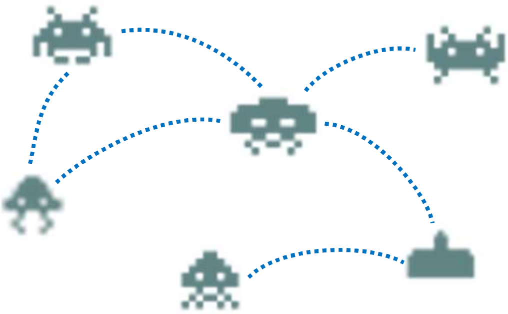
3D VideoGames 2021/2022
Università degli Studi di Milano

Networking for 3D Games



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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 Materials
- lec. 10: Networking for 3D Games
- lec. 11: Artificial Intelligence for 3D Games
- lec. 12: 3D Audio for 3D Games
- lec. 13: Rendering Techniques for 3D Games

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Player 2 has joined the game

- Multiplayer game types, according to gameplay
  - collaborative
  - competitive
  - versus
  - teams…
- *How much* multiplayer?
  - no: single player
  - 2 players?
  - 10 players?
  - >100?
  - > 1000?

  } («massively» multiplayer, MMO)

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Player 2 has joined the game

- Types of multiplayer games
  - Hot-seat
    - players time-share
  - Local multiplayer (Side-to-side)
    - e.g., split screen
    - players share a terminal
  - Networked
    - each player on a terminal
    - terminals connected…
      - …over a LAN
      - …over the internet

← Needs networking

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Networking in Games

(see course on: Online Game Design)

- One task of a Game Engine
- Different scenarios:
  - number of players? (2, 10, 100, 100.000?)
  - game pace? (real time action ≠ chess match)
  - joining ongoing games : allowed?
  - cheating : must it be prevented?
  - security: is it an issue (e.g. DoS attacks)
  - medium : LAN only? internet too?
    Letency tolerance? Bandwith tolerance?

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Networking in 3D Games

Objective: all players *see* and *interact with* a common 3D virtual world

how can this illusion be achieved?

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Dev choices for a networked-game

- What to communicate?
  - complete status, status changes, inputs…
- How often ?
  - at which rate
- Over which protocol ?
  - TCP, UDP, WS …
- Over which network architecture ?
  - Client/Sever, Peer-To-Peer
- How to deal with networking problems
  - latency ("lag") <== one main issue
  - limited bandwidth
  - connection loss
  - loss of packets

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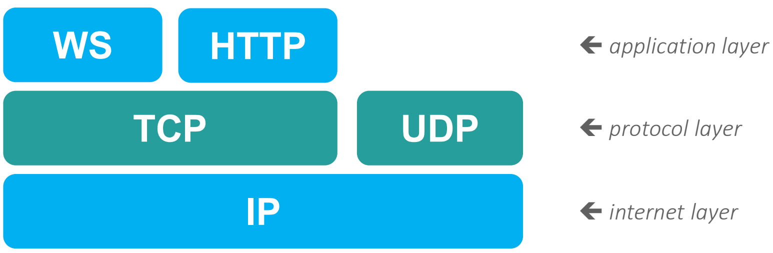
Reminder: Protocols

(see course on: Computer networks)



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Protocols

TCP sockets

- Connection based
- Guaranteed reliable
- Guaranteed ordered
- Automatic breaking of data into packets
- Flow control
- Easy to use, feels like read and write data to a file

UDP sockets

- *What's a connection?*
- No reliability
- No ordering
- Break your data yourself
- No flow control
- Hard. Must detect and deal with problems yourself.

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UDP vs TCP

- Problem with TCP
  - too many strong guarantees
    - they cost in terms of latency (==>lag)!
  - no good for time critical application
    - (if they must be used, at least enable the option TCP_NODELAY)
- Problem with UDP
  - not enough guarantees
    - guarantees: "packets arrives all-or-nothing". The end.
    - no concept of connection
      - no timeouts, no handshake, a port receives from anyone
    - no guarantees: packets can arrive...
      - ...out of order :-O , ...not at all :-O , ...in multiple copies :-O

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UDP vs TCP

- Problem with TCP
  - too many costly guarantees
- Problem with UDP
  - not enough guarantees

- The hard way:
  - use UDP,
    but *manually re-implement a few guarantees*
  - best, for the most challenging scenario
    - fast paced games, not on LAN

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Virtual connections over UDP: how-to (notes)

- add connection ID to packets
  - to filter out unrelated ones
- time out on prolonged silence (~ few secs)
  - declare "connection" dead
- add serial number to packets
  - to detect when one went missing / is out of order / is duplicate
  - (warning: int numbers *do* loop – solutions?)
- give ack back for received packets
  - optimize for lucky (& common) cases!
    - *N* (say 100) received msg == 1 ack (with bitmask)
  - resend? only a few times, then give up (data expired)
- congestion avoidance: measure delivery time
  - tune send-rate (packets-per-sec) accordingly
- obviously: NON blocking receives!

