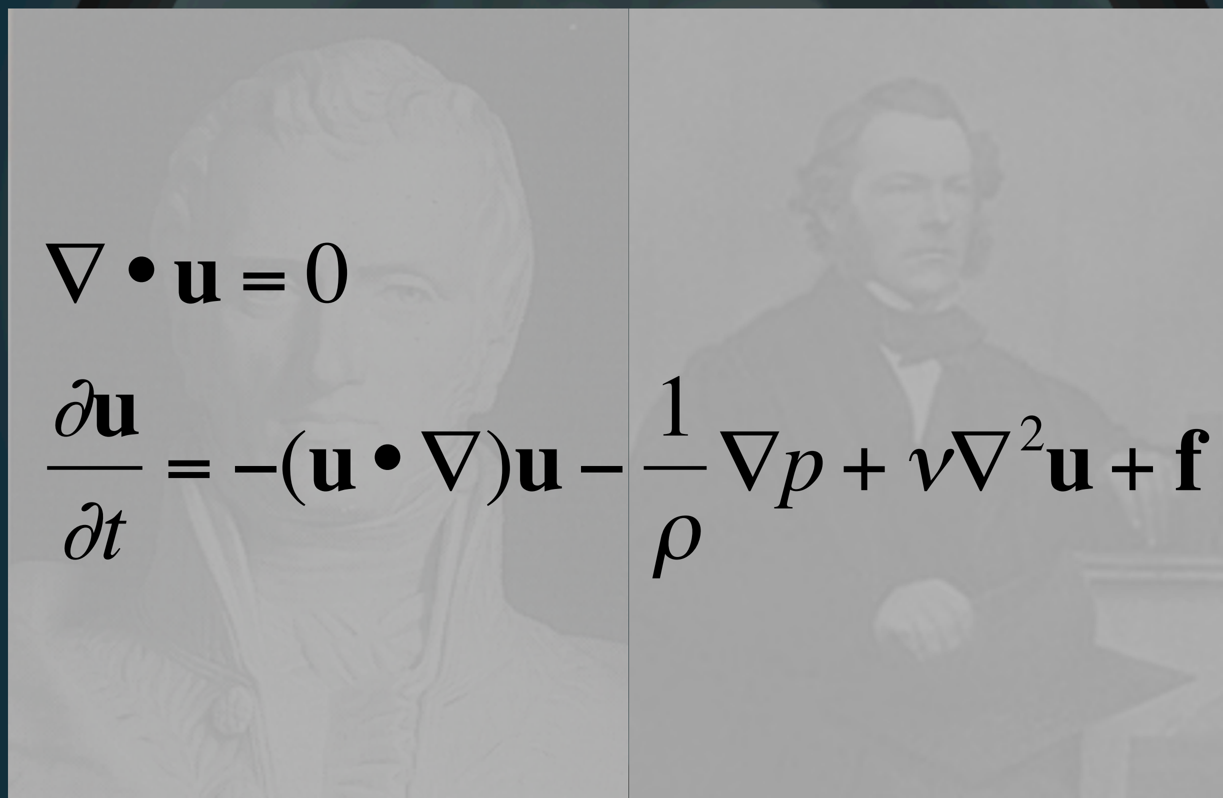
- What affects it?

Pressure



Fluid Concepts

- Back to Navier-Stokes

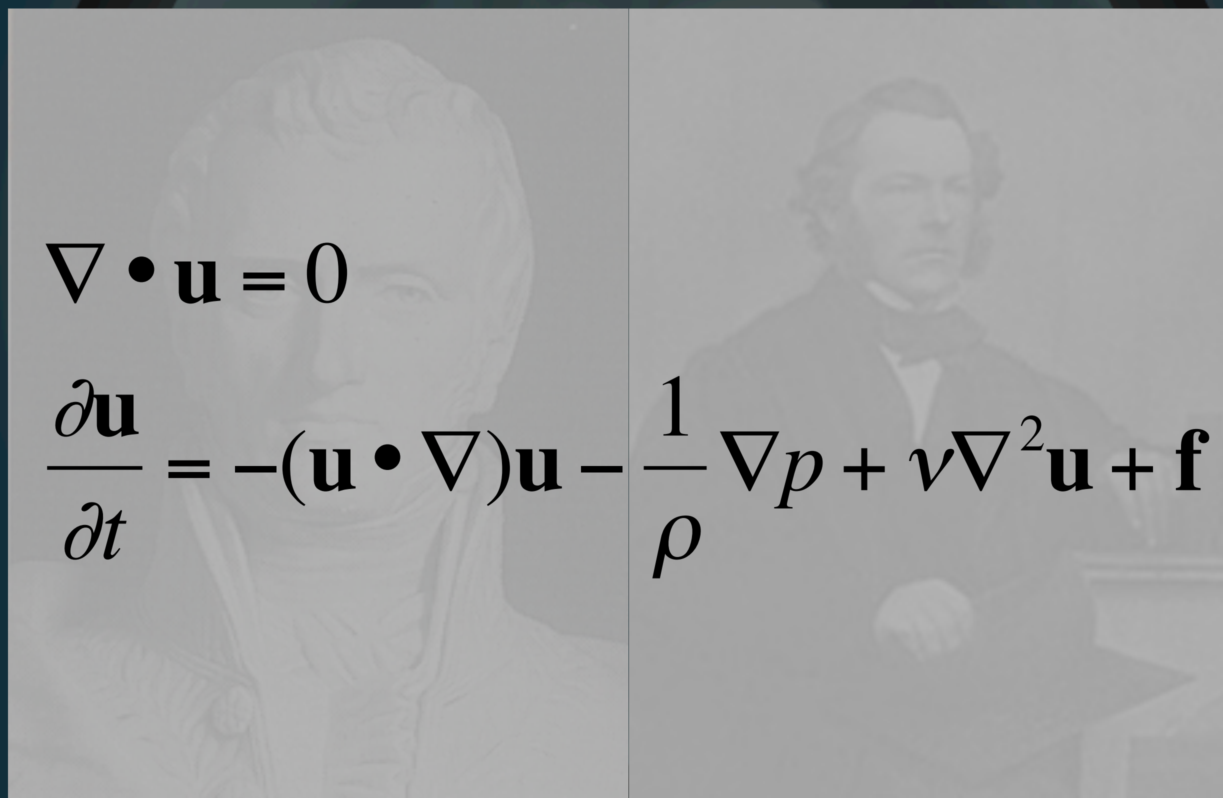


$$\nabla \bullet \mathbf{u} = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u} \bullet \nabla)\mathbf{u} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}$$

Fluid Concepts

- Brief notational diversion



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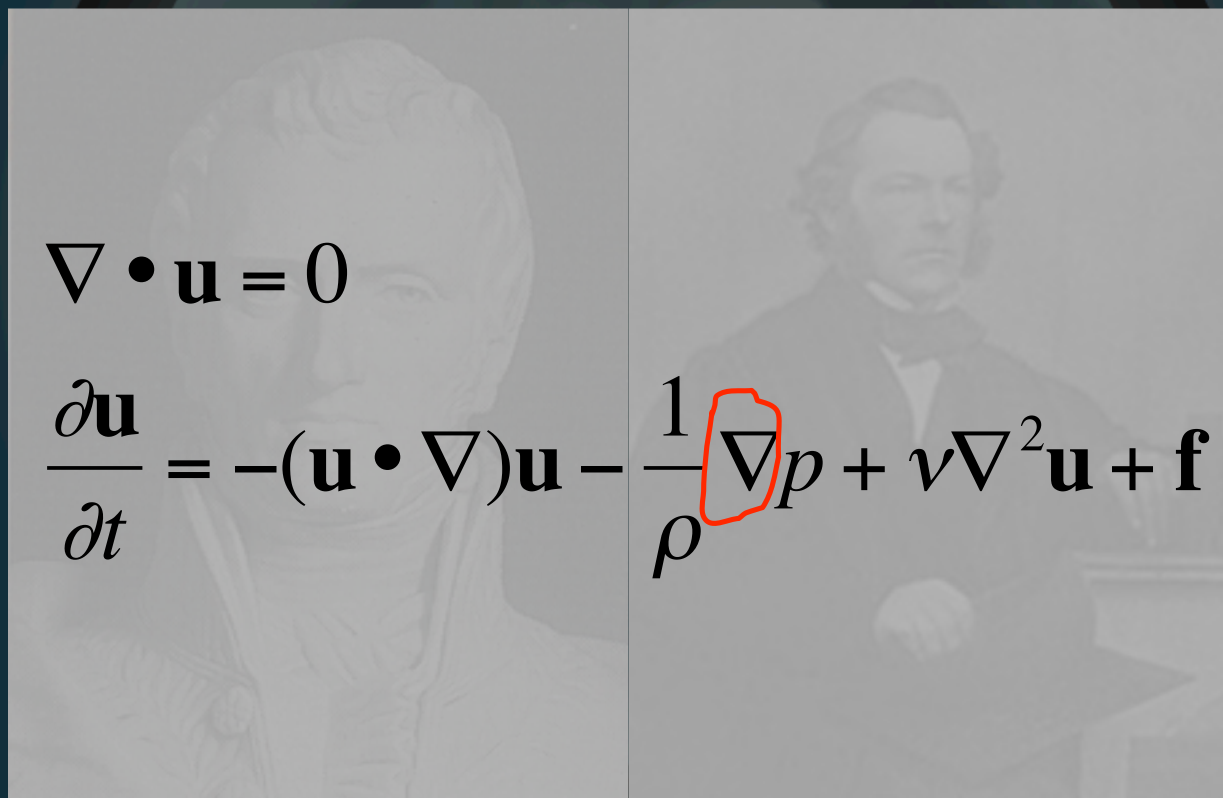

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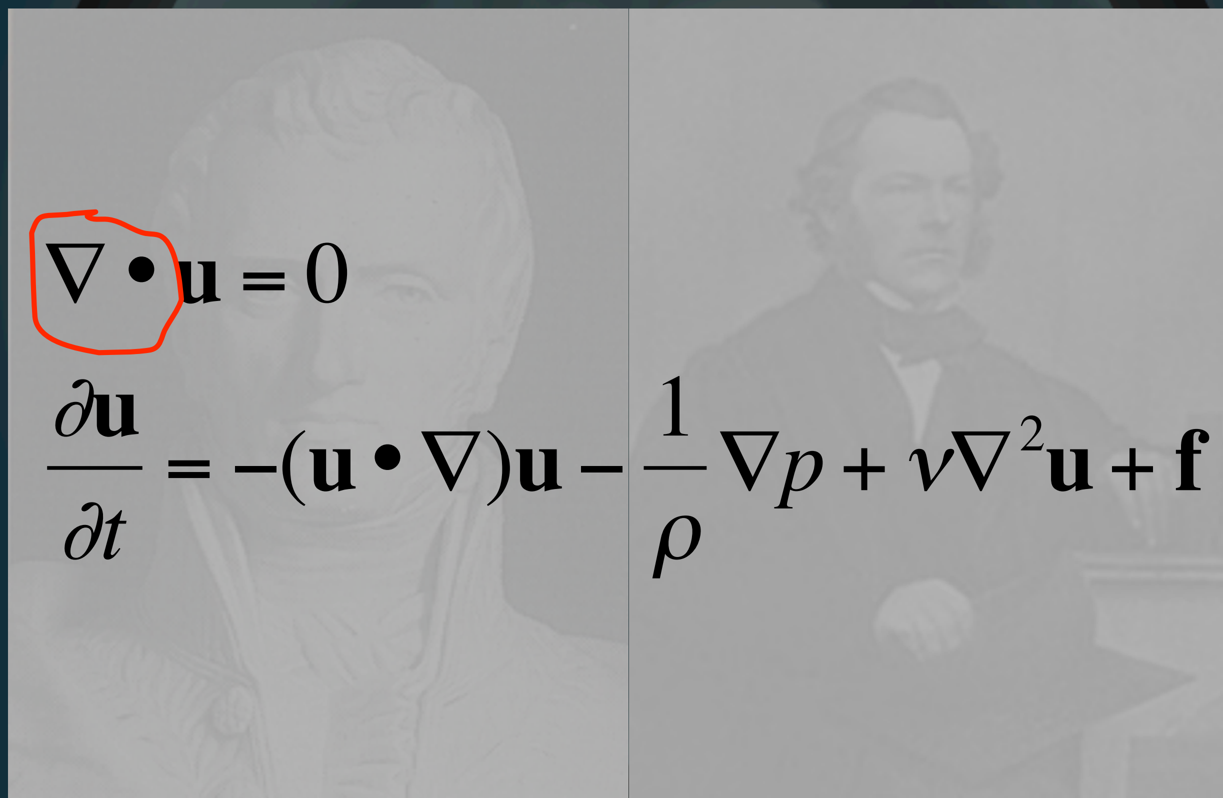
Gradient (vector along partial derivative)

Fluid Concepts

- Brief notational diversion



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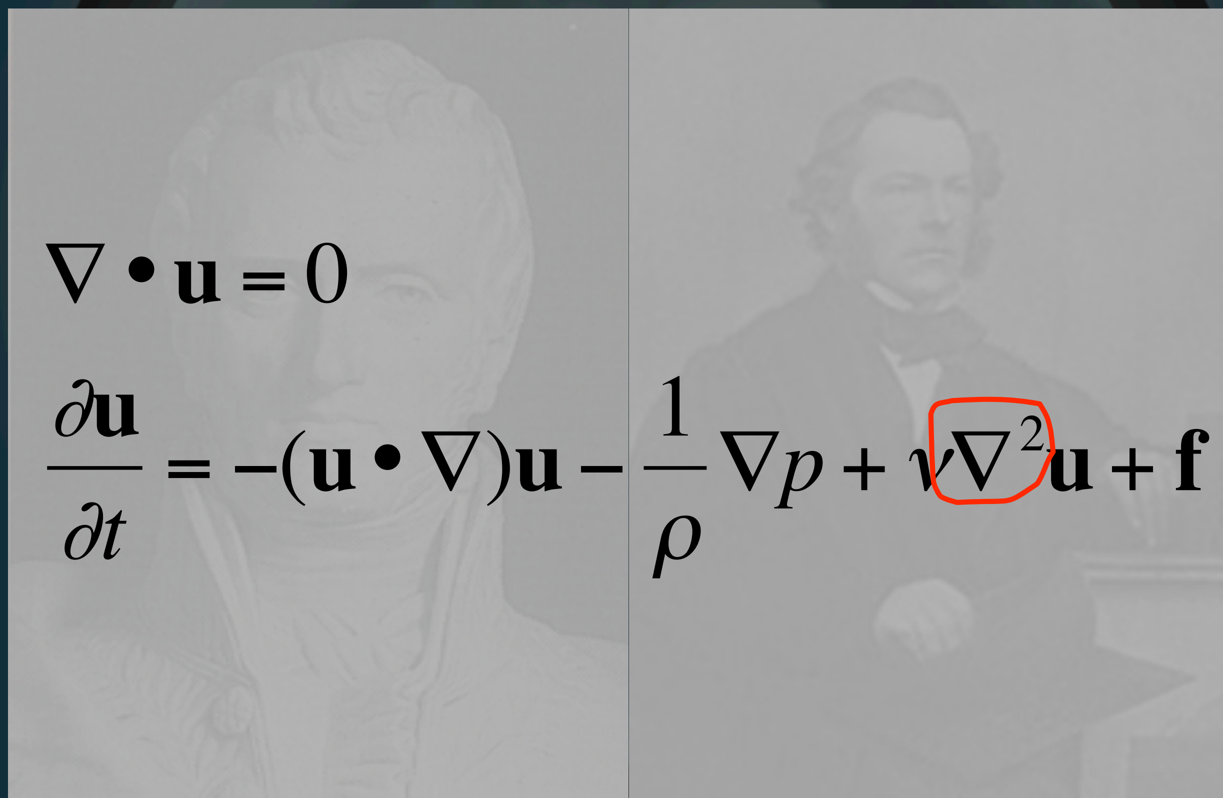
Divergence (real derivative of vec. field)

Fluid Concepts

- Brief notational diversion



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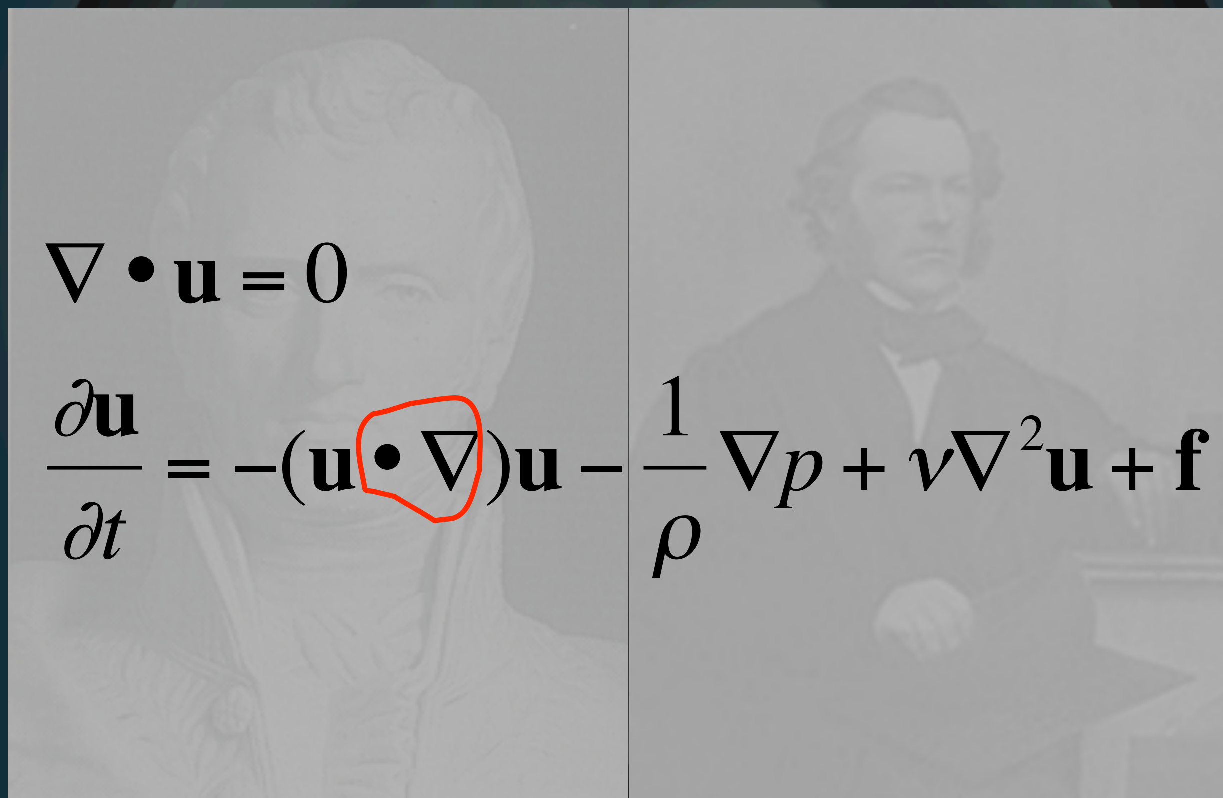
Laplacian (divergence of gradient)

