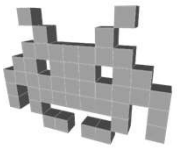
3D video games

Game Physics



Marco Tarini

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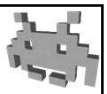
Course Plan



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 **3D Animations**
lec. 9: Game **3D Audio**
lec. 10: **Networking** for 3D Games
lec. 11: **Artificial Intelligence** for 3D Games
lec. 12: Game **3D Rendering Techniques**

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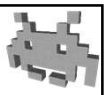
Animation in games



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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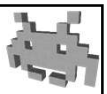
Physics simulation in videogames



- 3D, or 2D
- "soft" real-time
- efficiency
  - 1 frame = 33 msec (at 30 FpS)
  - physics = 5% - 30% max of computation time
- plausibility
  - (not necessarily *accuracy*)
- robustness
  - (should almost never "explode")

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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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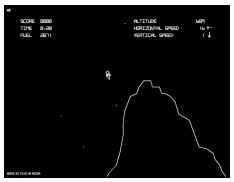

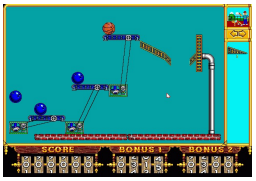

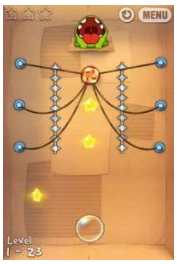

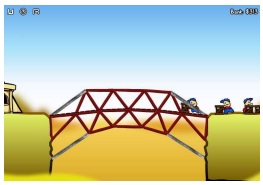

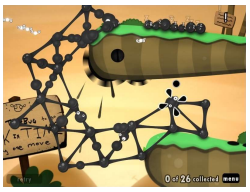

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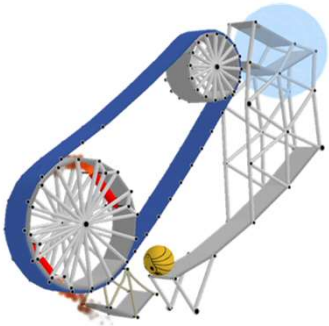
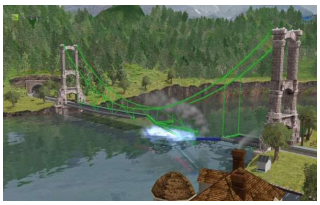
Physics in games: cosmetics or gameplay?

- 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
- Then: GP-GPU
  - "General Purpose Graphics Processing Unit"
    - Use of the graphics card for generic tasks (not related with 3D computer graphics)
  - Ex.: Cuda (nVidia)

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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