what TPC doesn't understand

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Choosing a Protocol

- In summary, it is a question of pacing
  - fast paced game?
    - action games, FPS, …
    - (sync every 20-100 msec)
    - → UDP necessary (unless LAN only)
  - slow paced game?
    - RTS, RPG…
    - (sync every ~500 msec)
    - → can get away with TPC
  - *slower* paced games?
    - MMORPGs, cards …
    - (sync every few sec)
    - → why not just HTTP
  - traditional turn based ?
    - chess, checker
    - (sync every hour/day)
    - → may as well use EMAIL

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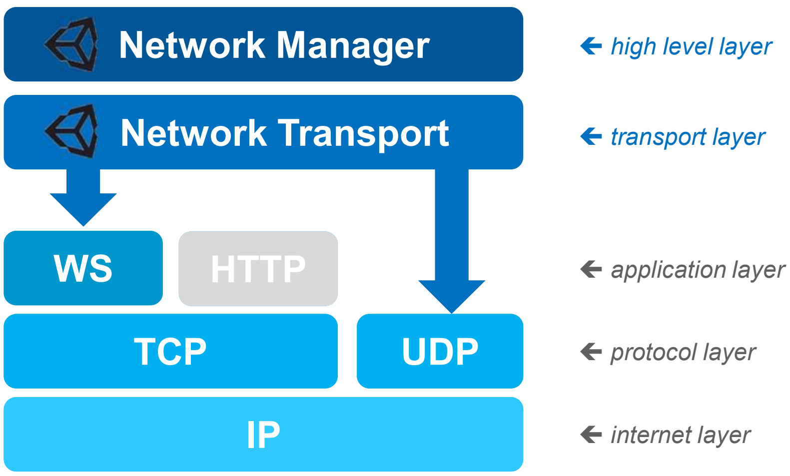
In Unity:



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In Unity:

- Low level: **`Transport Layer`**
  - Builds up guarantees over UDP (connections)
  - Easy to use as TCP, but optimized for games
    - see how-to list above
  - Can work over WS instead UDP (abstracts the differences)
    - WS needs be used for web / WebGL games
- Hi level: **`Network Manager`**
  - presets network connectivity
  - standard “client hosted” games
    - server is also a player
  - controls shared state of the game
  - deals with clients
  - sends remote commands

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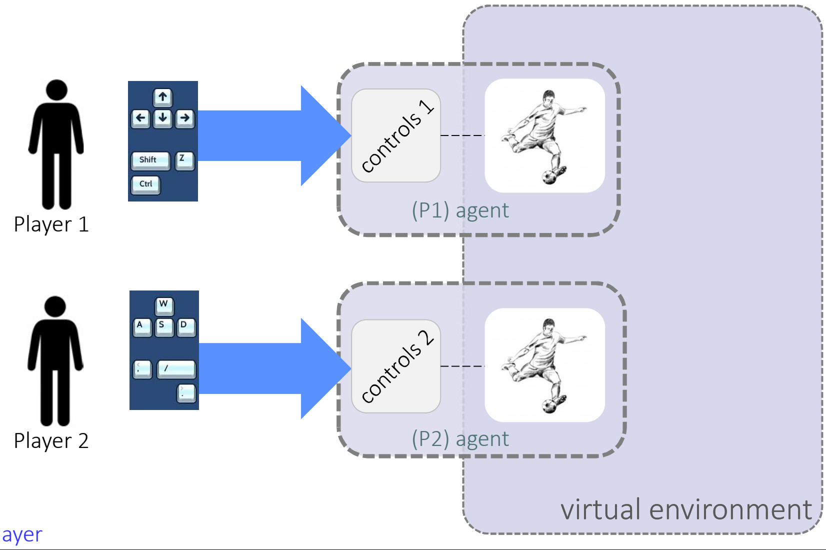
Controls and Agent

(a useful abstraction)



local multiplayer

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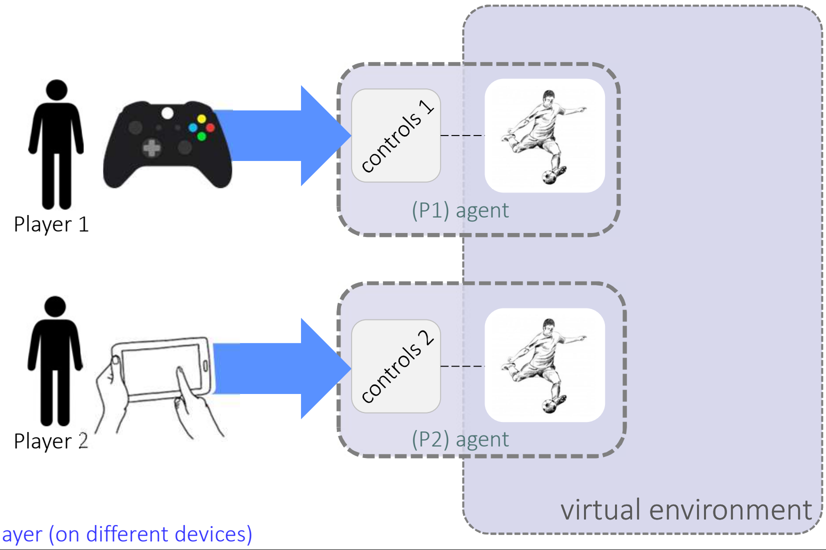
Controls and Agent
(a useful abstraction)



local multiplayer (on different devices)