Fluid Concepts

- Brief notational diversion



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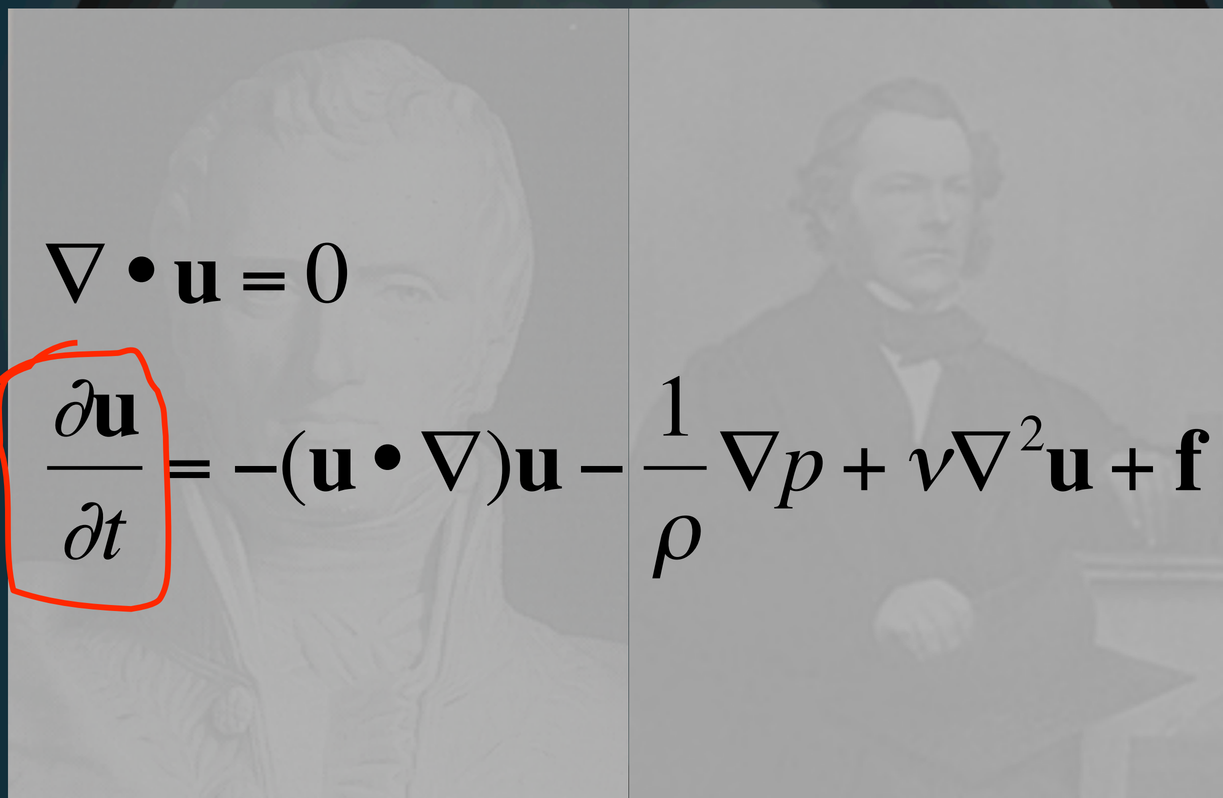
Advection operator (transport of flow)

Fluid Concepts

- Back to Navier-Stokes



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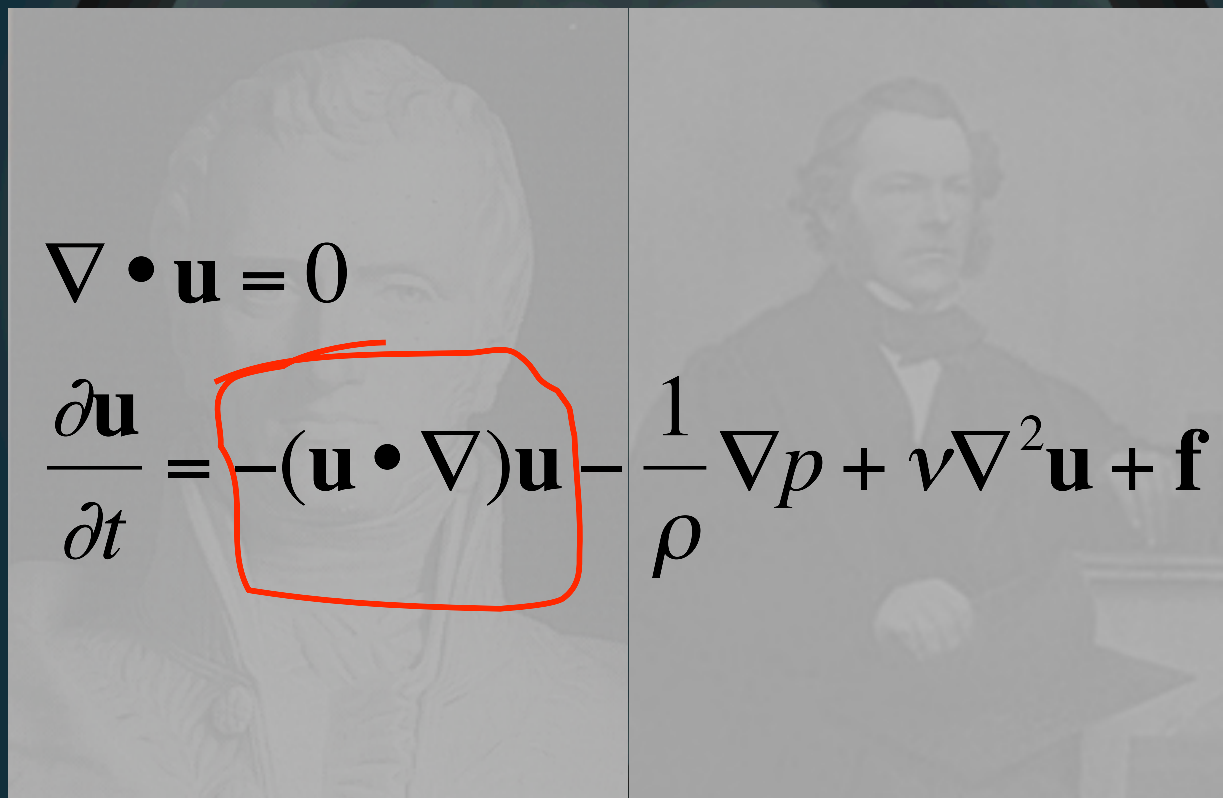
Change in Velocity

Fluid Concepts

- Back to Navier-Stokes



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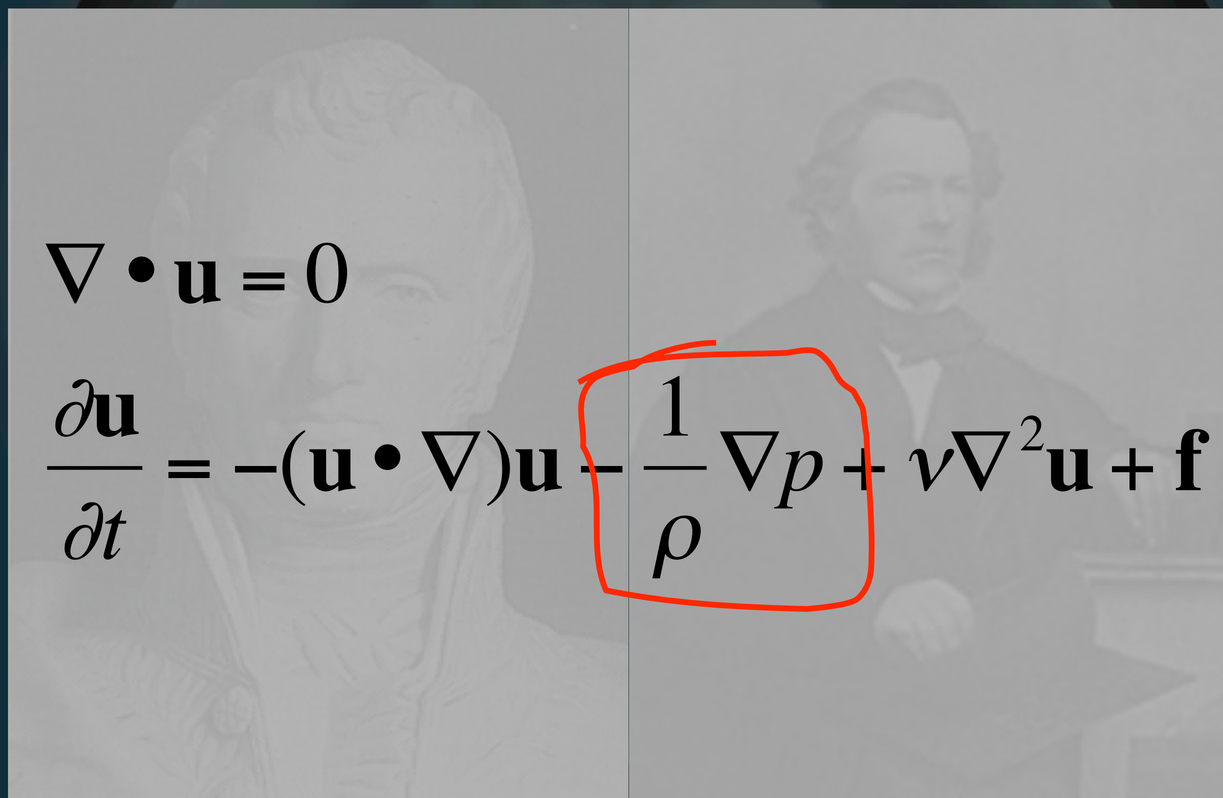
Advection

Fluid Concepts

- Back to Navier-Stokes



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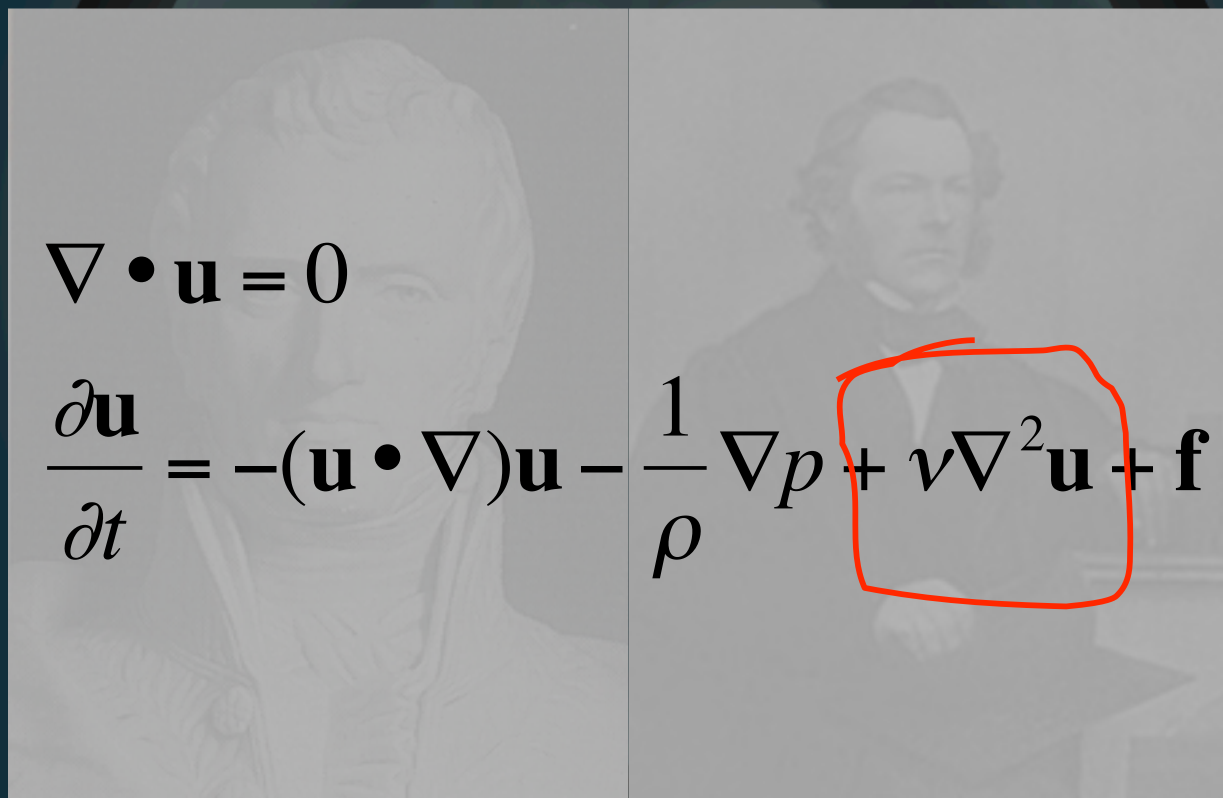
Pressure

Fluid Concepts

- Back to Navier-Stokes



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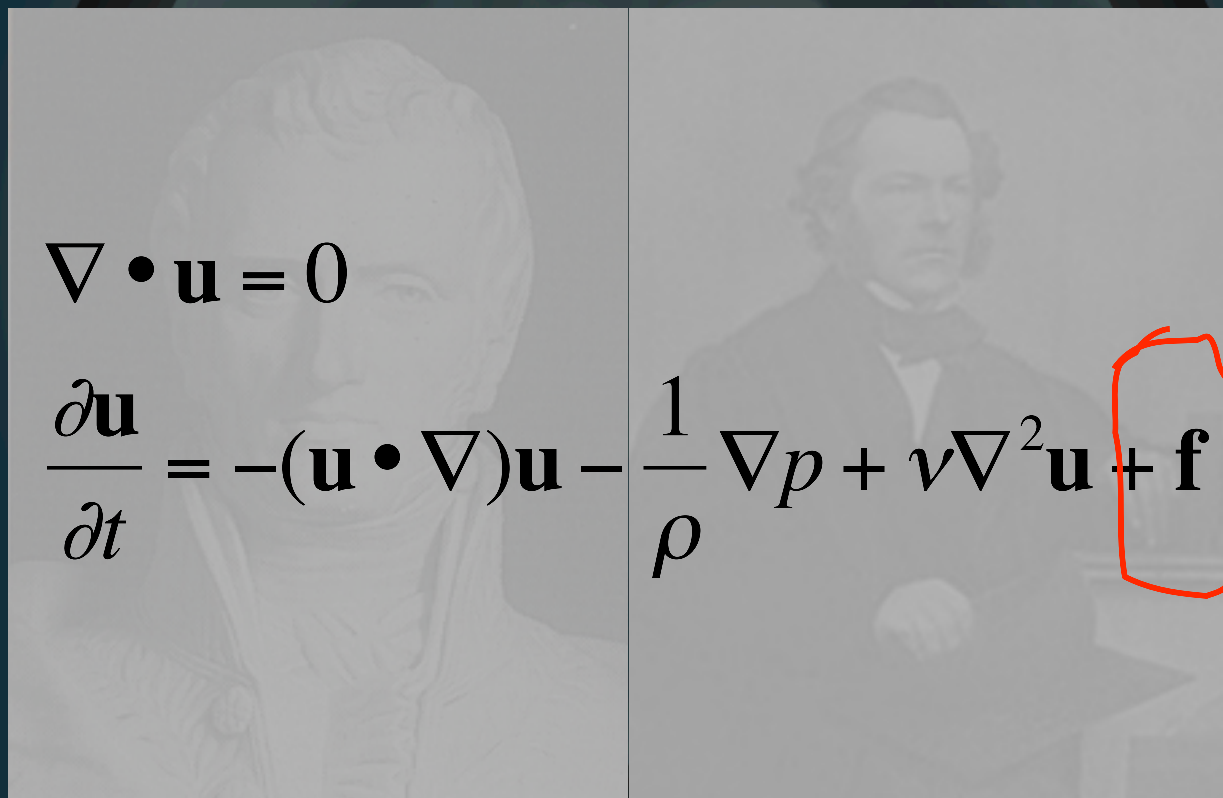
Viscosity

Fluid Concepts

- Back to Navier-Stokes



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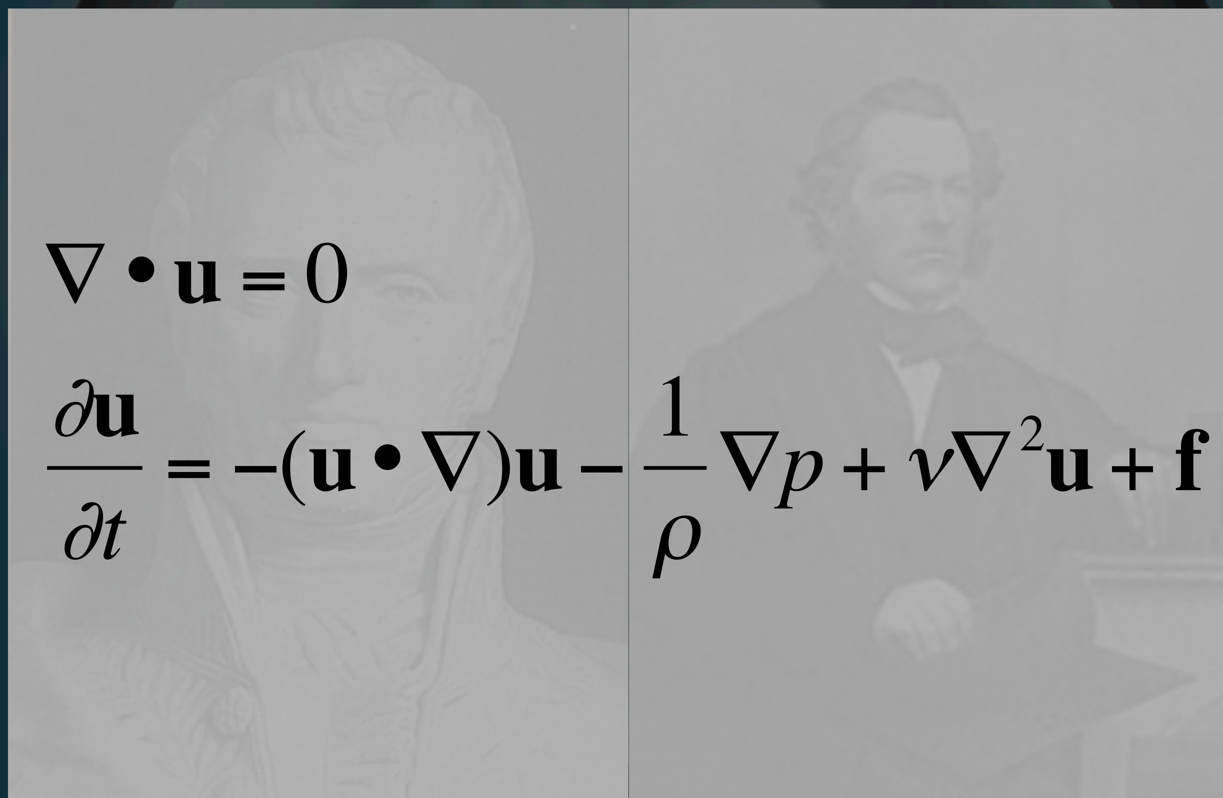
External Forces

Fluid Concepts

- Back to Navier-Stokes



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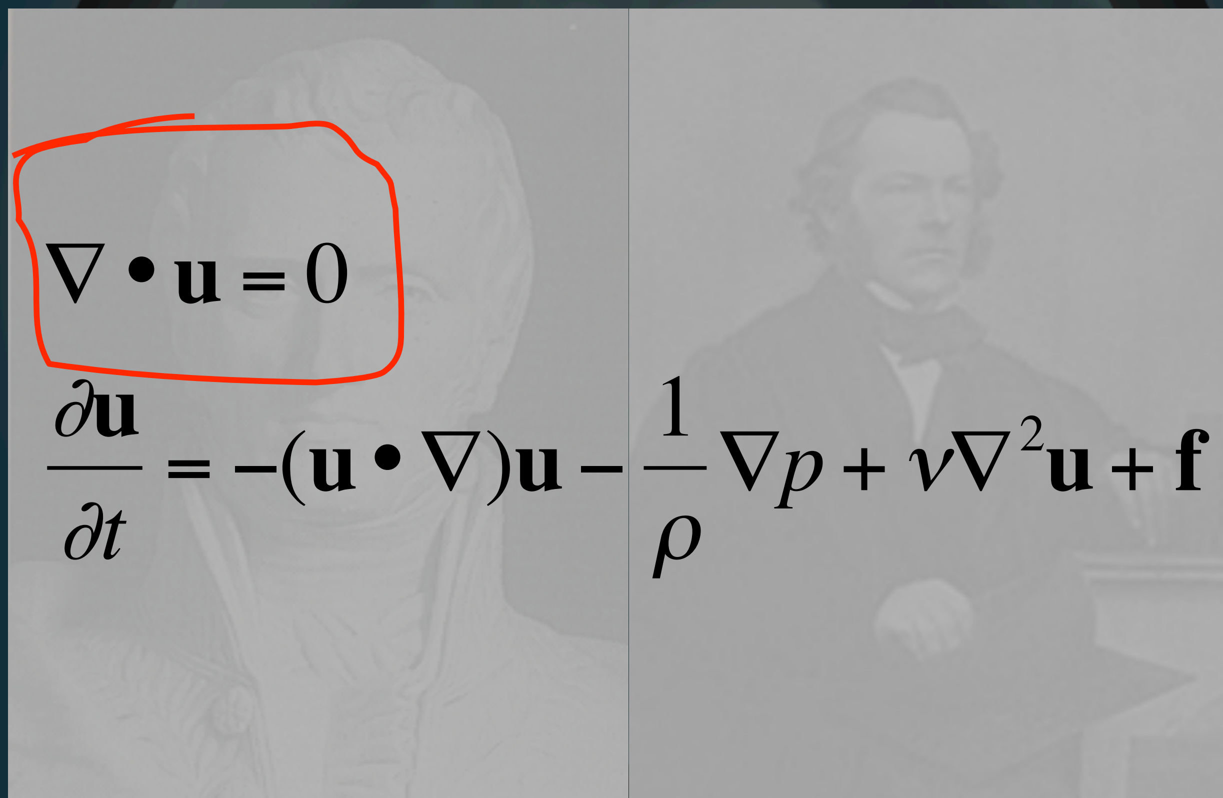
HOLD ON THERE BUCKO…

