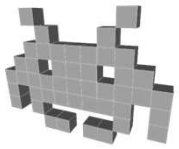
3D video games

3D Game Physics



Marco Tarini

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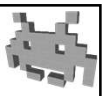
Course Plan



lec. 1: **Introduction**
lec. 2: **Mathematics** for 3D Games
lec. 3: **Scene Graph**
lec. 4: Game **3D Physics**
lec. 5: Game **Particle Systems**
lec. 6: Game **3D Models**
lec. 7: Game **Textures**
lec. 8: Game **Materials**
lec. 9: Game **3D Animations**

computer animation

lec. 10: **3D Audio** for 3D Games
lec. 11: **Networking** for 3D Games
lec. 12: **Interactive Agents** for 3D Games
lec. 13: **Rendering Techniques** for 3D Games

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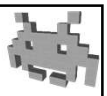
Animation in games



but, a note on terminology:
in some contexts, procedural means
"produced by a ***simple*** procedure"
as opposed to "physically simulated"

Non procedural

- Assets!
- Fully controlled by artist/designer (dramatic effects!)
- Realism: depends on artist's skill
- Does not adapt to context
- Repetition artefacts

Procedural

- Physics engine
- Less control
- Physics-driven realism
- Auto adaptation to context
- Naturally repretition free

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Physics simulation in videogames

- 3D, or 2D
- "soft" real-time
- efficiency
  - 1 frame = 33 msec (at 30 FpS)
  - physics = 5% - 30% max of computation time
- plausibility
  - but not necessarily *accuracy*
- robustness
  - should almost never "explode"
  - it's tolerable to have inconsistencies over a few frames, as long as it recovers in subsequent frames

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Physics in games: cosmetics or gameplay?

- Just a graphic accessory? (for realism!)
  - e.g.:
    - particle effects (w/o feedback)
    - secondary animations
    - Ragdolling
- Or a gameplay component?
  - e.g. physics based puzzles
  - Popular approach in 2D (since always!)

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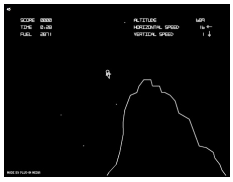

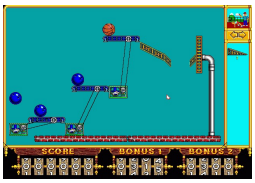

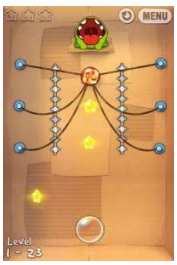

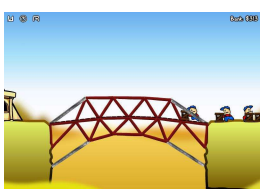

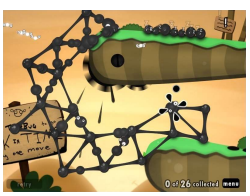

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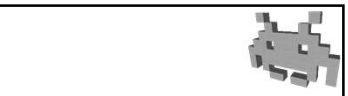
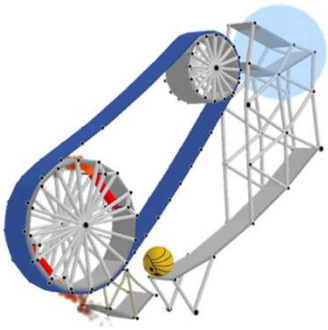
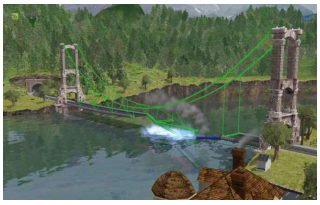
Physics in games: cosmetics or gameplay?



- Just a graphic accessory? (for realism!)
  - e.g.:
    - particle effects (w/o feedback)
    - secondary animations
    - Ragdolling
- Or a gameplay component?
  - e.g. physics based puzzles
  - Rising trend in 3D





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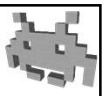
Physics engine: intro



- Game engine module
  - executed in real time at game run-time
- A high-demanding computation
  - on a very limited time budget!
- …but highly parallelizable
  - potentially, highly parallel

==> good fit for hardware support

(just like the Rendering Engine)

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Hardware for Physics engine

To exploit a **strong parallelism**,
you need a **strongly parallel** hardware!