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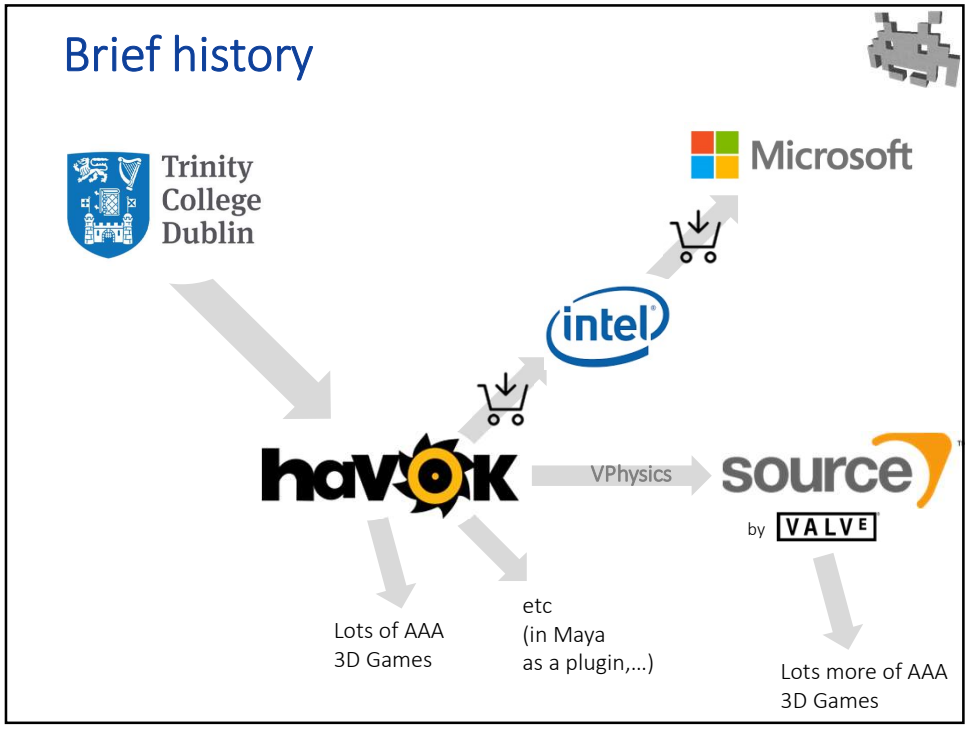
Brief history
Trinity College Dublin
Microsoft
intel
havok
VPhysics
source
by VALVE
Lots of AAA 3D Games
etc (in Maya as a plugin,…)
Lots more of AAA 3D Games

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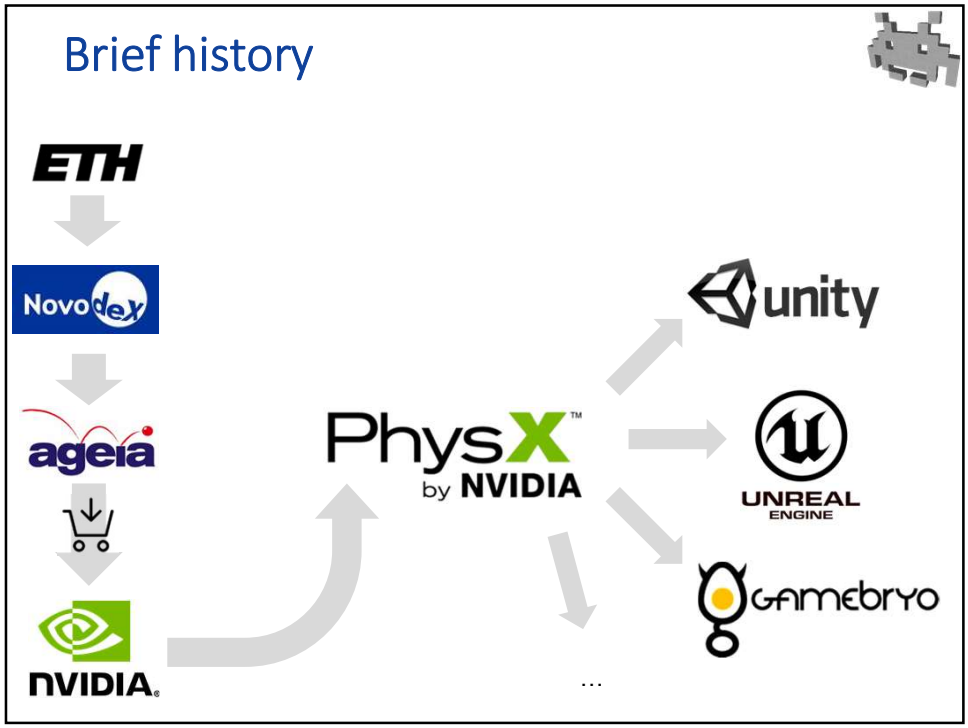
Brief history
ETH
Novodex
ageia
NVIDIA
PhysX by NVIDIA
unity
UNREAL ENGINE
Gamebryo
…

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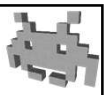
The 2 tasks of the Physics engine