Fluid Concepts

- Back to Navier-Stokes



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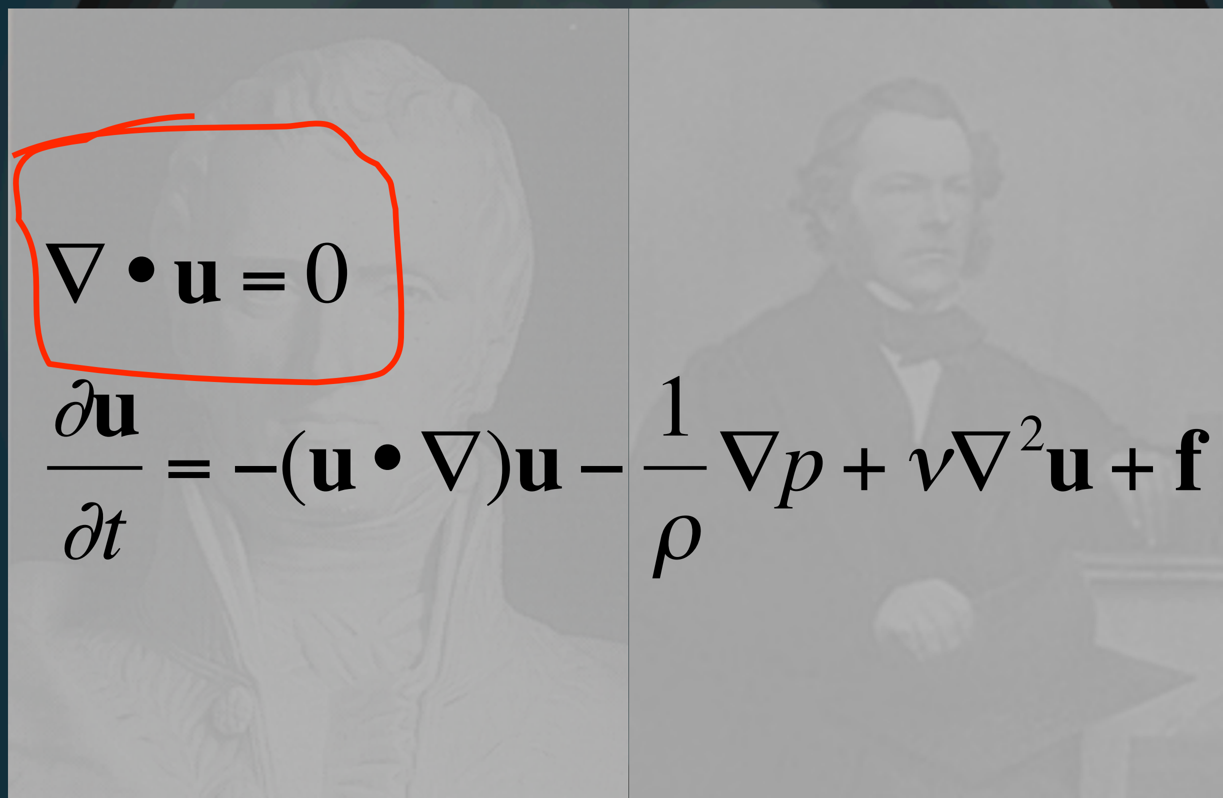
WHAT'S THIS ONE?

Fluid Concepts

- Back to Navier-Stokes



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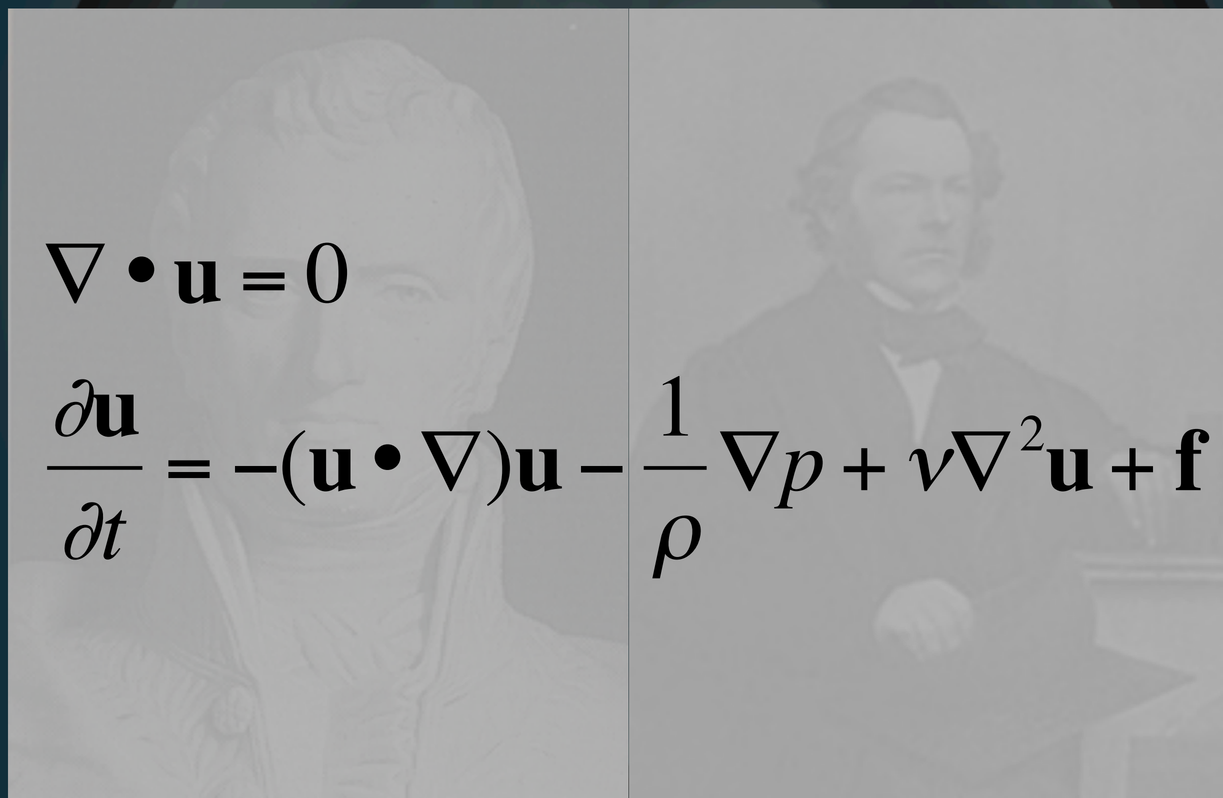
Mass Conservation

Fluid Concepts

- In principle then, Navier-Stokes is…



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Fluid Concepts

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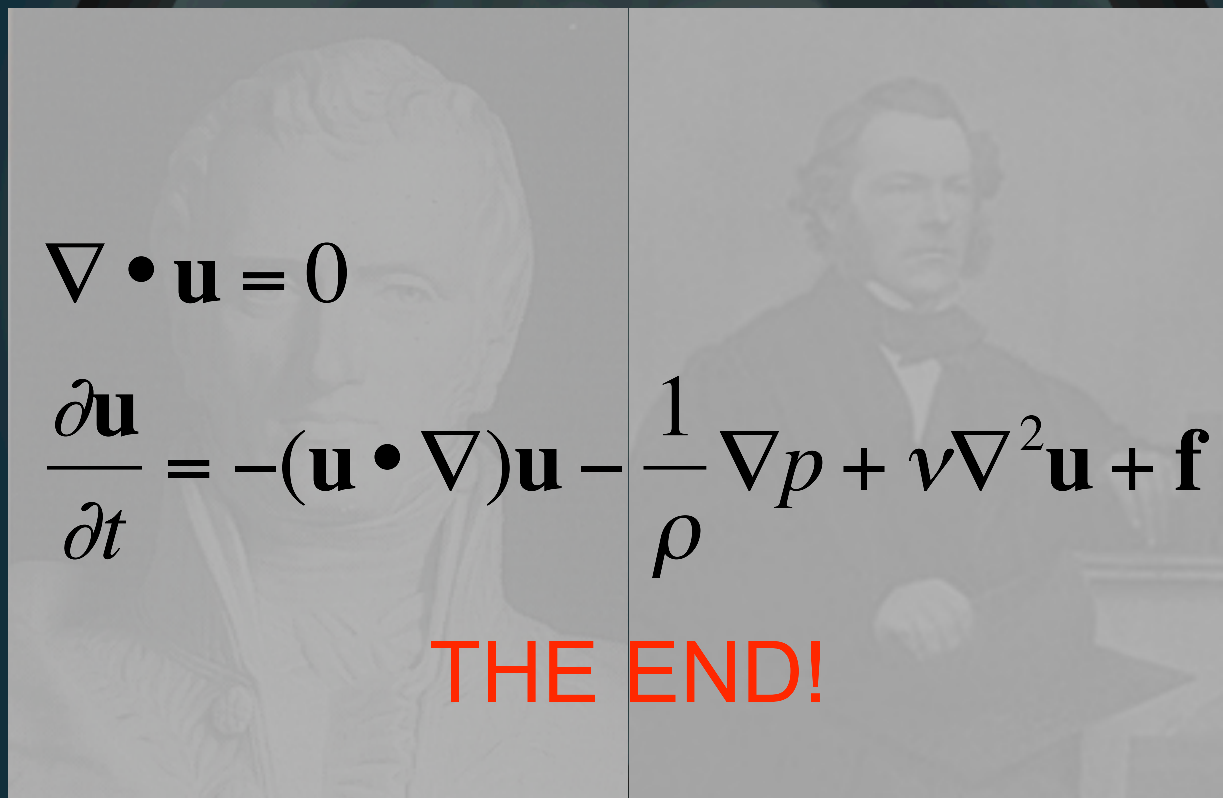

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THE END!

Fluid Concepts

- But not really, of course

Fluid Concepts

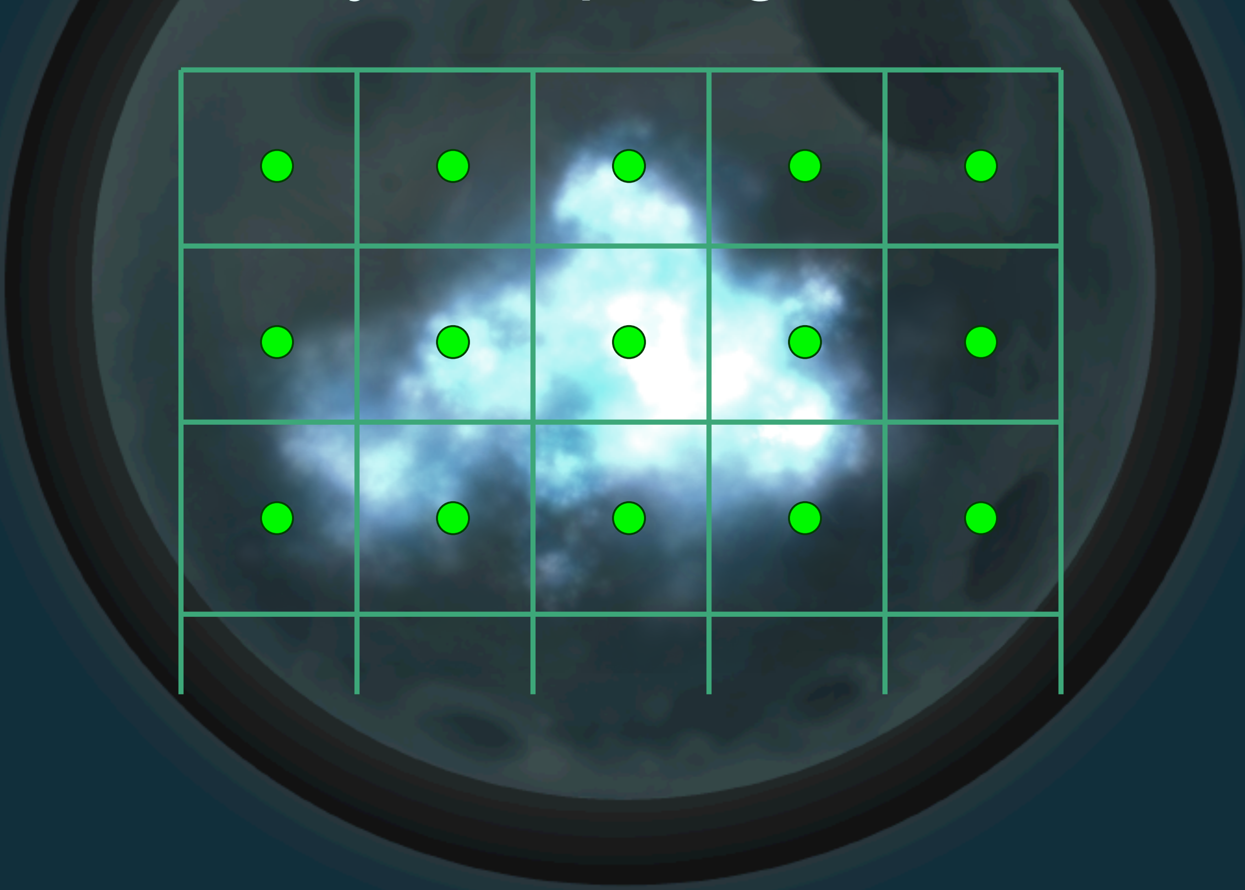
- But not really, of course
- Little tiny detail of implementation

Computational Fluid Types

- Grid-based/Eulerian (Stable Fluids)
- Particle-based/Lagrangian (Smoothed Particle Hydrodynamics)
- Surface-based (wave composition)

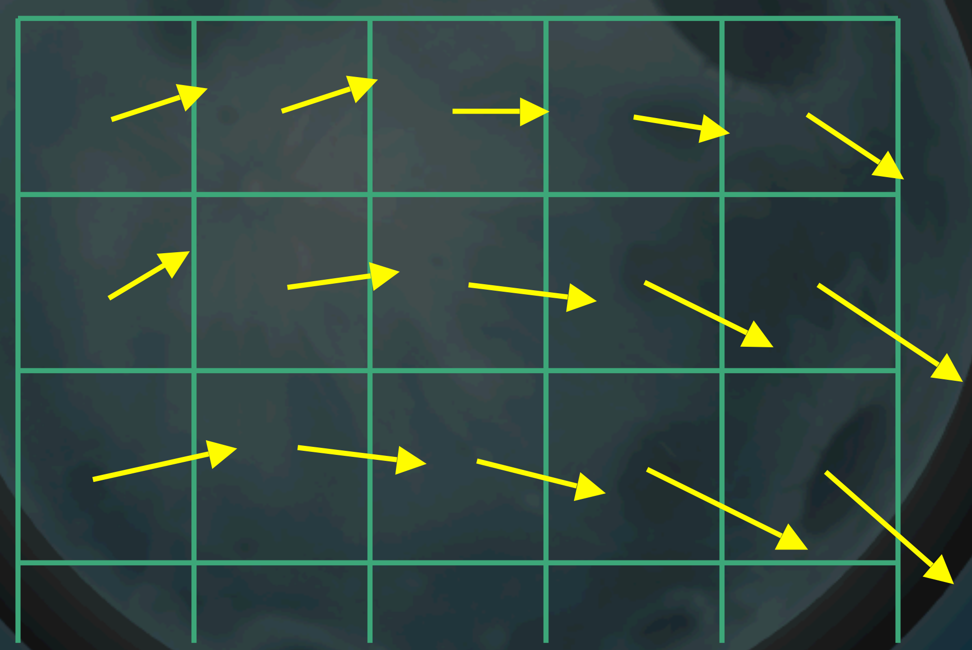
Grid-Based

- Store density, temp in grid centers



Grid-Based

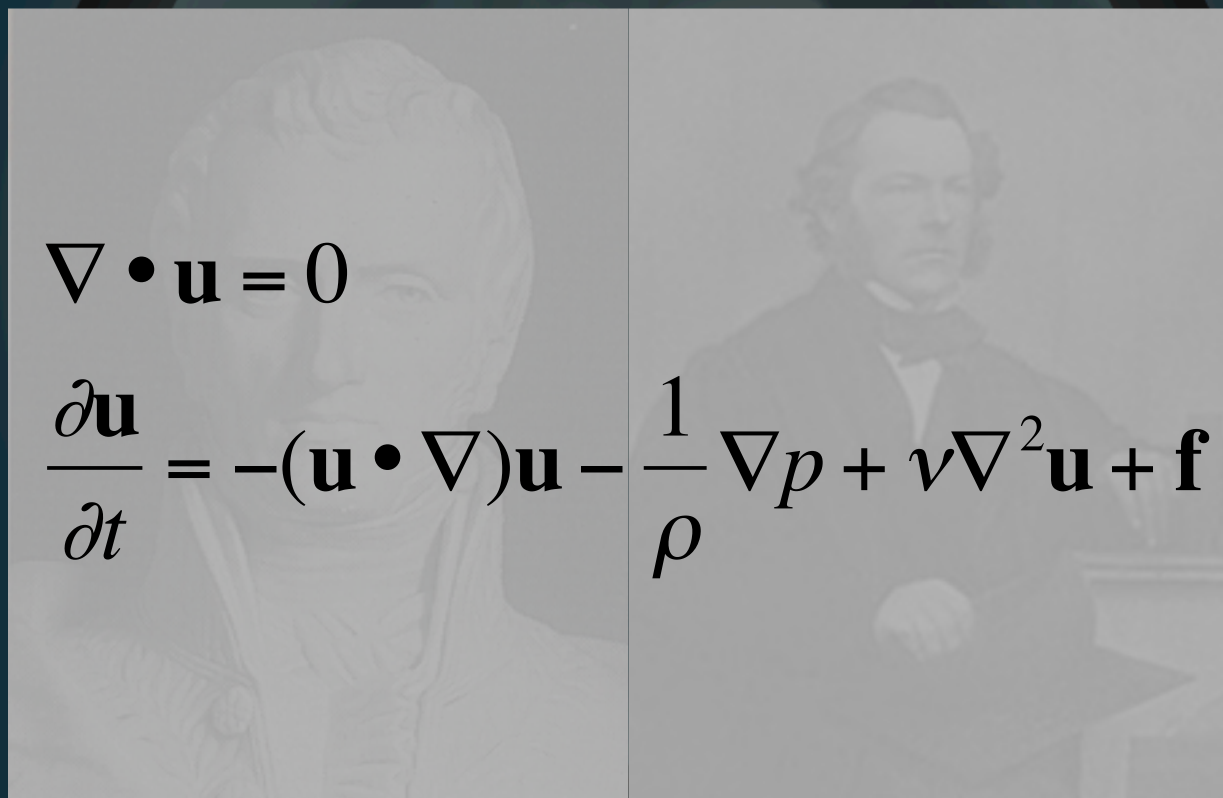
- Velocity (flow) from centers as well



- Could also do edges

Grid-Based

- How do we use this?



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Grid-Based

- Jos Stam devised stable approximation: “Stable Fluids”, SIGGRAPH ‘99

Grid-Based

- How do we use this?

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

Must maintain

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u} \cdot \nabla)\mathbf{u} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}$$

Grid-Based

- How do we use this?