- For a brief moment ~2006: PPU
  - "Physics Processing Unit"
  - HW unit specialized for physics
- After that: GP-GPU
  - "General Purpose Graphics Processing Unit"
    = Use of the graphics card for generic tasks
    (not related with 3D computer graphics)
  - or, Cuda (nVidia), OpenCL (openSource)

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Main Software (libraries, SDK)

havok	mostly CPU (Microsoft)
PhysX	CPU+GPU (CUDA) NVidia
BULLET PHYSICS LIBRARY	open source, free, HW accelerated (OpenCL) + CPU
OPEN DYNAMICS ENGINE	open source, free
Box2D	2D, open source, free (adopted by Unity 2D)
Jolt Physics	open source, free

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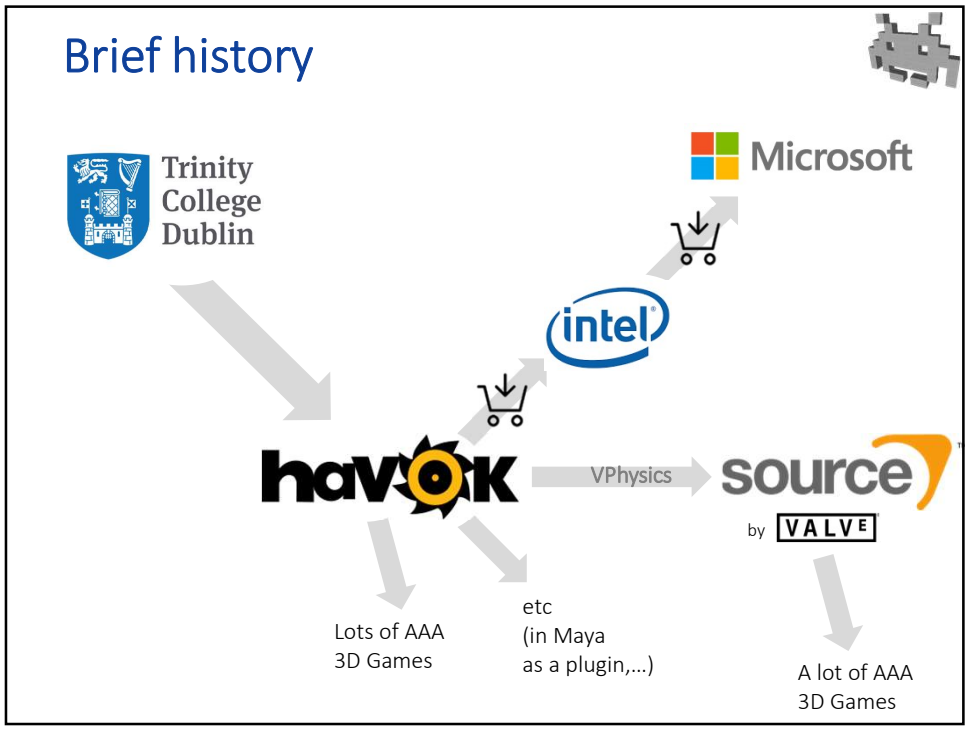
Brief history
Trinity College Dublin
Microsoft
intel
havok
VPhysics
source
by VALVE
Lots of AAA 3D Games
etc (in Maya as a plugin,...)
A lot of AAA 3D Games