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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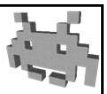
Fields of study



- **Dynamics**
  - The motion, as a result of forces
  - *"Subject to gravity, how will this pendulum swing?"*
- **Statics**
  - Equilibrium states, energy minimization states
  - *"In which state(s) can this pendulum be still?"*
- **Kinematics**
  - The motion itself, irrespective of why it's moving
  - *"If the angular speed of at the base of the pendulum is currently X, how fast is the tip moving?"* (or vice versa)

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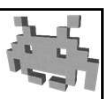
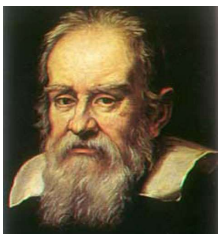
Newtonian Dynamics



- The one with:
  - Masses
  - position and its derivative: velocity
    - and momentum
  - direction and angular velocity
    - and angular momentum
  - forces acceleration…



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Reminder: Spatial location of an object

2D Physics	3D Physics
• Position: (x,y)	• Position: (x,y,z)
• Orientation: (α) – angle (scalar)	• Orientation: quaternion or axis,angle or axis x angle or 3x3 matrix or Euler angles

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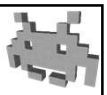
Newtonian dynamics: summary



Actual object location	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 $\vec{v}$ $\vec{v} = \dot{p}$ ($\lvert\vec{v}\rvert$ = "speed")	Momentum $\vec{v} \cdot m$	Acceleration $\vec{a} = \dot{\vec{v}} = \ddot{p}$	Force $\vec{f}$ $\vec{f} = \vec{a} \cdot m$
Orientation (e.g. quaternion)	Angular velocity $\vec{\omega}$	Angular momentum $\vec{\omega} \cdot I$ I = moment of inertia (for axis) ("rotational inertia")	Angular acc. $\vec{\alpha}$	Torque $\vec{\tau}$ $\vec{\tau} = \vec{a} \cdot I$ ("mechanic momentum")

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

Change the state
(no memory)

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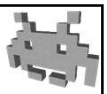
A few constants per object

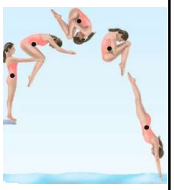


A few quantities associated to each object

- constants: they don't (usually) change
- input of the physical simulation, not output

- Mass:
  - resistance to change of velocity

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



- Barycenter:
  - the center of mass

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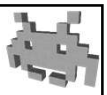
Mass



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

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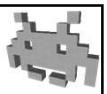
Moment of inertia



- Resistance to change of angular velocity

high

low

- (an object rotates around its barycenter)

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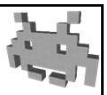
Moment of inertia



- Scalar moment of inertia
  - Resistance to change of angular velocity
  - Depends on the mass, and on its *distribution*
    - the farthest one sub-mass from the axis, the > the resistance
  - In 3D: its different for each axis of rotation
    - It can be computed for any axis, thanks to…
- Moment of inertia as a 3x3 Matrix
  - a matrix **A** used to extract the scalar, for any given axis
  - given an axis **a** (**a** = unit vector), the *moment of inertia* is

$$\mathbf{a}^T \mathbf{A} \mathbf{a}$$

  - matrix **A** can be computed once and for all for a rigid object
    - how: that's beyond this course
    - in practice: use given formulas for common shapes
    - or sum the contributions for each sub-mass

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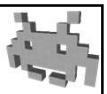
Barycenter



- Aka the center of mass
  - a position
- In the discrete setting:
  simply the *weighted average* of the positions of the subparts composing an object
  - literally "weighted": with their masses
- Does not necessarily coincide with the origin of the local frame of that object
  - but it can and often will

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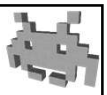
State of an object



```
Point position
Rotation orientation
```
current