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

Idea: compute

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u} \bullet \nabla)\mathbf{u} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}$$

Grid-Based

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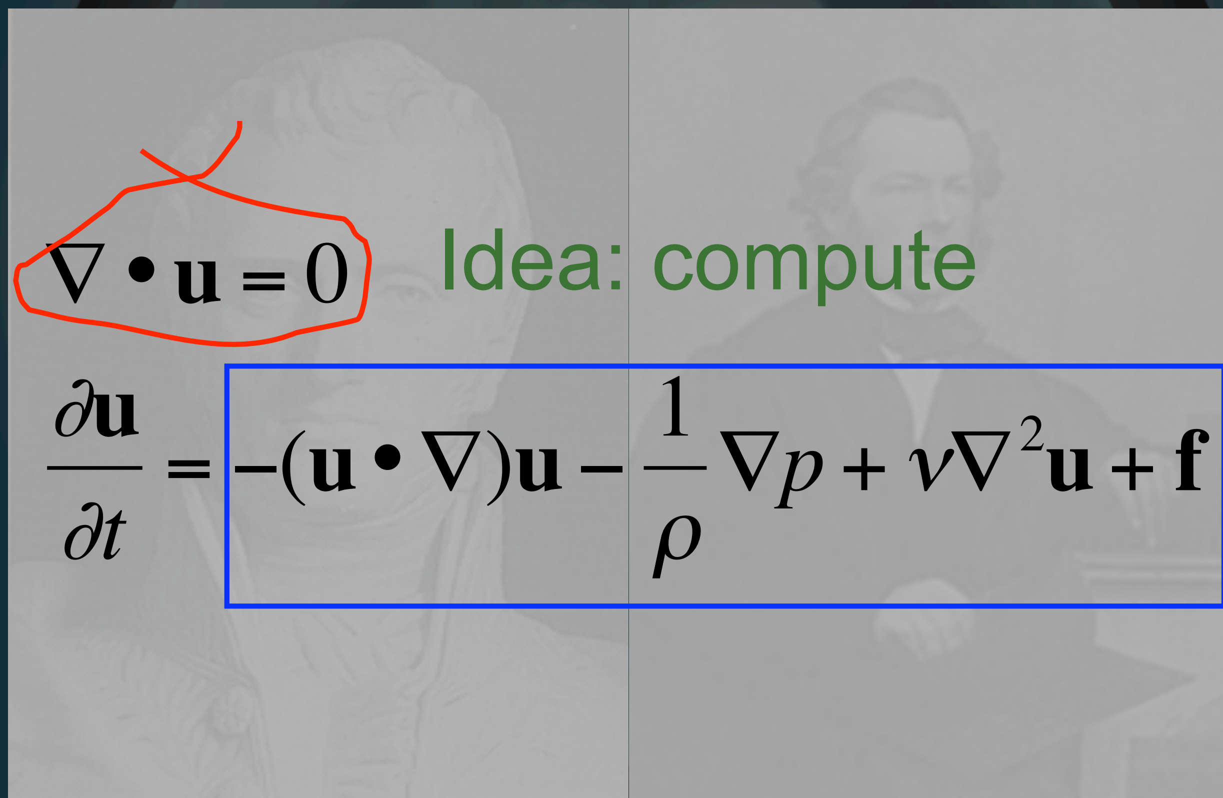

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$$\frac{\partial \mathbf{u}}{\partial t} = \boxed{-(\mathbf{u} \bullet \nabla)\mathbf{u} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}}$$

Grid-Based

- How do we use this?

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

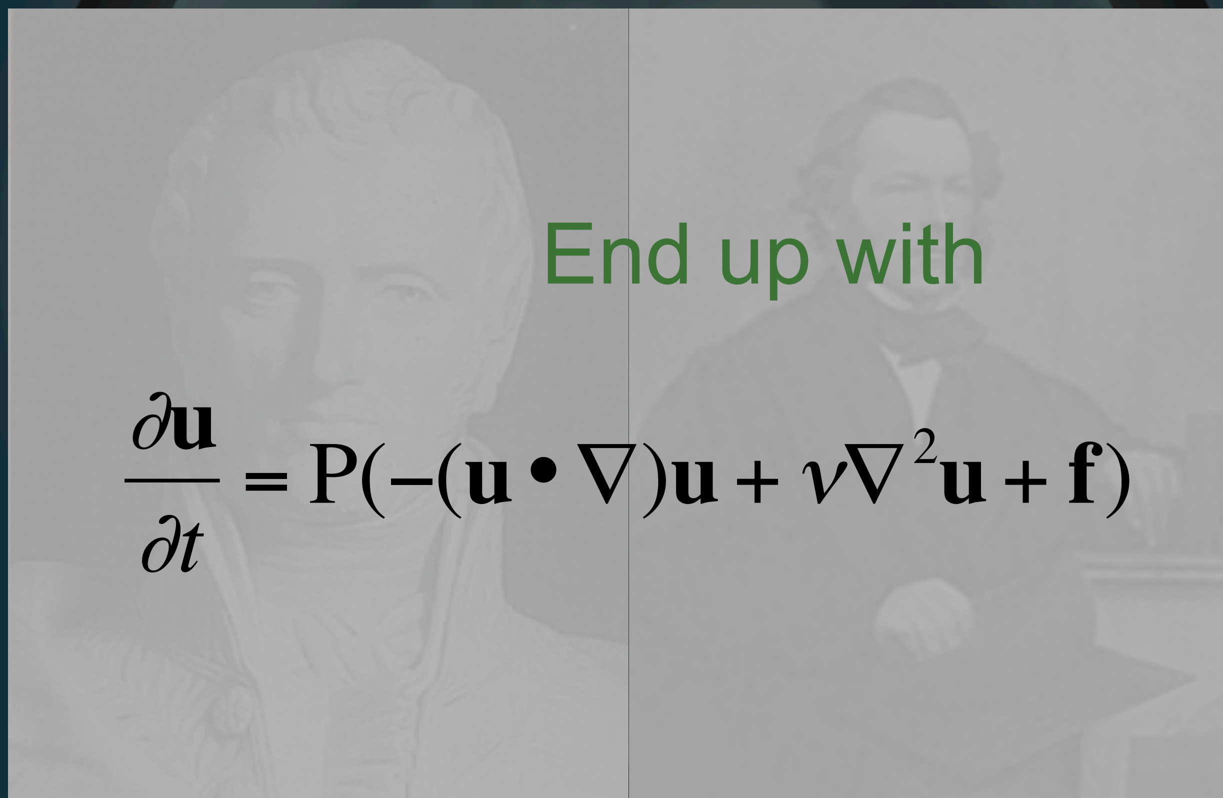
Idea: compute

$$\frac{\partial \mathbf{u}}{\partial t} = \boxed{-(\mathbf{u} \bullet \nabla)\mathbf{u} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}}$$

then project to 0 div field

Grid-Based

- How do we use this?

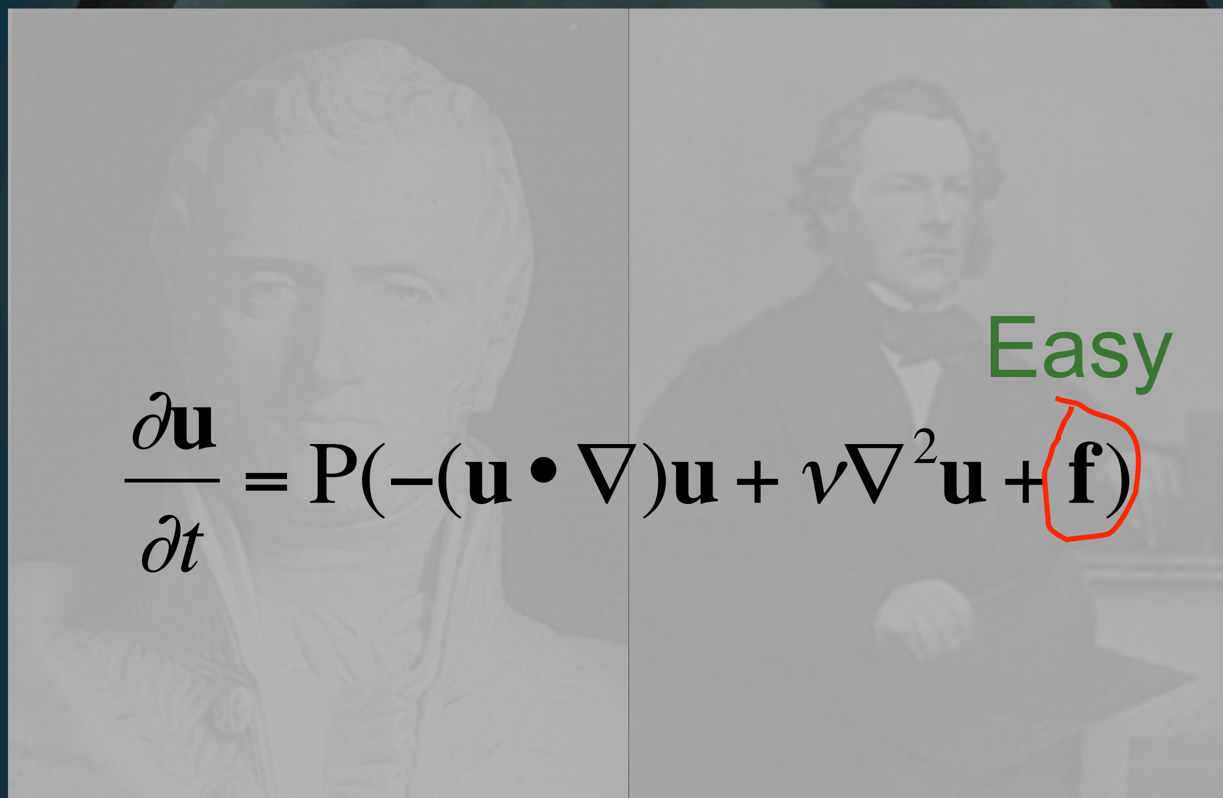


End up with

$$\frac{\partial \mathbf{u}}{\partial t} = \mathrm{P}(-(\mathbf{u} \bullet \nabla)\mathbf{u} + \nu \nabla^2 \mathbf{u} + \mathbf{f})$$

Grid-Based

- How do we use this?

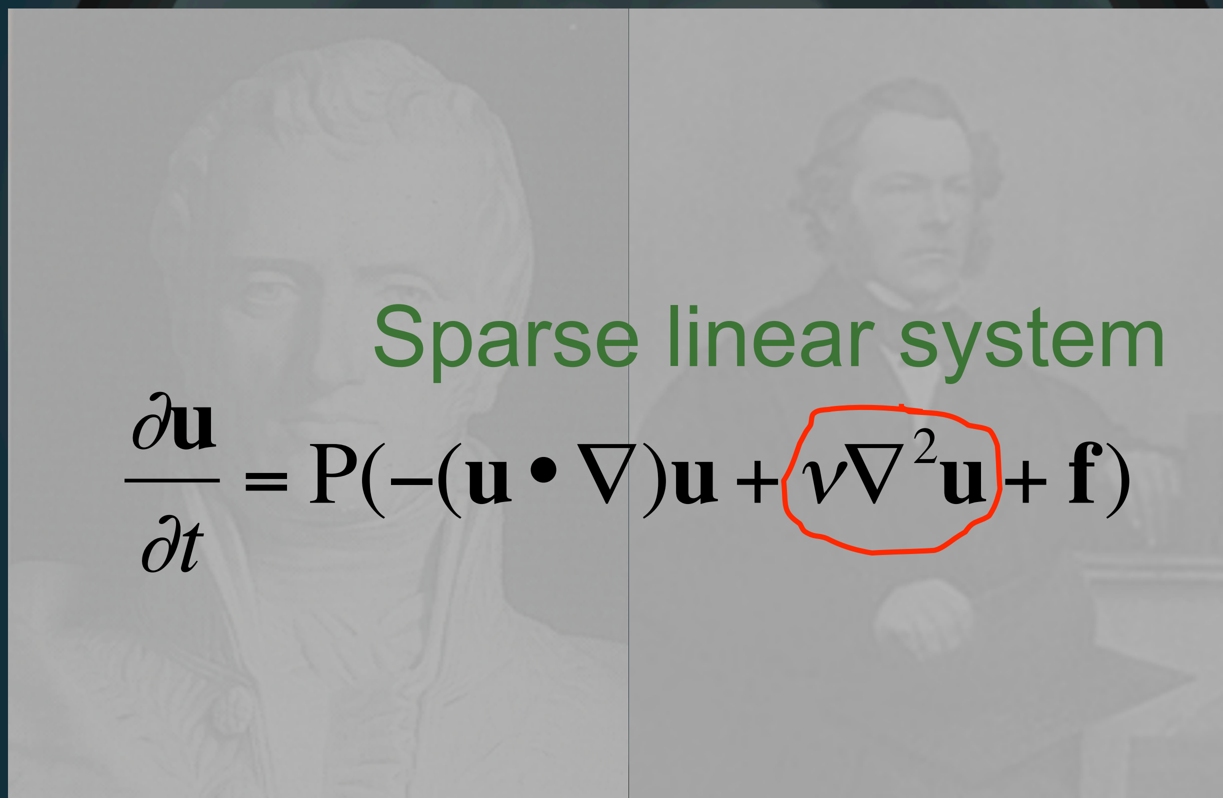


Easy

$$\frac{\partial \mathbf{u}}{\partial t} = \mathrm{P}(-(\mathbf{u} \bullet \nabla)\mathbf{u} + \nu \nabla^2 \mathbf{u} + \mathbf{f})$$

Grid-Based

- How do we use this?

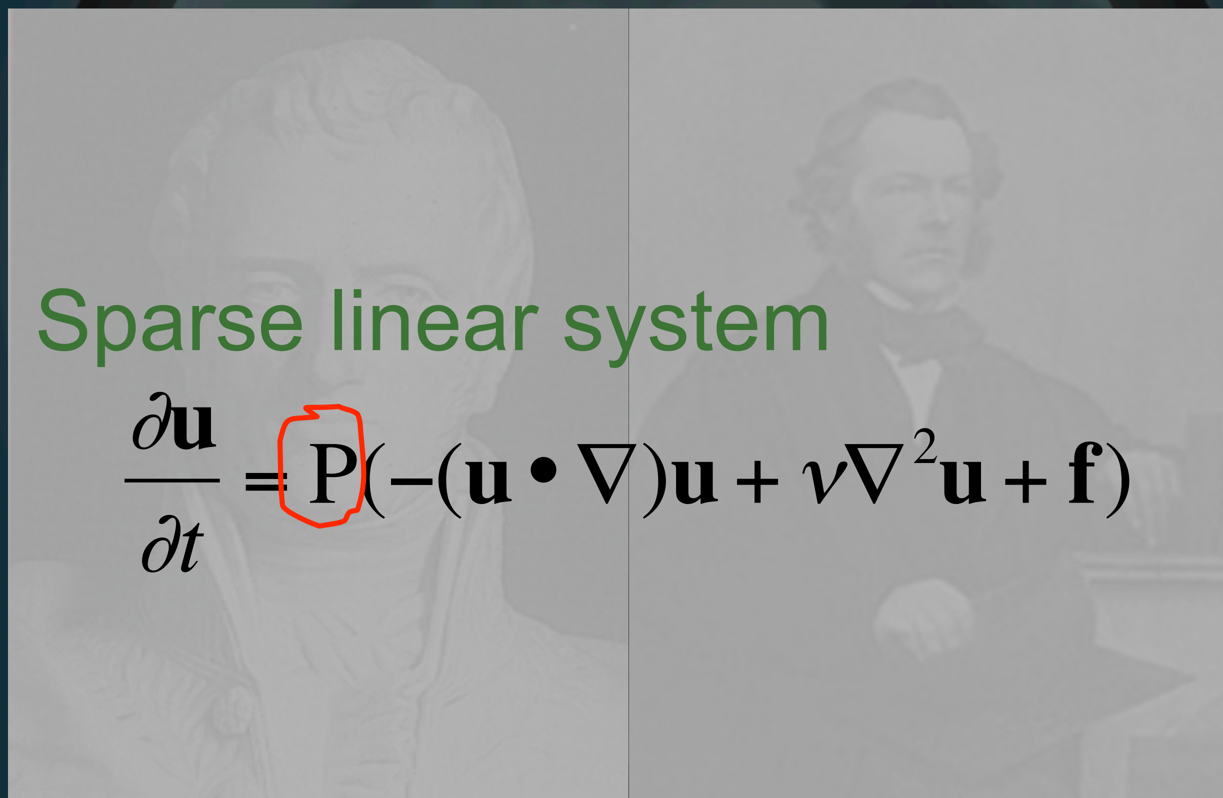


Sparse linear system

$$\frac{\partial \mathbf{u}}{\partial t} = \mathrm{P}(-(\mathbf{u} \bullet \nabla)\mathbf{u} + \nu \nabla^2 \mathbf{u} + \mathbf{f})$$

Grid-Based

- How do we use this?

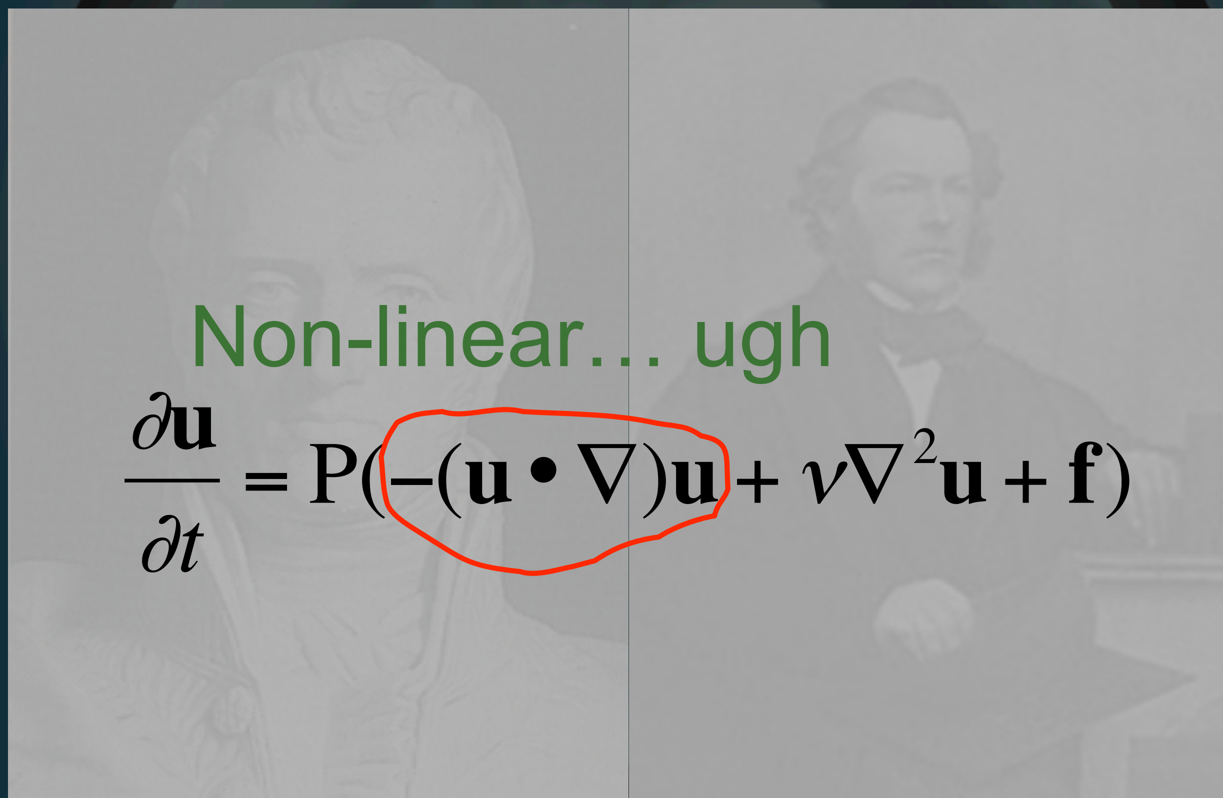


Sparse linear system

$$\frac{\partial \mathbf{u}}{\partial t} = \mathrm{P}\left(-(\mathbf{u} \bullet \nabla)\mathbf{u} + \nu \nabla^2 \mathbf{u} + \mathbf{f}\right)$$

Grid-Based

- How do we use this?