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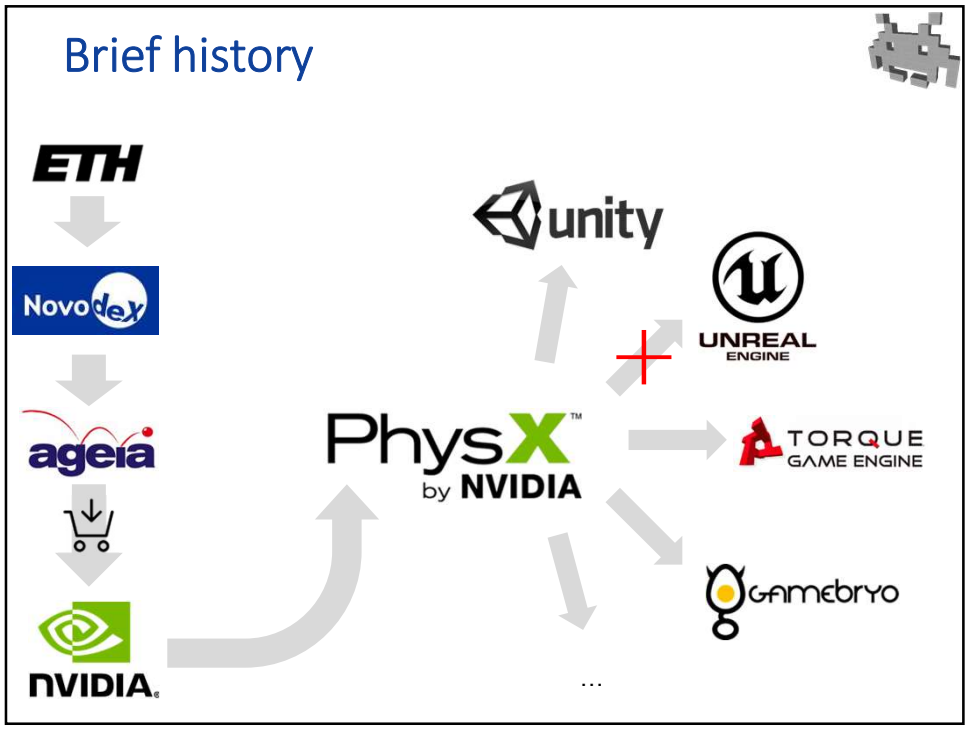
Brief history
ETH
Novodex
ageia
NVIDIA
unity
UNREAL ENGINE
PhysX by NVIDIA
TORQUE GAME ENGINE
Gamebryo
...

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Fields of study

Dynamics

The motion, as a result of **forces**

Example:
"Subject to gravity, how will this pendulum swing?"

Statics

Equilibrium states, minimal **energy** states

Example:
"In which state(s) can this pendulum be still?"

Kinematics

The **motion** itself, no matter why it moves

Example:
"If the angular speed of the pendulum is currently X, how fast is the ball moving?" (or vice versa)

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The 2 tasks of the Physics engine

1. Dynamics (Newtonian)

for objects such as:

- Particles
- Rigid bodies
- Articulated bodies
  - e.g. "ragdolling"
- Soft bodies
  - Ropes (specific solutions)
  - Cloth (specific solutions)
  - Hair (specific solutions)
  - Free-form deformation bodies (general)
- Fluids
  - Expensive!