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

updated by physics

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

constants

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

*Note: acceleration/forces/torques are **not** part of the state*

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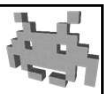
In unity



```
Point position
Rotation orientation
```
part of **Transform** component

```
Vector velocity
Vector angular_velocity
Scalar mass
Matrix moment_of_inertia
Point barycenter
Scalar drag
bool isKinematic
```
the **RigidBody** component

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

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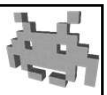
In unity (using Unity terminology)



```
Vector3 position
Quaternion rotation
```

part of **Transform** component

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

```
Vector3 velocity
Vector3 angular_velocity
float mass
Vector3 inertiaTensor
Quaternion inertiaTensorRotation
Vector3 centerOfMass
float drag
bool isKinematic
```

the **RigidBody** component

note: speed = velocity.magnitude

per second (not per frame)

moment of inertia matrix

the Vector3 = a diagonal matrix D by rotating it R^TDR → the final matrix

the barycenter (in local space)

it true: disable dynamics (keeps e.g. collisions)

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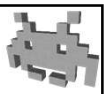
State of a point-particle



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

not used !

One trend in game phys engines is to simulate point-particles only.

Much 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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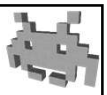
Dynamics (Newtonian)



describe the forces
given the particle positions (and more)

$$\vec{f} = \text{function}(p,...)$$

$$\vec{a} = \vec{f} / m$$

$$\vec{v} = \vec{v}_0 + \int \vec{a} \cdot dt$$

$$p = p_0 + \int \vec{v} \cdot dt$$

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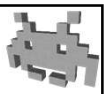
Dynamics (Newtonian)



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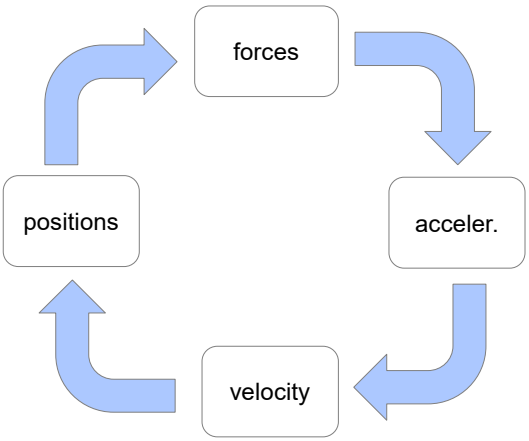

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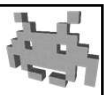
An (obvious) precisation



- t_C = virtual time != real time
  - Wall time
  - e.g.:
    - game paused → t costant.
    - Fast forward, replay, rallenty, reverse → change of speed/flow direction of t

occasionally,
gameplay exploit this difference in spectacular ways!

PoP – the sands of times serie (Ubisoft, 2003-…)

Braid (Jonathan Blow, 2008)

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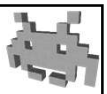
Computing physics evolution



- **Analytical** solutions:

  state = function(t)

  Given force functions (and acc), find the functions (pos, vel,…) in the specified relations:

$$\vec{f}(t_C) = funz(p(t_C),...)$$
$$\vec{a}(t_C) = \vec{f}(t_C)/m$$
$$\vec{v}(t_C) = \vec{v}_0 + \int_0^{t_C} \vec{a}(t)\cdot dt$$
$$p(t_C) = p_0 + \int_0^{t_C} \vec{v}(t)\cdot dt$$

- **Numerical** solutions:

  1. $state_{(t=0)}$ ← init
  2. $state_{(t+1)}$ ← evolve($state_t$)
  3. goto 2

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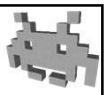
Analytical solutions



$$\vec{f}(t_C) = \text{function}(p(t_C),\ldots)$$

$$\vec{a}(t_C) = \vec{f}(t_C)/m$$

$$\vec{v}(t_C) = \vec{v}_0 + \int_0^{t_C} \vec{a}(t)\cdot dt$$

$$p(t_C) = p_0 + \int_0^{t_C} \vec{v}(t)\cdot dt$$

pos, acc, vel, forces: in function of current time t_C

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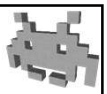
Analytical solutions



that is, find position as function p of time s.t.

$$\ddot{p}(t) = \text{function}(p(t))/\text{m}$$

with

$$\dot{p}(0) = \vec{v}_0$$

$$p(0) = \text{p}_0$$

sometimes, of other things too (e.g. velocity). Harder to solve!