Non-linear… ugh

$$\frac{\partial \mathbf{u}}{\partial t} = \mathrm{P}(-(\mathbf{u} \bullet \nabla)\mathbf{u} + \nu \nabla^2 \mathbf{u} + \mathbf{f})$$

Grid-Based

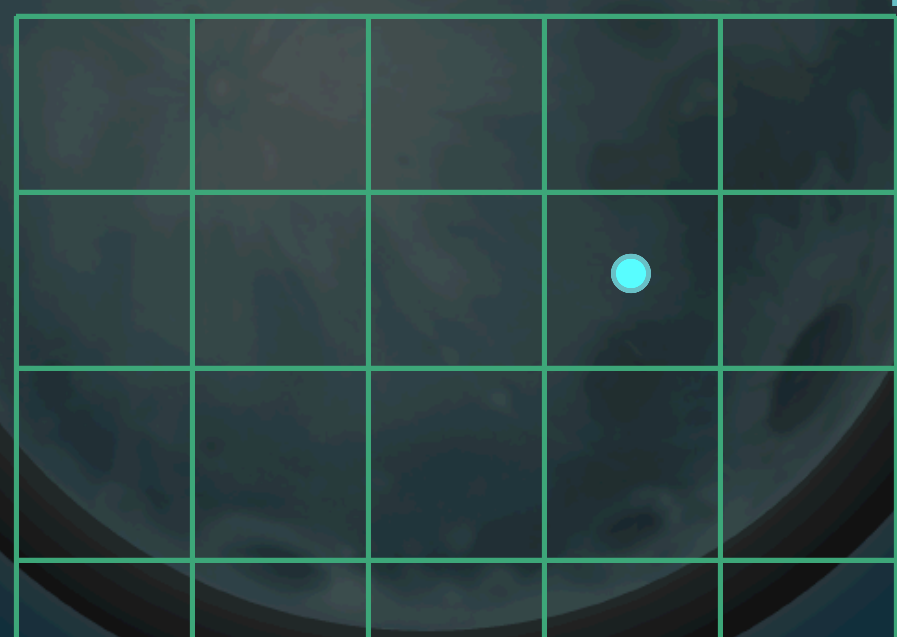
- Updating advection

General idea:

Grid-Based

- Updating advection

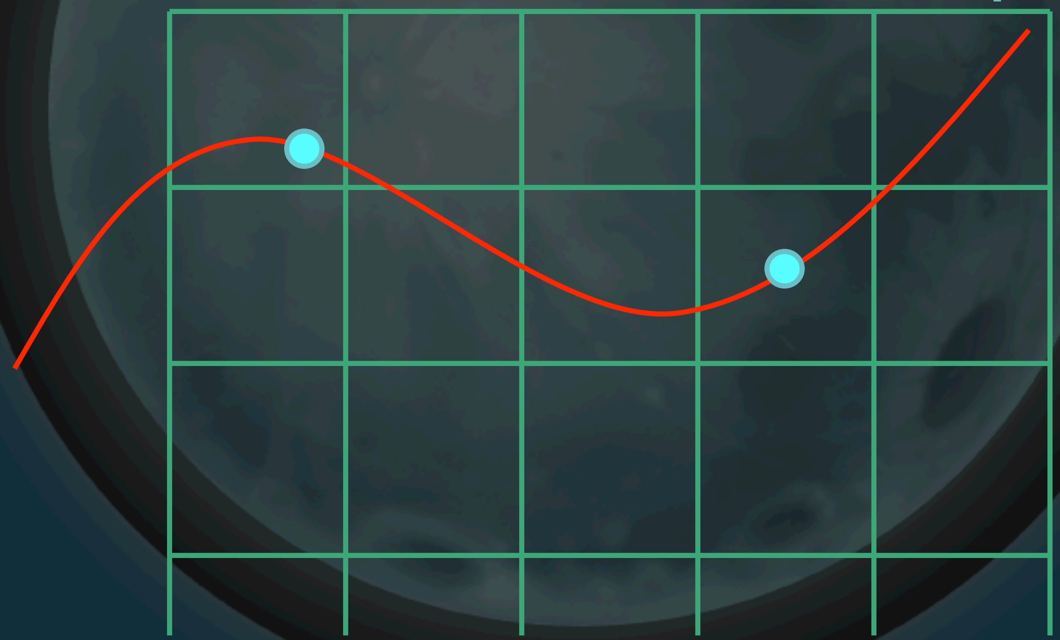
General idea: look at current position



Grid-Based

- Updating advection

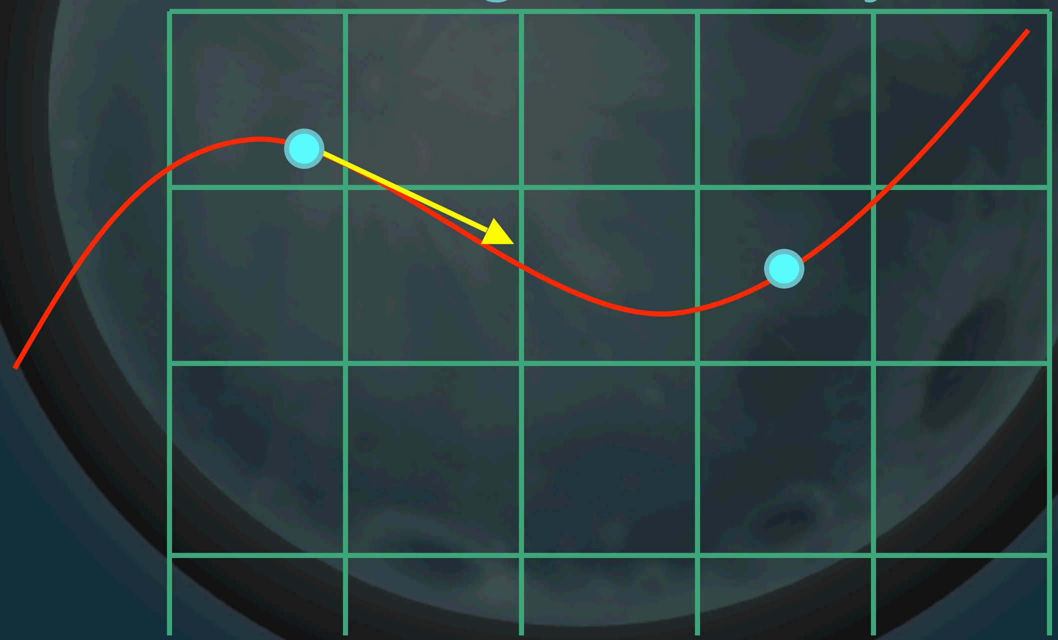
General idea: follow flow to prev. position



Grid-Based

- Updating advection

General idea: get velocity there



Grid-Based

- Updating advection

General idea: assign to current position

Grid-Based

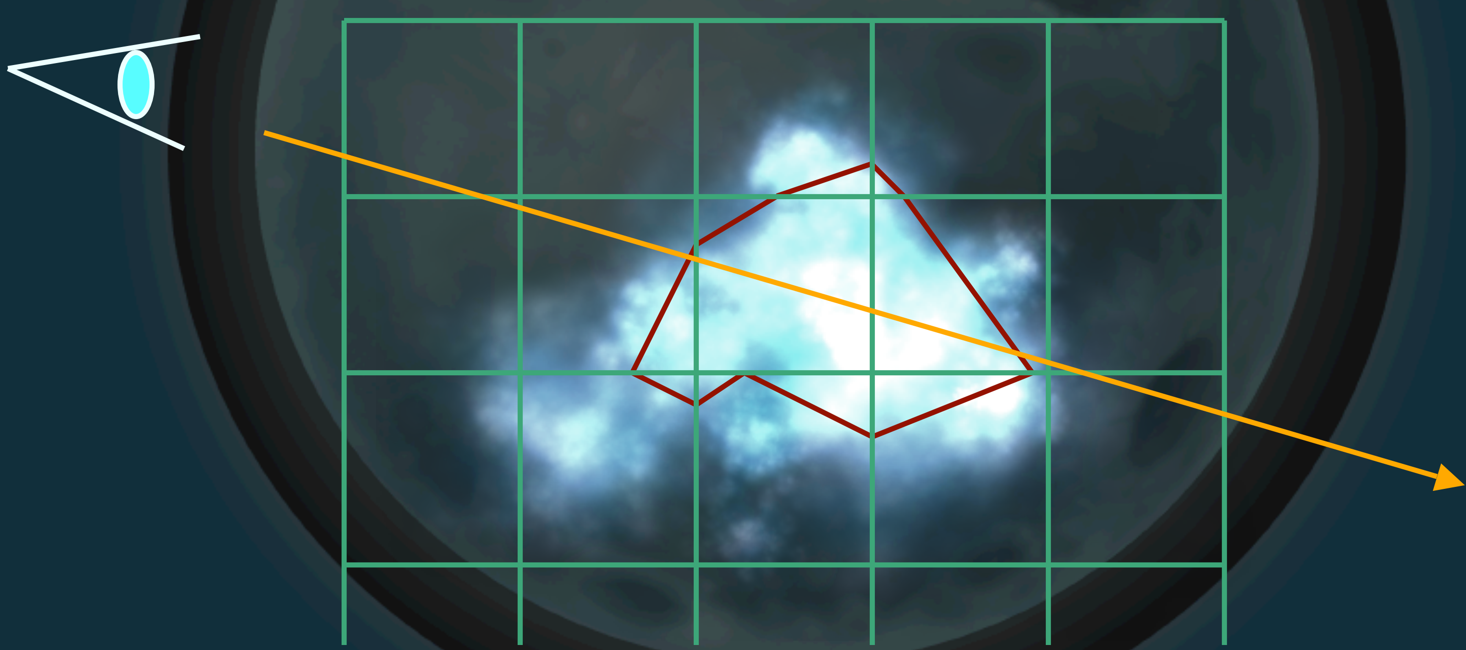
- Overview
  - Update velocities based on
    - Forces, then
    - Advection, then
    - Viscosity
  - Project velocities to zero divergence
  - Update densities based on
    - Input sources
    - Velocity
    - Diffusion (similar to viscosity, sometimes not used)
  - Draw it

Rendering Grid-Based

- Build level surface

Rendering Grid-Based

- Determining color, transparency



Issues

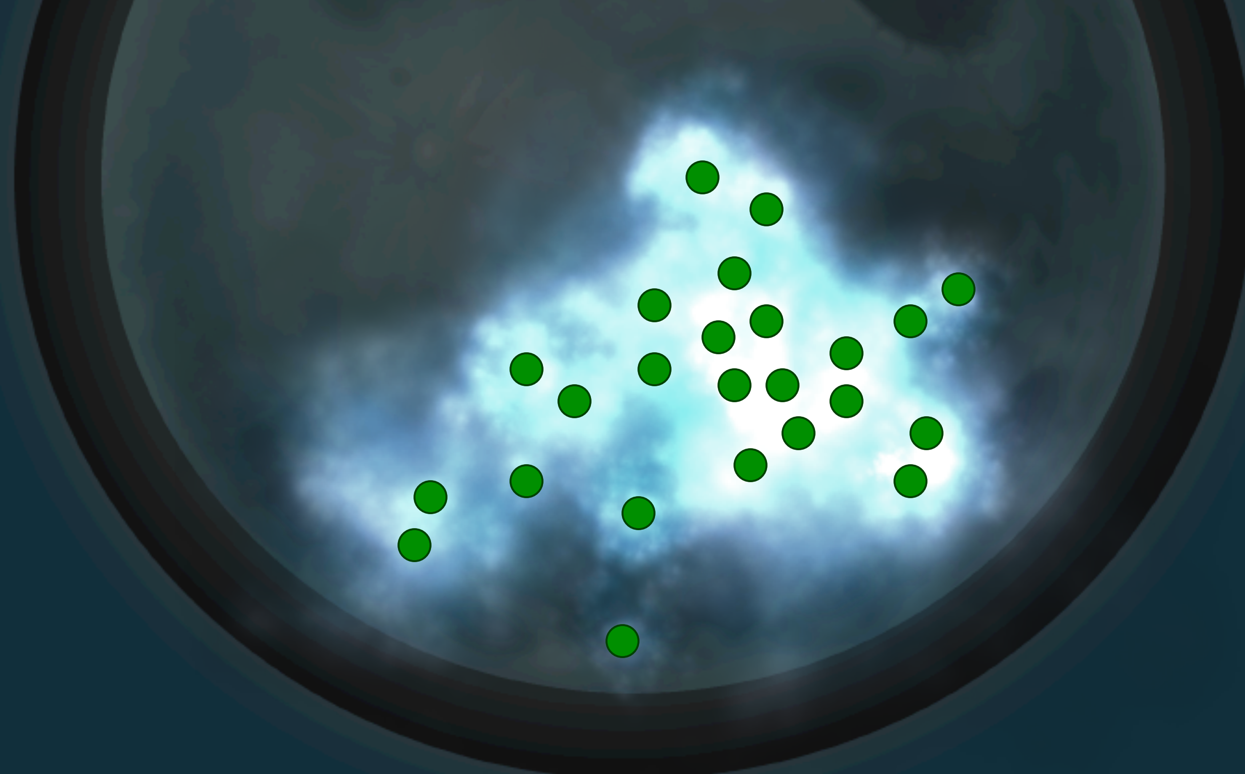
- Limited space
- Water “splashes” get lost
- Can be computationally expensive
- Dampens down
- But stable

Implementation

- Little Big Planet
  - "Death smoke"
  - Bubble pop
  - Other smoke effects
- Hellgate: London
- GDC09 NVIDIA demo