2. Collision handling

- Collision detection
- Collision response

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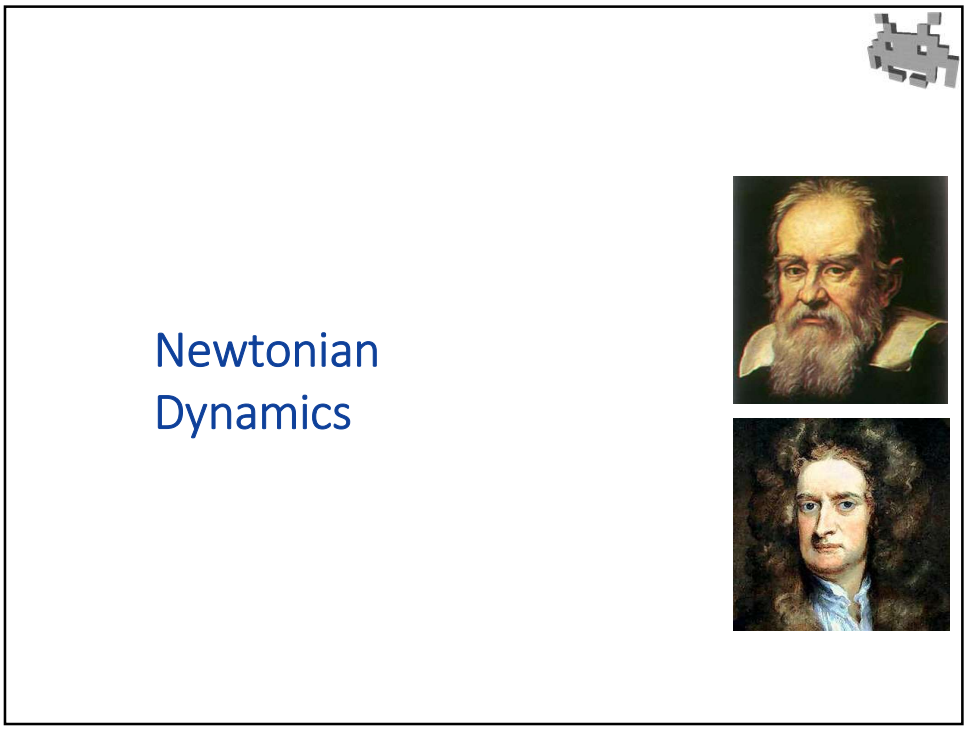

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Physics and spaces (observation)

- The scene hierarchy (the scene graph), and the entire distinction between local and global space, its's entirely "in our mind"
  - It's a useful abstraction to control or code *scripted* animations
  - E.g., kinematics animations, skeletal animations…
- But physics *doesn't care* about any of it
  - Physics happens entirely in global (world) space
  - Persistent spatial relationships (e.g., between a car and its wheels) either exists due to physical constraints, or they are irrelevant
  - Even if they physically exists, they are still enforced in global space, like all the rest of the physics simulation
  - Physics simulation computes changes to objects states (position, orientation…) in global space
  - But, as we know, these updates can be converted/stored in local space

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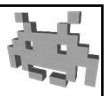
Spatial placement of a (rigid) object



2D Physics

- Position:
  (x,y)
- Orientation:
  (α) – angle (scalar)

3D Physics

- Position:
  (x,y,z)
- Orientation:
  quaternion or
  axis,angle or
  axis * angle or
  3x3 matrix or
  Euler angles

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Newtonian dynamics: summary

Current object placement	Rate of change of ← (d / dt)	← "with mass" (momentum)	What changes the rate of change (d^2 / dt^2)	← "with mass"
Position p p = (x,y,z)	Velocity $\vec{v}$ $\vec{v} = \dot{p}$ ($\|\vec{v}\|$ = "speed")	Momentum $m\,\vec{v}$	Acceleration $\vec{a} = \dot{\vec{v}} = \ddot{p}$	Force $\vec{f}$ $\vec{f} = m\,\vec{a}$
Orientation (e.g. quaternion)	Angular velocity $\vec{\omega}$	Angular momentum $I\,\vec{\omega}$ I = moment of inertia	Angular acc. $\vec{\alpha}$	Torque $\vec{\tau}$ $\vec{\tau} = I\,\vec{a}$ · ("mechanic momentum")

state (is kept! inertia!)
(changes, but only continuously)

change the state
(no memory)

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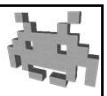
Per-object constant: mass & its distribution (for non point-shaped ones)



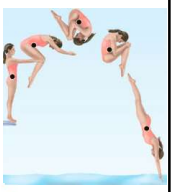
A few quantities associated to each rigid object

- constants: they don't (normally) change
- *input* of the physics dynamic simulation, not output

- Mass:
  - resistance to change of velocity

distribution of mass

- Moment of Inertia:
  - resistance to change of *angular* velocity



- Barycenter:
  - the center of mass

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Mass: notes

- resistance to change of velocity
  - also called *inertial* mass
- also, incidentally:
  ability to attract every other object
  - also called *gravitational* mass
  - happens to be the same
- it's what you measure with a scale
- Unity of measure:
  kg, g, etc…

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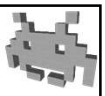
Barycenter (of a rigid body): notes



- Aka the center of mass of an object
  - constant: it's a fixed point in *local* space for a rigid body
- Often (but not necessarily) is the origin of the local frame
  - if so, the *position* of a rigid body (the translation of its transform) = the position of its barycenter
- It's the *weighted average* of the positions of the subparts composing an object
  - literally "weighted": with their masses
- In absence of external forces, the object rotates (orbits, spins) around this position.