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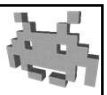
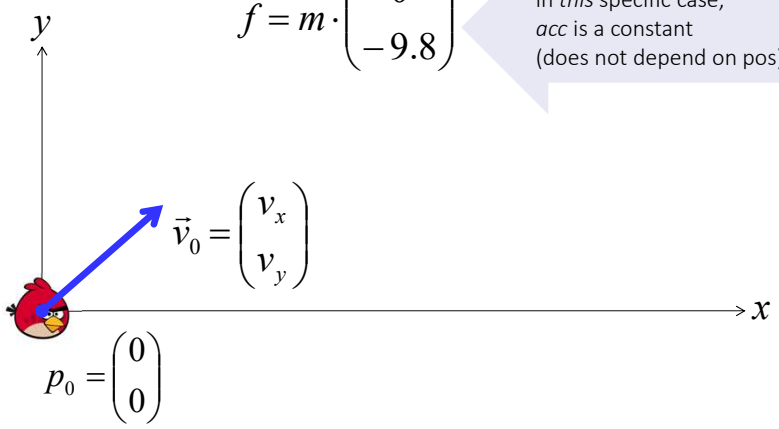
Simple example: analytical solution



«ballistic shooting»
of a mass,
in 2D, ignoring friction...

$$\vec{f} = m \cdot \begin{pmatrix} 0 \\ -9.8 \end{pmatrix}$$

in *this* specific case,
acc is a constant
(does not depend on pos)



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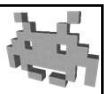
Simple example: analytical solution



Solving...

$$\vec{f}(t_C) = fun(p(t_C),...)$$
$$\vec{a}(t_C) = \vec{f}(t_C)/m$$
$$\vec{v}(t_C) = \vec{v}_0 + \int_0^{t_C} \vec{a}(t) \cdot dt$$
$$p(t_C) = p_0 + \int_0^{t_C} \vec{v}(t) \cdot dt$$

$$\vec{f}(t_C) = m \cdot \begin{pmatrix} 0 \\ -9.8 \end{pmatrix}$$

$$\vec{a}(t_C) = \vec{f}(t_C)/m = \begin{pmatrix} 0 \\ -9.8 \end{pmatrix}$$

$$\vec{v}(t_C) = \begin{pmatrix} v_x \\ v_y \end{pmatrix} + \int_0^{t_C} \begin{pmatrix} 0 \\ -9.8 \end{pmatrix} \cdot dt = \begin{pmatrix} v_x \\ v_y - 9.8 \cdot t_C \end{pmatrix}$$

$$p(t_C) = p_0 + \int_0^{t_C} \vec{v}(t) \cdot dt = \begin{pmatrix} 0 \\ 0 \end{pmatrix} + \int_0^{t_C} \begin{pmatrix} v_x \\ v_y - 9.8 \cdot t \end{pmatrix} \cdot dt = \begin{pmatrix} v_x \cdot t_C \\ v_y \cdot t_C - 9.8/2 \cdot {t_C}^2 \end{pmatrix}$$

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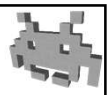
Simple example: analytical solution