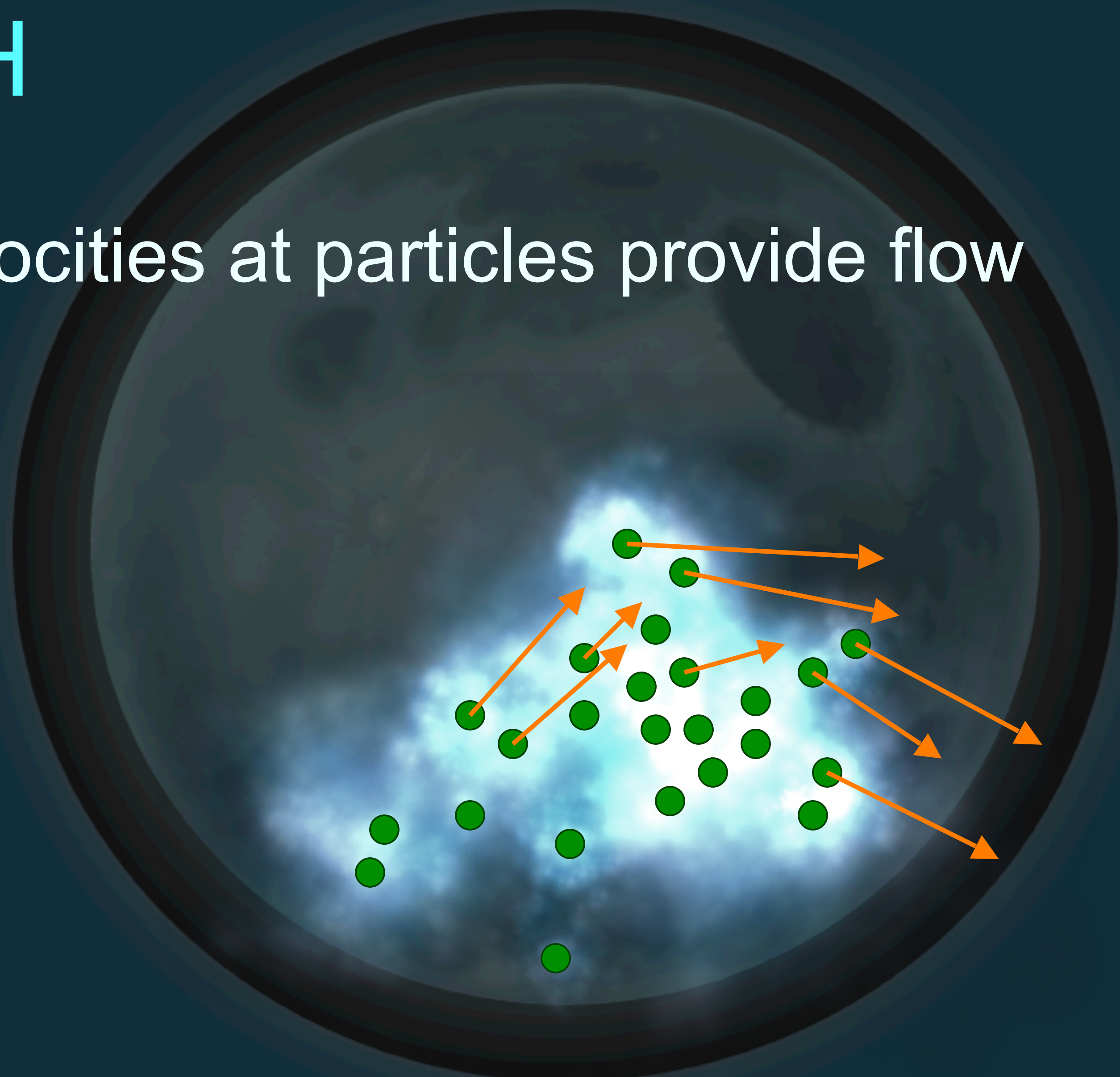
Smoothed Particle Hydrodynamics

- Approximate fluid with small(er) set of particles



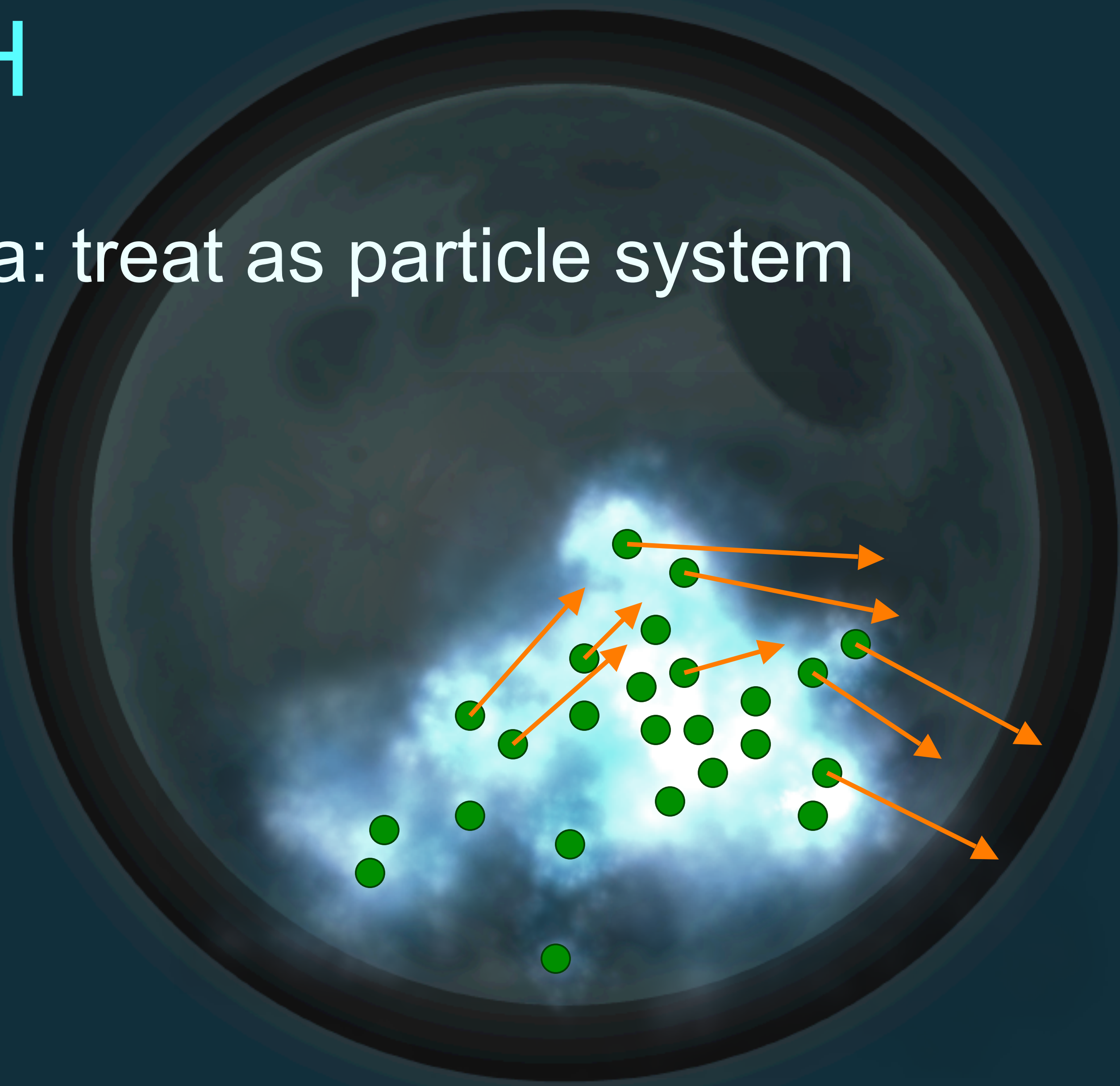
SPH

- Velocities at particles provide flow



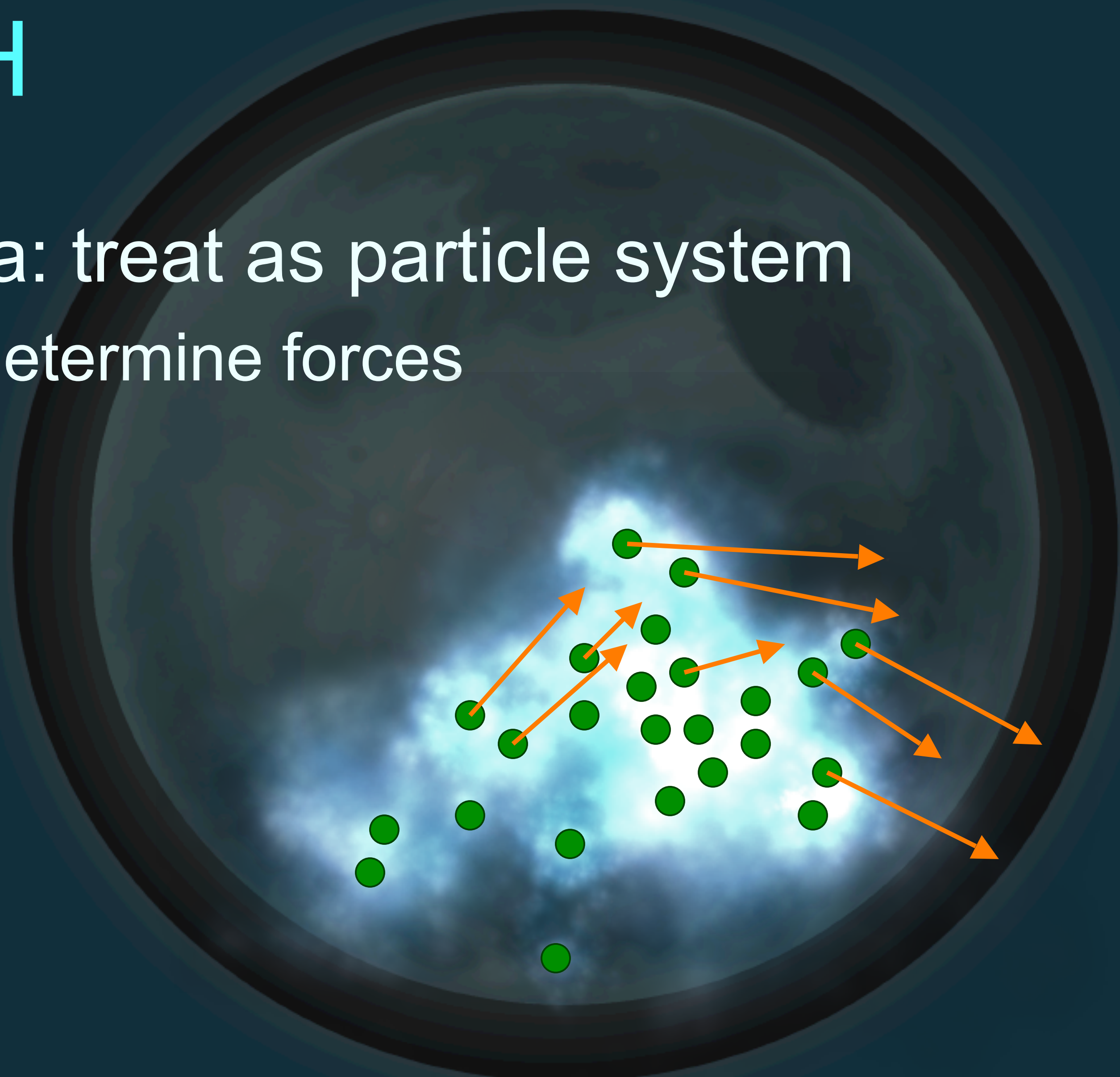
SPH

- Idea: treat as particle system



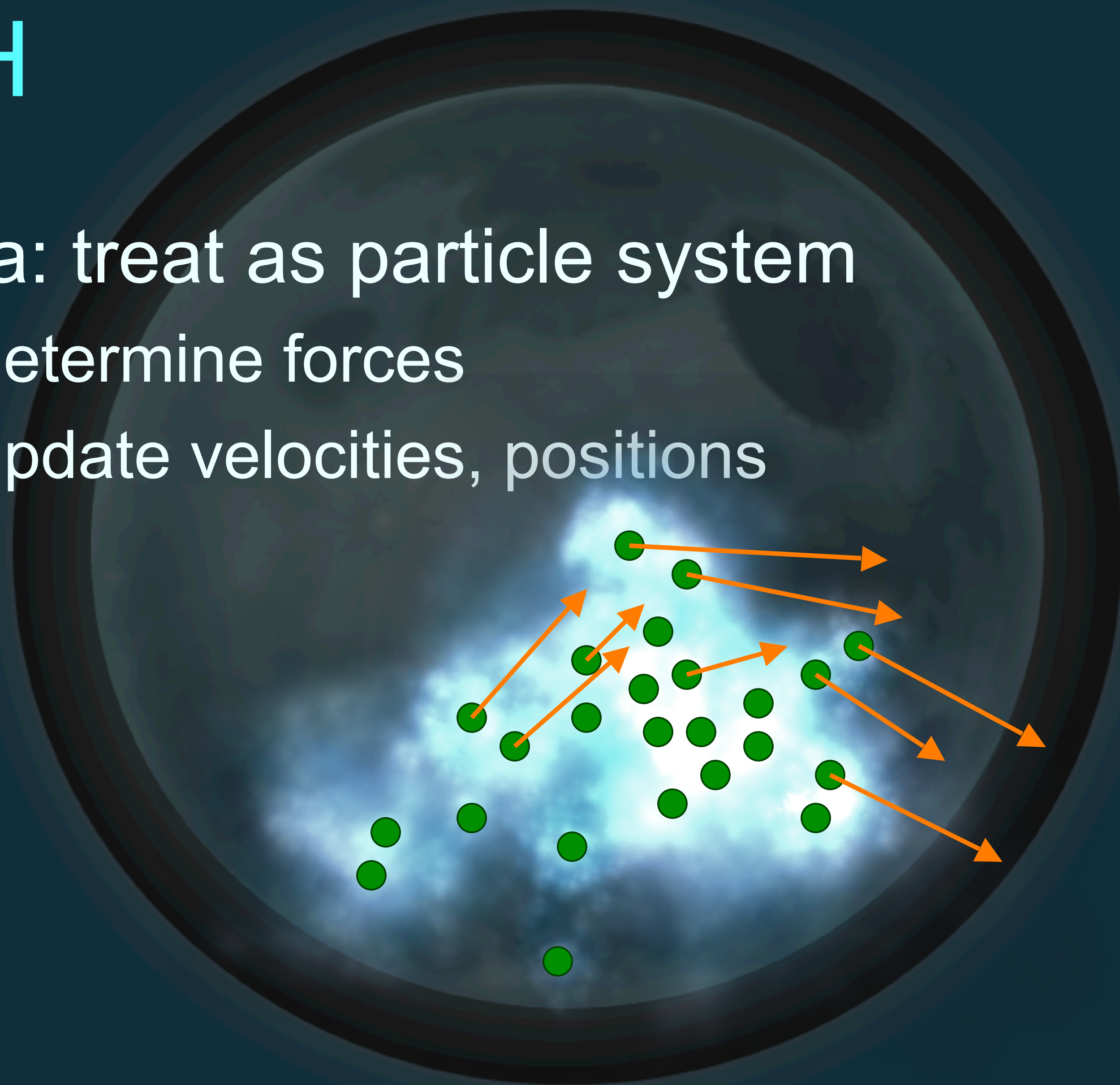
SPH

- Idea: treat as particle system
  - Determine forces



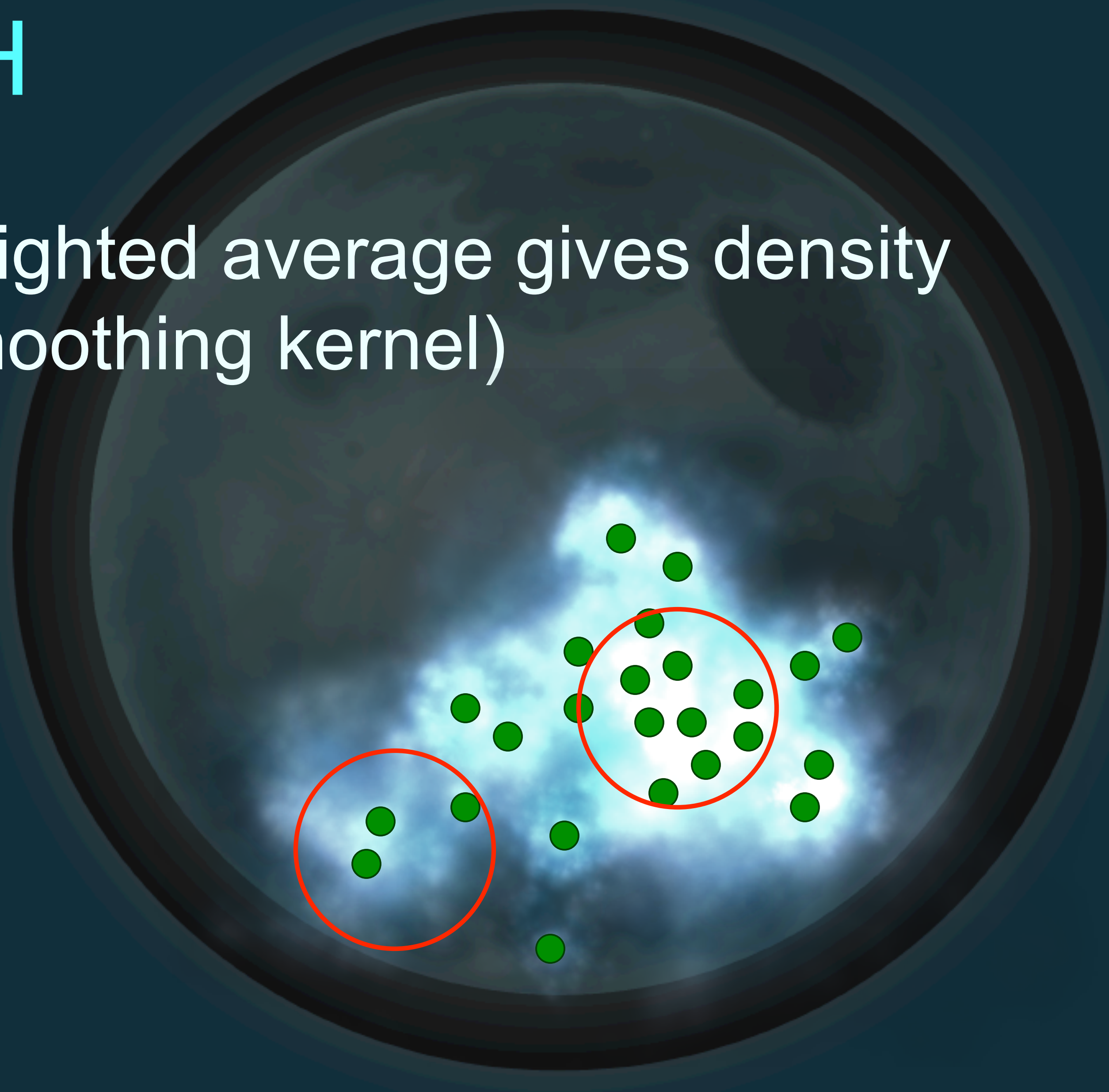
SPH

- Idea: treat as particle system
  - Determine forces
  - Update velocities, positions



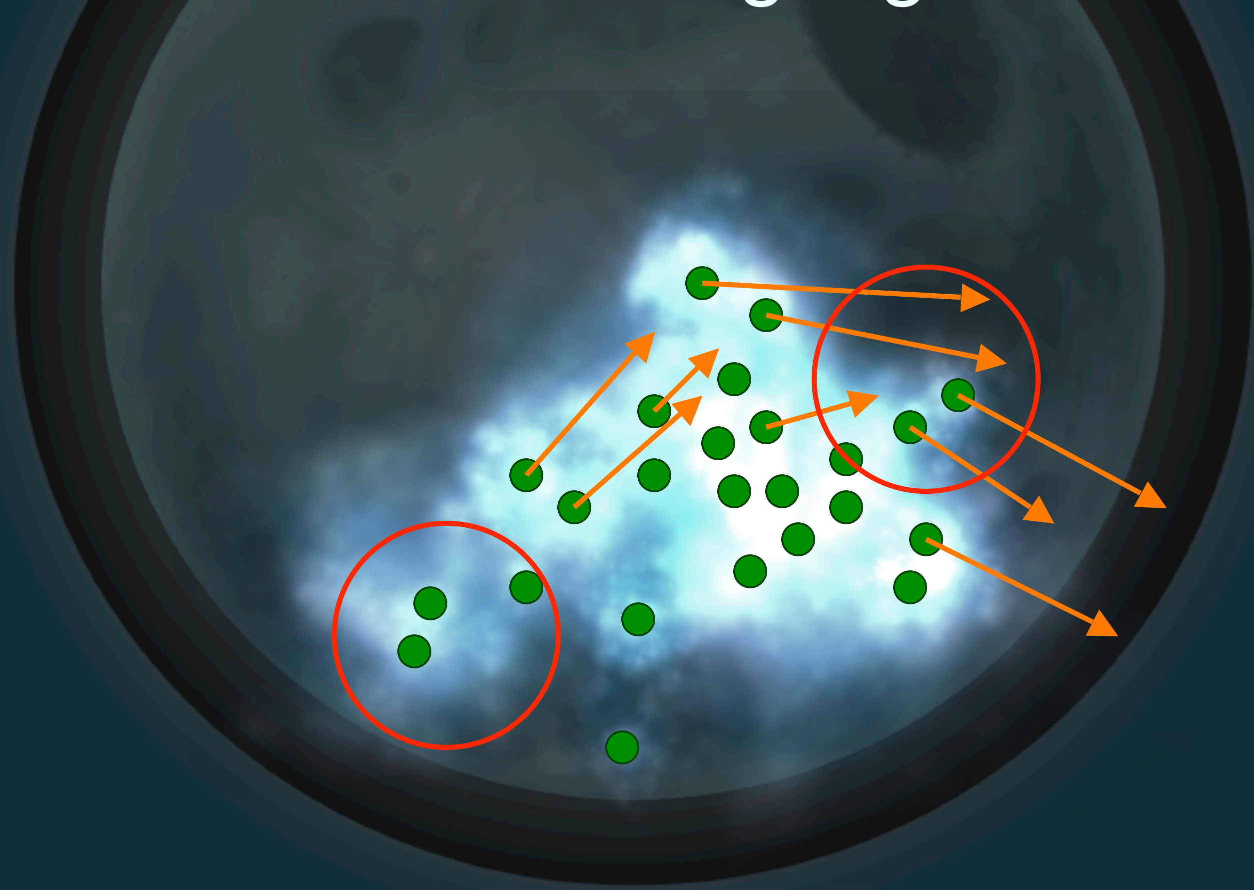
SPH

- Weighted average gives density (smoothing kernel)