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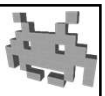
Moment of inertia: notes 1/3



- Resistance to change of angular velocity

high

low

- (an object rotates around its barycenter)

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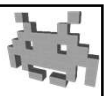
Moment of inertia: notes 2/3



- Scalar moment of inertia
  - Resistance to change of angular velocity
  - Depends on the total mass, and also on its *distribution*
    - the farthest one sub-mass from the axis, the > the resistance
- In 2D: it's a fixed value
  (for a given rigid object)
  - The object always spins around its barycenter

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Moment of inertia: notes 3/3

- In 3D: the rigid objects spins around an axis passing through the barycenter
  - for any possible axis of rotation,
    you have a different *scalar* moment of inertia
  - for a given axis $\hat{a}$ the scalar moment is given by

    $$\hat{a}^{\mathrm{T}}\ \mathrm{M}\ \hat{a}$$

    where 3×3 matrix M is the «(moment of) inertia *matrix*»
    aka the «(moment of) inertia *tensor*»)
  - M can be computed for a given rigid object
    - how: that's beyond this course
    - in practice: use given formulas for common shapes
    - or, sum the contributions for each sub-mass
  - M describes the scalar moment of inertia for any possible axis or rotation

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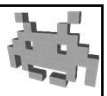
State of a rigid object in a physical simulation



```
Point position
Rotation orientation
```
current

```
Vector velocity
Vector angular_velocity
```
current rates of change

updated by physics (dynamics)

```
Scalar mass
Matrix moment_of_inertia
Point barycenter
Scalar drag
...
```
frictions; see later

constants

setup at initialization, rarely changes (e.g. by scripts)

*Note: acceleration/forces/torques are **not** part of the state. They will be ... local variable, used and*

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Unity

Adding a "RigidBody" component to a Game Object is to say: *"please let the Physics engine take care of the dynamics of this object"*

note: they are the components of the **global** transformation!

```
Vector3 position
Quaternion rotation
```
part of **Transform** component

note: speed = velocity.magnitude

```
Vector3 velocity
Vector3 angular_velocity
float mass
Vector3 inertiaTensor
Quaternion inertiaTensorRotation
Vector3 centerOfMass
float drag
bool isKinematic
```
the **RigidBody** component

per second (not per frame!)

moment of inertia matrix

the Vector3 = a diagonal matrix D by rotating it $R_I^T D R$ → the final matrix

the barycenter (in local space)

if true: disable dynamics (but keeps e.g. collisions)

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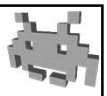
The case of particles



- For now, we will study a simpler case:
  the dynamics of particles (and its simulation)
- Particle = ideal object shaped like a point,
  with all the mass concentrated in that point
- Particles-only is easier because the following are irrelevant:
  - rotation (orientation): a point does not rotate
  - the center of mass (it's the position of the particle itself);
  - the distribution of mass, i.e. the moment of inertia (there's none);
  - the torques (only forces matter);
  - the angular velocity (there's only linear velocities)
- These things are only relevant for non-point sized (rigid) objects
- The algorithms we are bout to see can be extended to rigid bodies

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State of a particle (point sized obj) in a physical simulation

```
Point position
Rotation orientation
Vector velocity
Vector angular_velocity
Scalar mass
Matrix moment_of_inertia
Point barycenter
Scalar drag
…
```

not used for point sized objects! ("particles")

One possibility in a game phys engine is to only simulate point-particles.

Simpler: no rotation needed!

We will see later how to still get rigid bodies back.

For now, we focus on this simpler case.

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