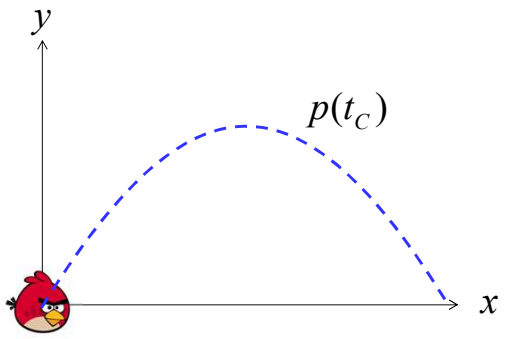
Final result:

$$\vec{f}(t_C) = m \cdot \begin{pmatrix} 0 \\ -9.8 \end{pmatrix}$$

$$\vec{a}(t_C) = \begin{pmatrix} 0 \\ -9.8 \end{pmatrix}$$

$$\vec{v}(t_C) = \begin{pmatrix} v_x \\ v_y - 9.8 \cdot t_C \end{pmatrix}$$

$$p(t_C) = \begin{pmatrix} v_x \cdot t_C \\ v_y \cdot t_C - 9.8/2 \cdot {t_C}^2 \end{pmatrix}$$



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Some numerical methods

- Numerical integrators:
  - Forward Euler method
    - (simple and direct)
  - Leapfrog method
  - Verlet method
- Strategies for modelling interactions (see later)
  - Constraints (position based dynamics)
  - Elastic forces

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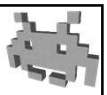
Numerical method features



- How efficient / expensive
  - must be at least soft real-time
    - (if from time to time computation delayed to next frame, ok)
- How accurate
  - must be at least plausible
    - (if stays plausible, differences from reality are acceptable)
- How robust
  - rare completely wrong results
    - (and never crash)
- How generic
  - Which phenomena / constraints / object types is it able to recreate?
  - requirements depend on the context (ex: gameplay)

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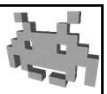
Euler integration



For each step:

$$\vec{f} = fun(p,...)$$ → (1) Evaluate the force (on each particle) as a function of position (even of other particles)

$$\vec{a} = \vec{f} / m$$ → (2) acceleration of each particle given by: forces on it and its mass

$$\vec{v} = \vec{v}_0 + \int \vec{a} \cdot dt$$ → (3) Update velocity with acceleration

$$p = p_0 + \int \vec{v} \cdot dt$$ → (4) Update position with velocity

(state / variables) , (temp variables)

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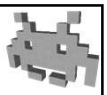
Euler methods



init state

$$p = \dots$$
$$\vec{v} = \dots$$

one step

$$\vec{f} = fun(p\ , \dots)$$
$$\vec{a} = \vec{f} / m$$
$$\vec{v} = \vec{v} + \vec{a} \cdot dt$$
$$p = p + \vec{v} \cdot dt$$

$$t = t + dt$$

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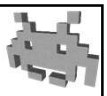
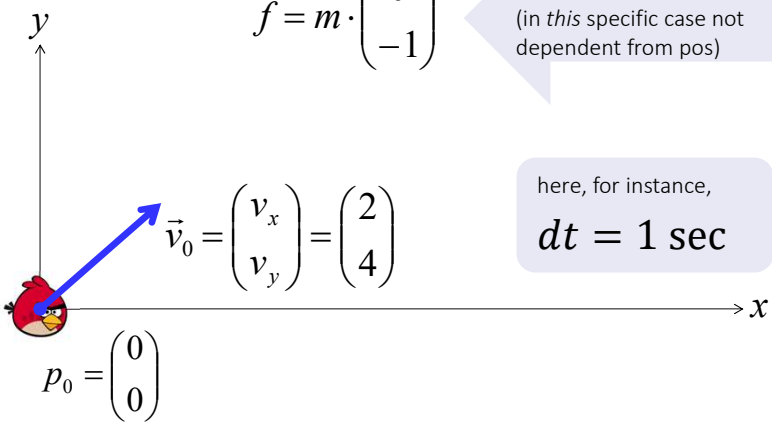
Simple example: numerical solution