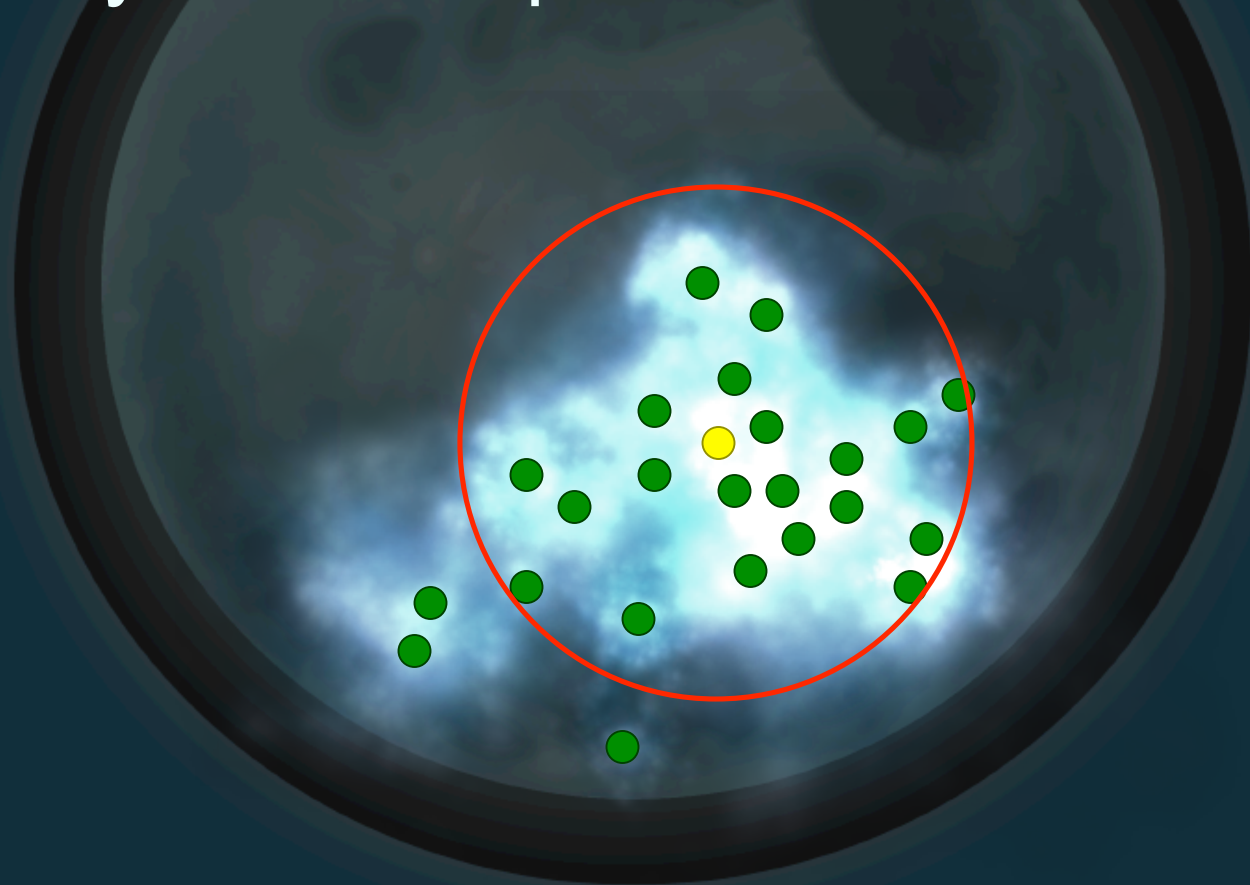
SPH

- Can also use kernel to get general velocity



SPH

- Usually center at particle



SPH

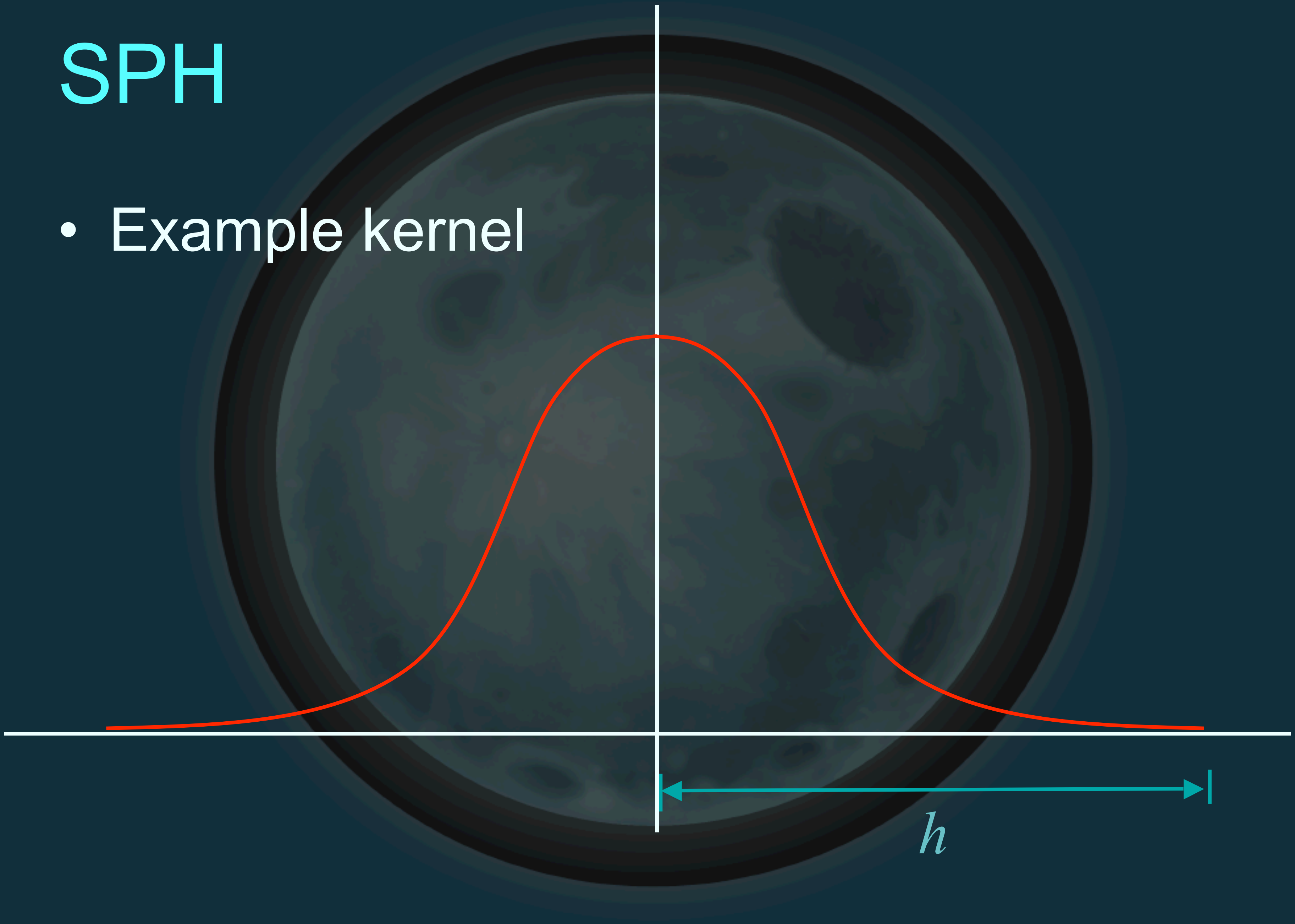
- Specify width by h

SPH

- Specify vector from other particles by $\mathbf{r}$

SPH

- Example kernel



SPH

- Common kernel

$$W_{poly6}(\mathbf{r},h) = \frac{315}{64\pi h^9}\begin{cases}(h^2 - r^2)^3 & 0 \le r \le h \\ 0 & \text{otherwise}\end{cases}$$

SPH

- Common kernel

$$W_{poly6}(\mathbf{r}, h) = \frac{315}{64\pi h^9} \begin{cases} (h^2 - r^2)^3 & 0 \le r \le h \\ 0 & \text{otherwise} \end{cases}$$

Clamps to zero at boundary

SPH

- Common kernel

$$W_{poly6}(\mathbf{r},h) = \frac{315}{64\pi h^9}\begin{cases}(h^2 - r^2)^3 & 0 \le r \le h \\ 0 & \text{otherwise}\end{cases}$$

Clamps to zero at boundary
Uses length squared

SPH

- General SPH rule

$$A_S(\mathbf{x}) = \sum_j m_j \frac{A_j}{\rho_j} W(\mathbf{r} - \mathbf{r}_j, h)$$

SPH

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Particle mass

SPH

- General SPH rule

$$A_S(\mathbf{x}) = \sum_j m_j \frac{A_j}{\rho_j} W(\mathbf{r} - \mathbf{r}_j, h)$$

Quantity at particle *j*

SPH

- General SPH rule

$$A_S(\mathbf{x}) = \sum_j m_j \frac{A_j}{\rho_j} W(\mathbf{r} - \mathbf{r}_j, h)$$

Density at particle *j*

SPH

- General SPH rule

$$A_S(\mathbf{x}) = \sum_j m_j \frac{A_j}{\rho_j} W(\mathbf{r} - \mathbf{r}_j, h)$$

Weighting function

SPH

- Computing density

$$\rho_S(\mathbf{x}) = \sum_j m_j \frac{\rho_j}{\rho_j} W(\mathbf{r} - \mathbf{r}_j, h)$$

SPH

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SPH

- Local pressure

$$p_i = k\rho_i$$

k is gas constant

SPH

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$$p_i = k\rho_i$$

k is gas constant

Can be unstable, so…

SPH

- Local pressure (alternative)

$$p_i = k(\rho_i - \rho_0)$$

No effect on gradient, more stable

SPH

- Back to Navier-Stokes

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

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u} \bullet \nabla)\mathbf{u} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}$$

SPH

- Back to Navier-Stokes

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

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u} \bullet \nabla)\mathbf{u} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}$$

Have fixed # particles and mass, so…

SPH

- Back to Navier-Stokes

$$\cancel{\nabla \bullet \mathbf{u} = 0}$$

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u} \bullet \nabla)\mathbf{u} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}$$

Have fixed # particles and mass, so…
mass is automatically conserved

SPH

- Back to Navier-Stokes

$$\cancel{\nabla \bullet \mathbf{u} = 0}$$

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u} \bullet \nabla)\mathbf{u} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}$$

Advection automagically handled by particle update, so…

SPH

- Back to Navier-Stokes

$$\cancel{\nabla \bullet \mathbf{u} = 0}$$

$$\frac{\partial \mathbf{u}}{\partial t} = \cancel{-(\mathbf{u} \bullet \nabla)\mathbf{u}} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}$$

Advection automagically handled by particle update, so…

SPH

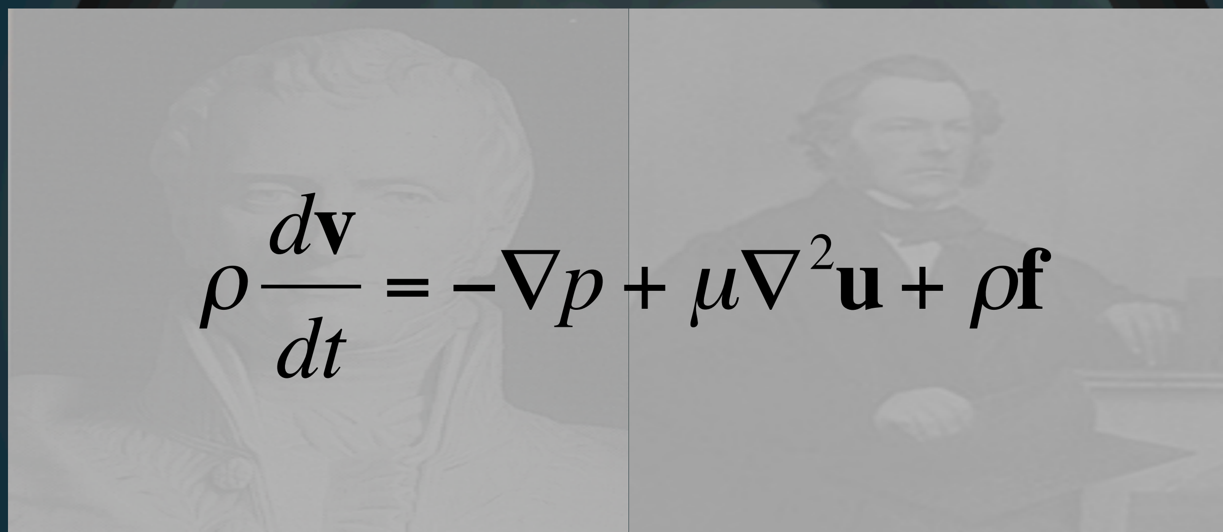
- Simplifies to

$$\cancel{\nabla \bullet \mathbf{u} = 0}$$

$$\frac{\partial \mathbf{u}}{\partial t} = -\cancel{(\mathbf{u} \bullet \nabla)\mathbf{u}} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}$$

SPH

- Simplifies to



$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \mathbf{f}$$

SPH

- Functional breakdown

$$\rho \frac{d\mathbf{u}}{dt} = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \mathbf{f}$$

SPH

- Functional breakdown

$$\rho \frac{d\mathbf{u}}{dt} = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \mathbf{f}$$

Change in velocity

SPH

- Functional breakdown

$$\rho \frac{d\mathbf{u}}{dt} = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \mathbf{f}$$

Pressure

SPH

- Functional breakdown

$$\rho \frac{d\mathbf{u}}{dt} = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \mathbf{f}$$

Viscosity

SPH

- Functional breakdown

$$\rho \frac{d\mathbf{u}}{dt} = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \mathbf{f}$$

External forces

SPH

- Compute densities, local pressure
- Generate forces on particles
  - External
  - Pressure
  - Viscosity
- Update velocities, positions
- Render

SPH

- Pressure

$$\mathbf{f}_i^{pressure} = -\nabla p(\mathbf{r}_i)$$

SPH

- Pressure

$$\mathbf{f}_i^{pressure} = \sum_j m_j \frac{p_j}{\rho_j} \nabla W(\mathbf{r}_i - \mathbf{r}_j, h)$$

SPH

- Pressure

$$\mathbf{f}_i^{pressure} = \sum_j m_j \frac{p_j}{\rho_j} \nabla W(\mathbf{r}_i - \mathbf{r}_j, h)$$

Asymmetric, so…

SPH

- Pressure

$$\mathbf{f}_i^{pressure} = \sum_j m_j \frac{p_i + p_j}{2\rho_j} \nabla W(\mathbf{r}_i - \mathbf{r}_j, h)$$

Ensures 2-particle interaction equal

SPH

- Pressure kernel

  Problem: gradient of poly6 kernel is zero at origin

SPH

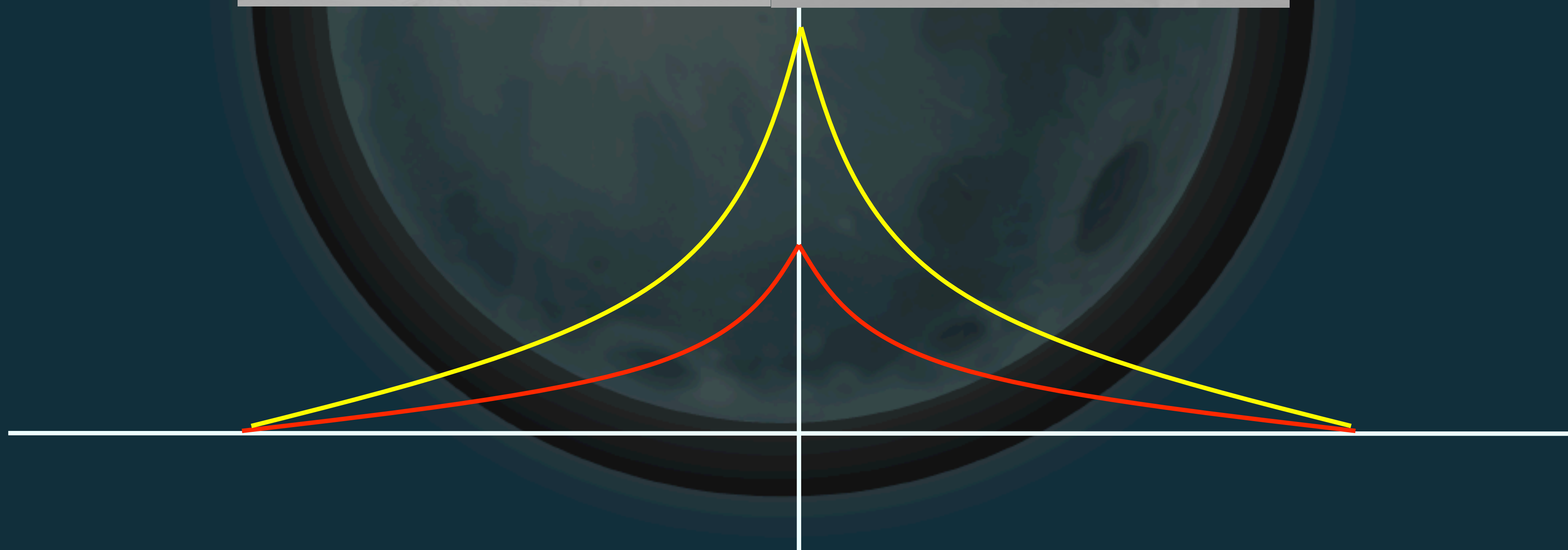
- Pressure kernel

  Problem: gradient of poly6 kernel is zero at origin

SPH

- Pressure kernel

$$W_{\text{spiky}}(\mathbf{r},h) = \frac{15}{\pi h^6} \begin{cases} (h-r)^3 & 0 \le r \le h \\ 0 & \text{otherwise} \end{cases}$$



SPH

- Viscosity

$$\mathbf{f}_i^{\text{viscosity}} = \mu \nabla^2 \mathbf{v}(\mathbf{r}_i)$$

SPH

- Viscosity

$$\mathbf{f}_i^{\text{viscosity}} = \mu \sum_j m_j \frac{\mathbf{v}_j}{\rho_j} \nabla^2 W(\mathbf{r}_i - \mathbf{r}_j, h)$$

SPH

- Viscosity

$$\mathbf{f}_i^{\text{viscosity}} = \mu \sum_j m_j \frac{\mathbf{v}_j}{\rho_j} \nabla^2 W(\mathbf{r}_i - \mathbf{r}_j, h)$$

Also asymmetric, so…

SPH

- Viscosity

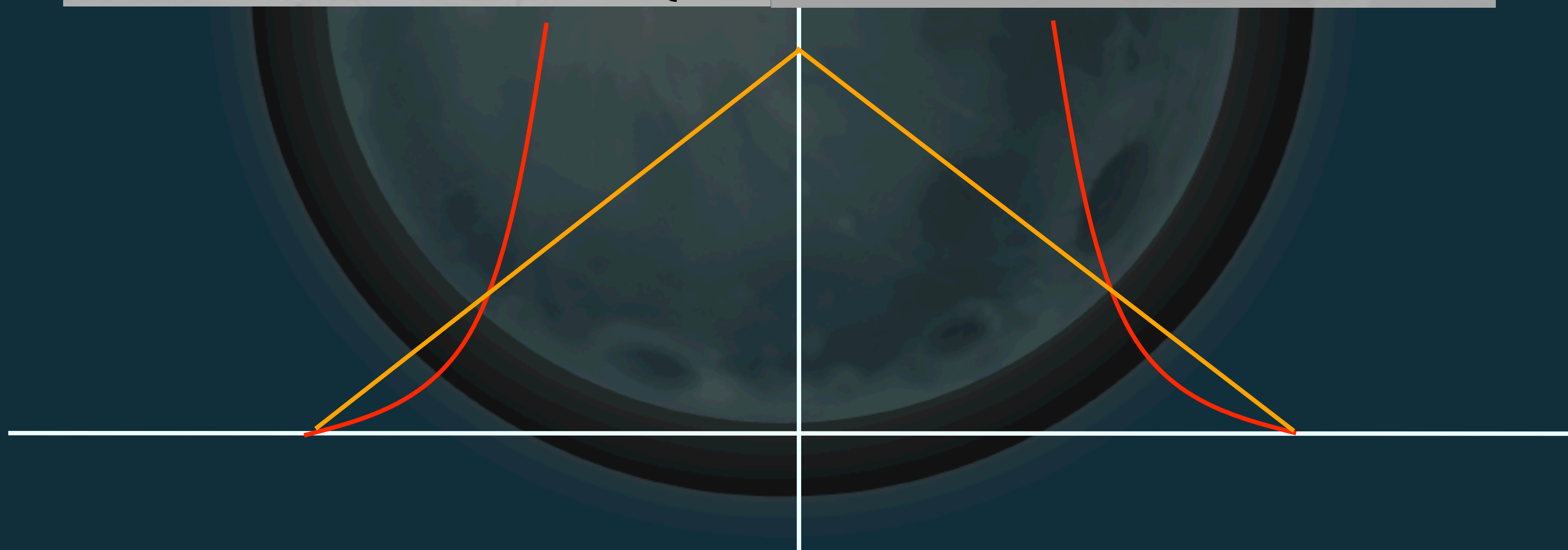
$$\mathbf{f}_i^{\text{viscosity}} = \mu \sum_j m_j \frac{\mathbf{v}_j - \mathbf{v}_i}{\rho_j} \nabla^2 W(\mathbf{r}_i - \mathbf{r}_j, h)$$

Ensures 2-particle interaction opposite

SPH

- Viscosity kernel

$$W_{\text{viscosity}}(\mathbf{r},h) = \frac{15}{2\pi h^3}\begin{cases} -\frac{r^3}{2h^3} + \frac{r^2}{h^2} + \frac{h}{2r} - 1 & 0 \le r \le h \\ 0 & \text{otherwise} \end{cases}$$



SPH

- Rendering
  - Marching cubes (using smoothing kernel)
  - Blobs around particles/splatting

SPH Implementations

- Takahiro Harada
- Kees van Kooten (Playlogic)
- NVIDIA PhysX
- Rama Hoetzlein* (SPH Fluids 2.0)
- Takashi AMADA*

* Source code available

SPH Issues

- Need a *lot* of particles
- Computing level surface can be a pain
- Can be difficult to get stable simulation

SPH Improvements

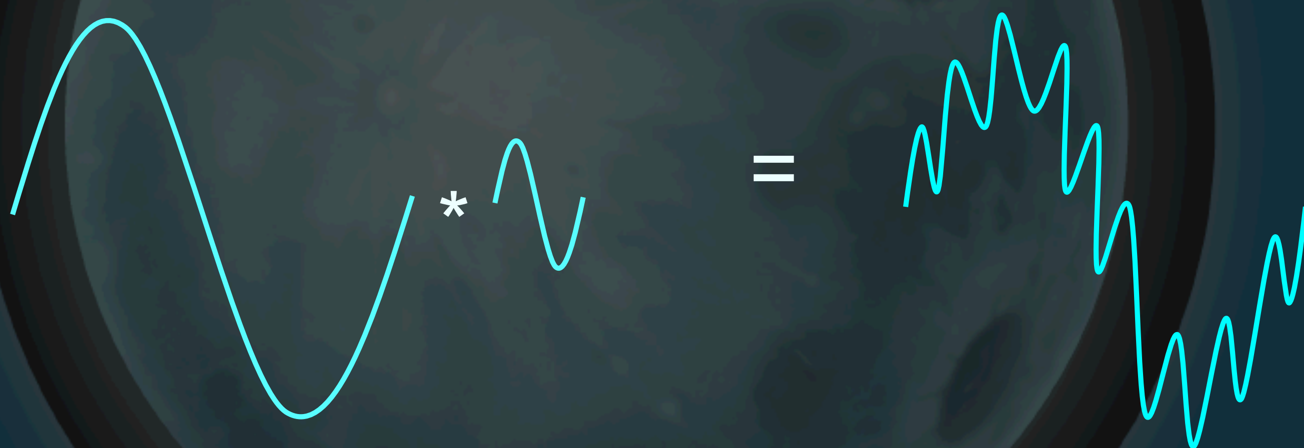
- Spatial hashing
- Variable kernel width
- CFD/SPH Hybrid
  – CFD manages general flow
  – SPH “splashes”

Surface Simulation

- Idea: for water, all we care about is the air-water boundary (level surface)
- Why simulate the rest?
- This is what Insomniac R20 system does

R20

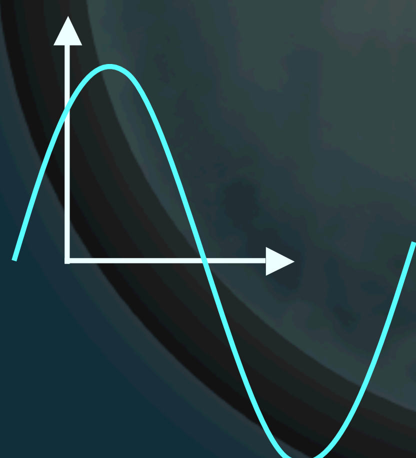
- Done by Mike Day, based on *Titanic* water
  - Basic idea: convolve sinusoids procedurally



  - Much cheaper to multiply in frequency domain and do FFT (assuming periodic)

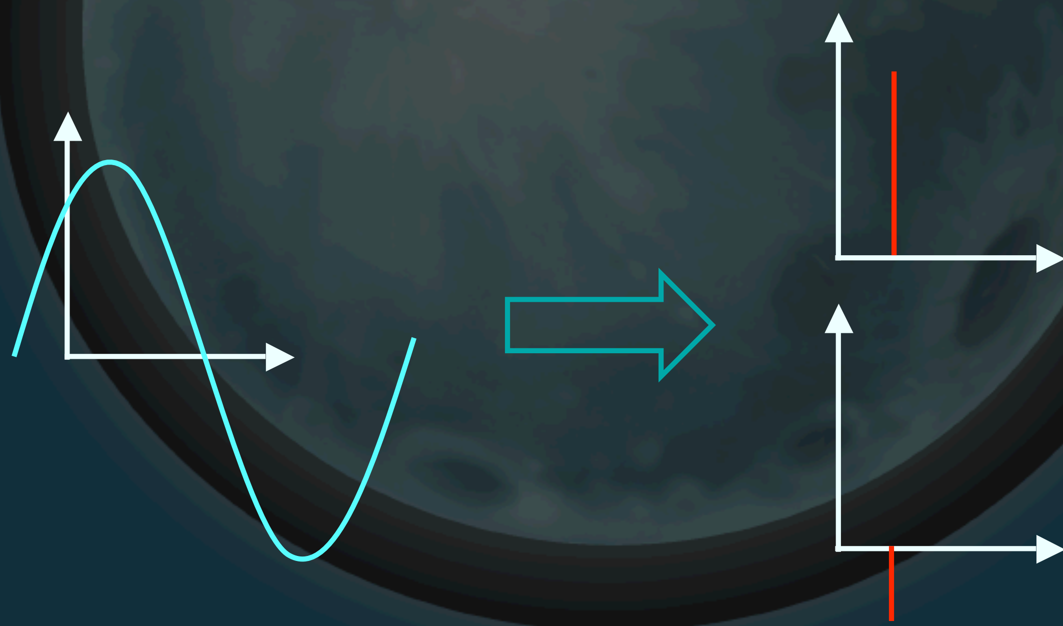
R2O

- Review
  - Sinusoid in spatial domain



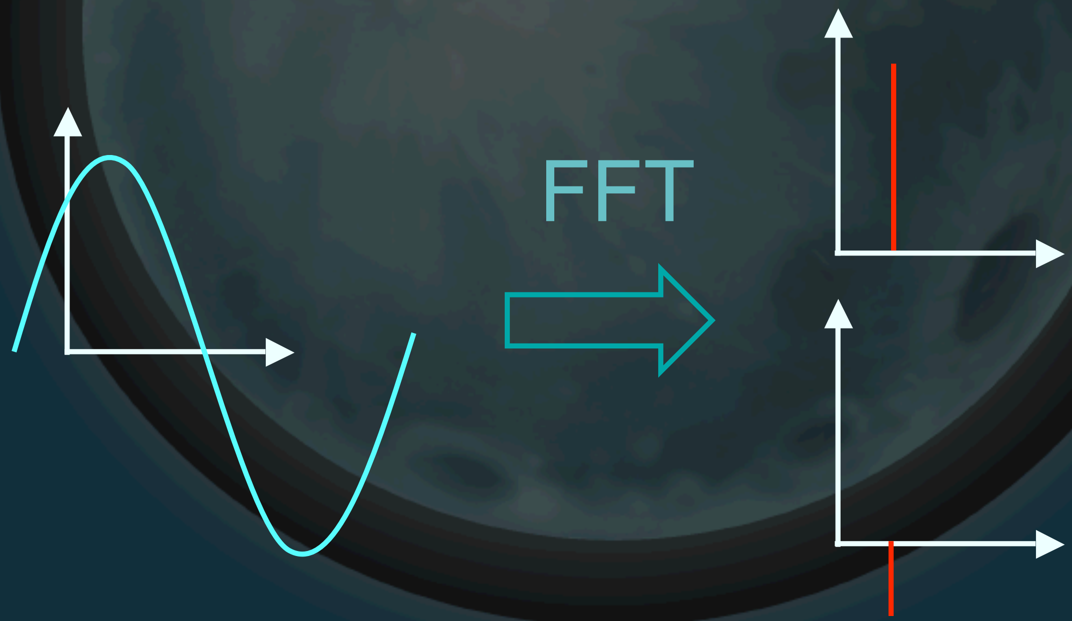
R2O

- Review
  - Can represent as magnitude+phase in frequency slot



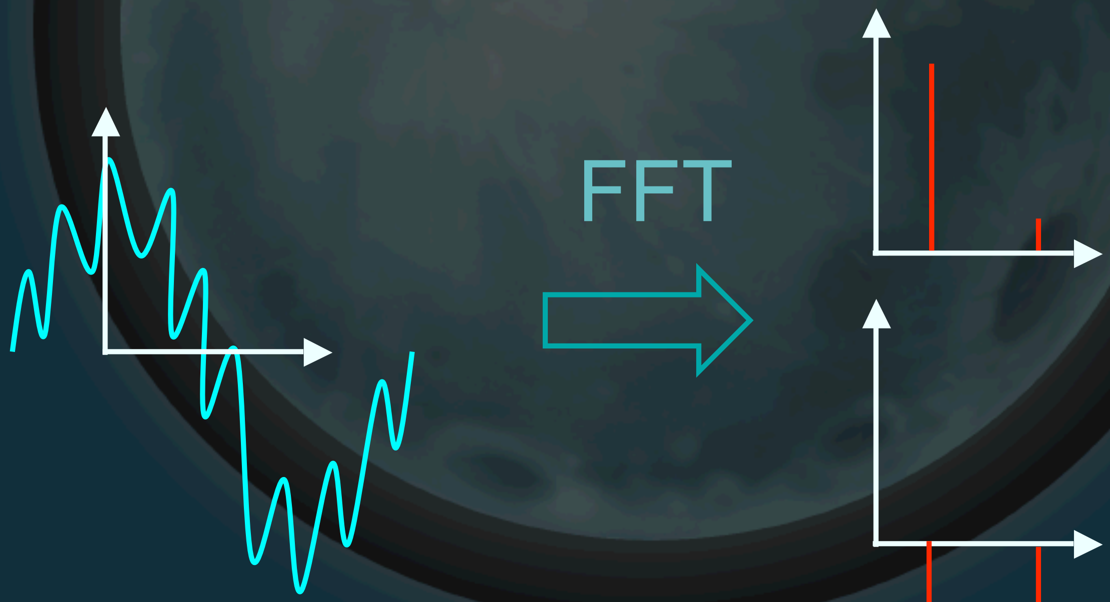
R2O

- Review
  - Requires periodic function



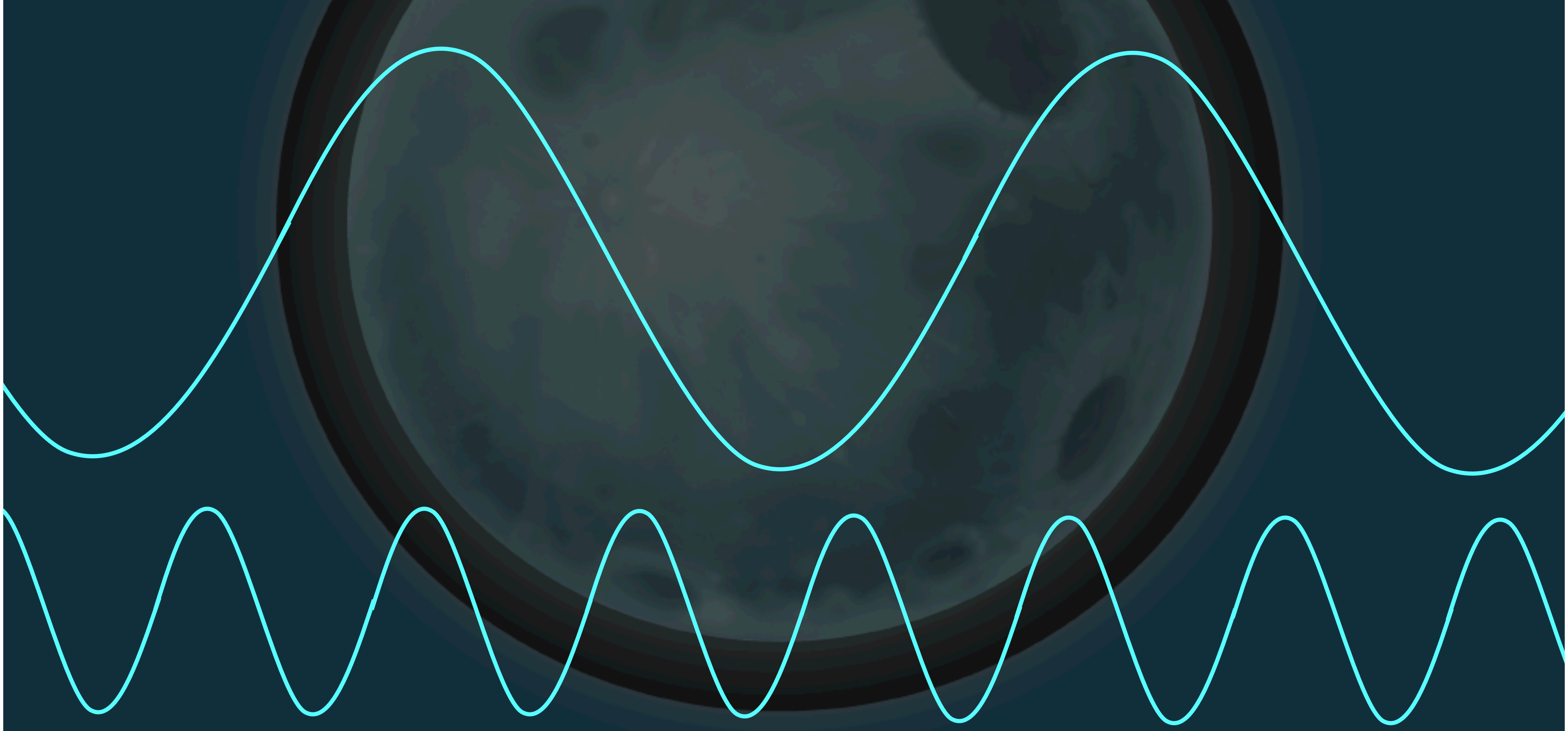
R2O

- Review
  - Multiple sinusoids end up at multiple entries



R2O

- Wave speed dependant on wavelength



R2O

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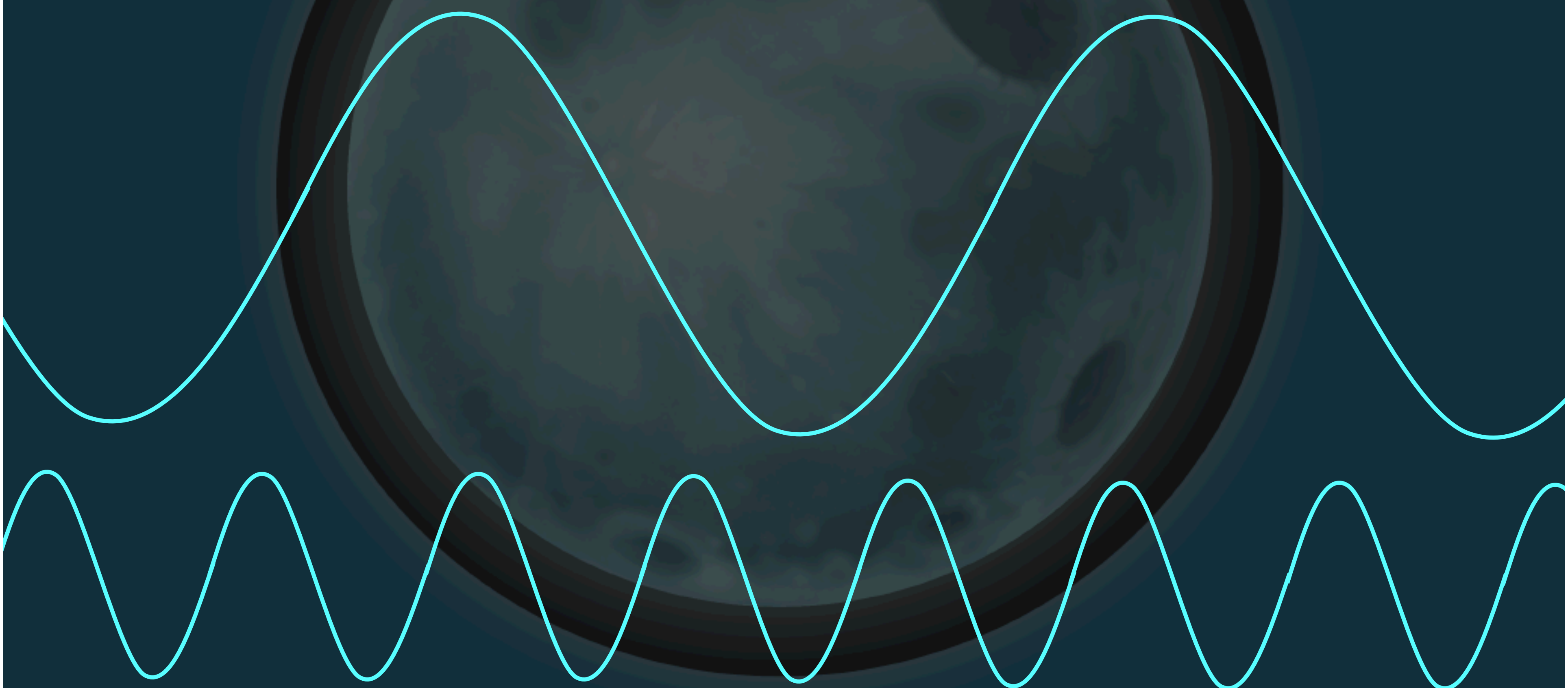

R2O

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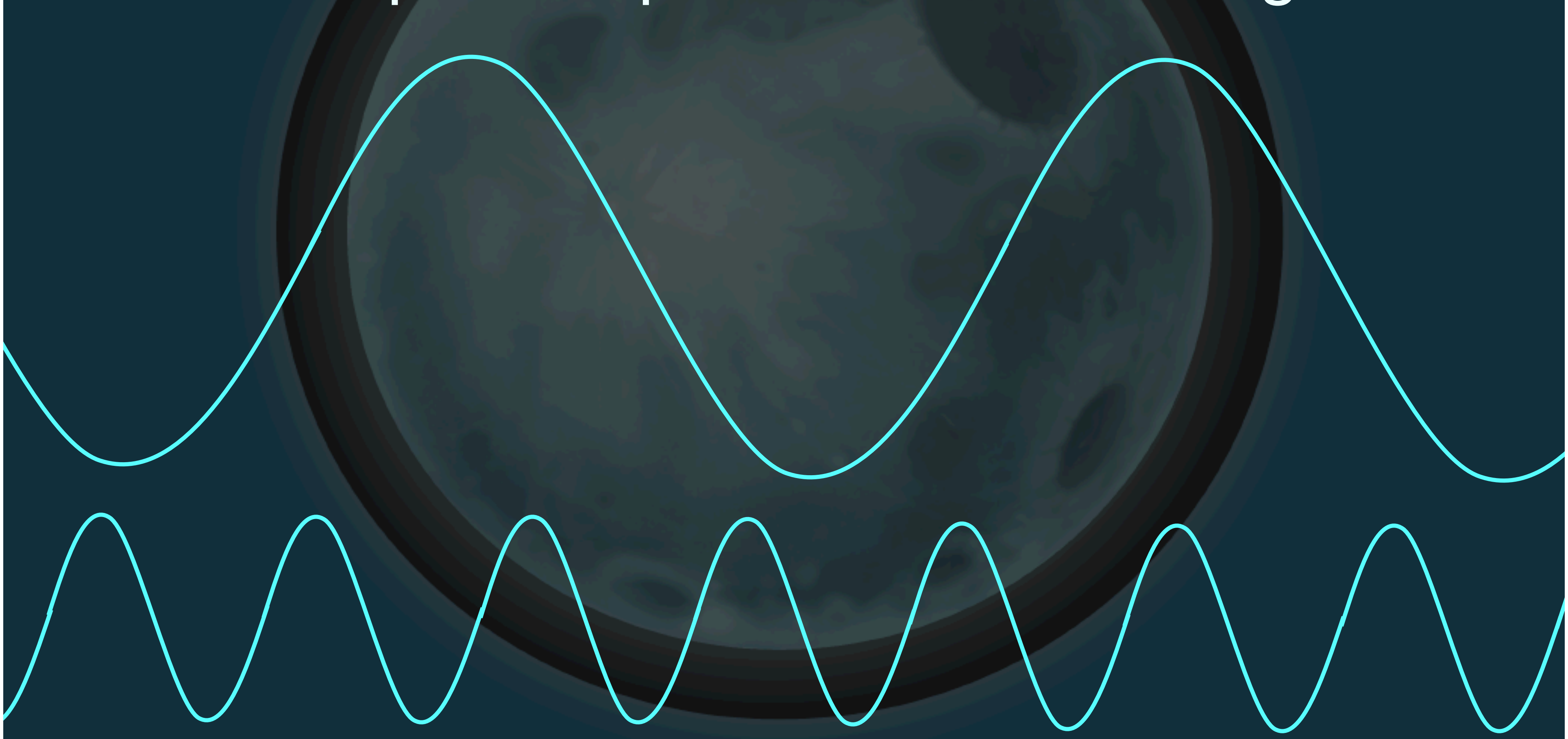

R2O

- Wave speed dependant on wavelength

R2O

- Wave speed dependant on wavelength
  - I.e. phases update at different rates
  - AKA dispersion

R2O

- General procedure
  - Start with convolved data in (r,φ) form
  - Update phase angles for each sinusoid
    - Angular velocity*dt
    - Dependent on frequency
  - Do inverse FFT to get spatial result

R2O

- FFT kernel limited to 32x32
- Combine multiple levels via LOD height field scheme
  - Gives high detail close to camera

R2O

- Interactive waves
  - Just adding in splashes looks fake
  - Instead, do some more FFT trickery so all our work occurs in the same domain
  - Non-periodic, so have to manage edges
  - Gives nice dispersion effects

R2O

- Rendering
  - – Rendered as height field mesh
  - – Add normal map for detail
  - – Cube map/frame buffer map for reflections
  - – Distortion effect for refractions

R2O

- Nifty video

References

- Jos Stam, “Stable Fluids”, SIGGRAPH 1999
- Mattias Müller, et. al, “Particle-Based Fluid Simulation for Interactive Applications”, SIGGRAPH Symposium on Computer Animation 2003
- Jerry Tessendorf, “Simulating Ocean Water,” SIGGRAPH Course Notes.
- http://www.insomniacgames.com/tech