Same phenomena of previous example



$$\vec{f} = m \cdot \begin{pmatrix} 0 \\ -1 \end{pmatrix}$$

constant
(in *this* specific case not dependent from pos)



$$\vec{v}_0 = \begin{pmatrix} v_x \\ v_y \end{pmatrix} = \begin{pmatrix} 2 \\ 4 \end{pmatrix}$$

$$p_0 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

here, for instance,

$$dt = 1 \text{ sec}$$

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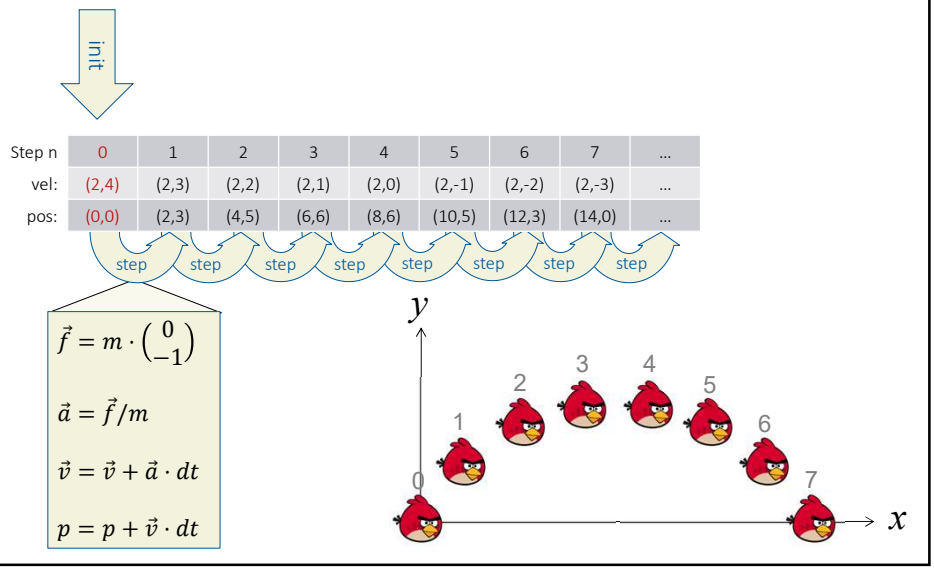
Simple example: numerical solution



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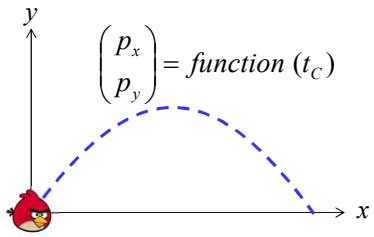
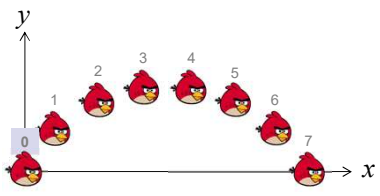
Physics evolution computation

- Analytical solutions:
- Numerical solutions:





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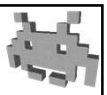
Physics evolution computation



- Analytical solutions:
  - Super efficient!
    - Close form solution
  - Accurate
  - Only simple systems
  - formulas found case by case (often not existing!)
  - NO (but, for instance, useful to allow the AI to make predictions)
- Numerical solutions:
  - Expensive (iterative)
    - but *interactive*
  - Integration errors
  - Flexible
  - Generic
  - YES

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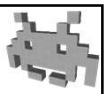
Integration errors



- Depends on *dt*
  - Small *dt* ==> more steps needed (for same virtual time) ==> more computationally expensive, but smaller error, i.e. more accurate simulation (smaller difference with exact analytical solution)
  - *dt* = 1.0 sec / FPS of physics simulation
    - (recall: not necessarily same rendering frame rate)
  - How much does error decreasing when *dt* decreases?
    - That's the «Order» of the simulation
    - Euler is 1st order: the error can be as large as O(dt^1) (but usually not that bad)
- Error keeps on accumulating with time
  - (dependent also from t_{tot})

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