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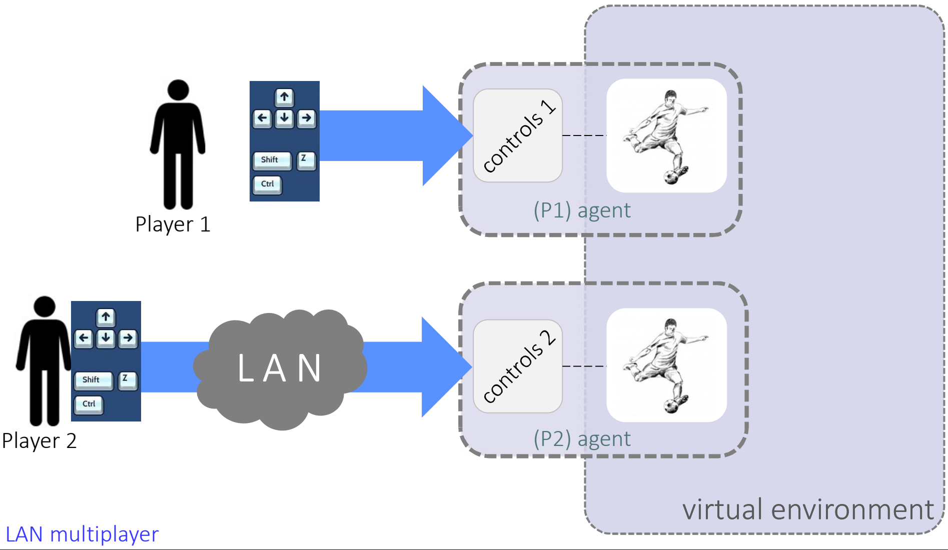
Controls and Agent
(a useful abstraction)



LAN multiplayer

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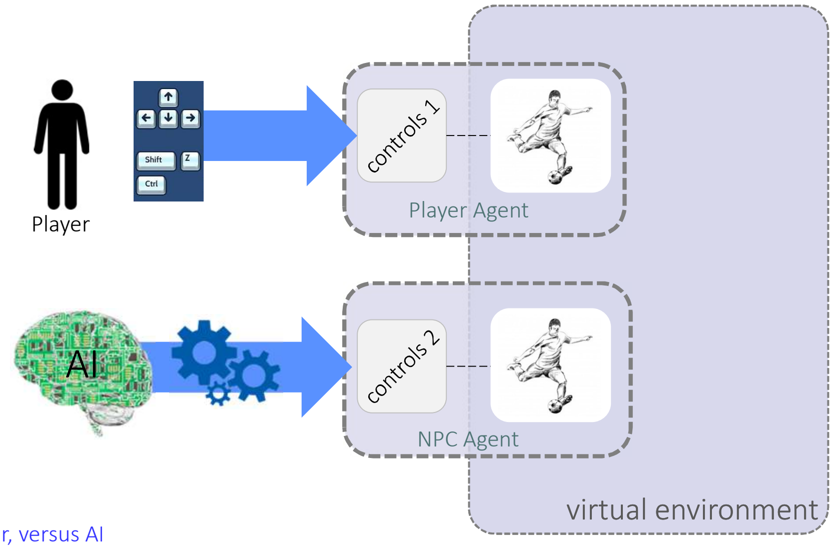
Controls and Agent
(a useful abstraction)



single player, versus AI

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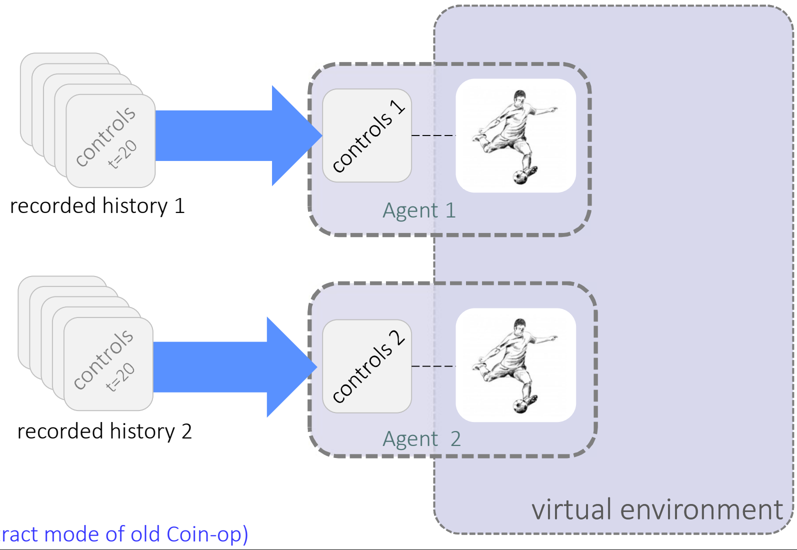
Controls and Agent
(a useful abstraction)



replay! (e.g. attract mode of old Coin-op)

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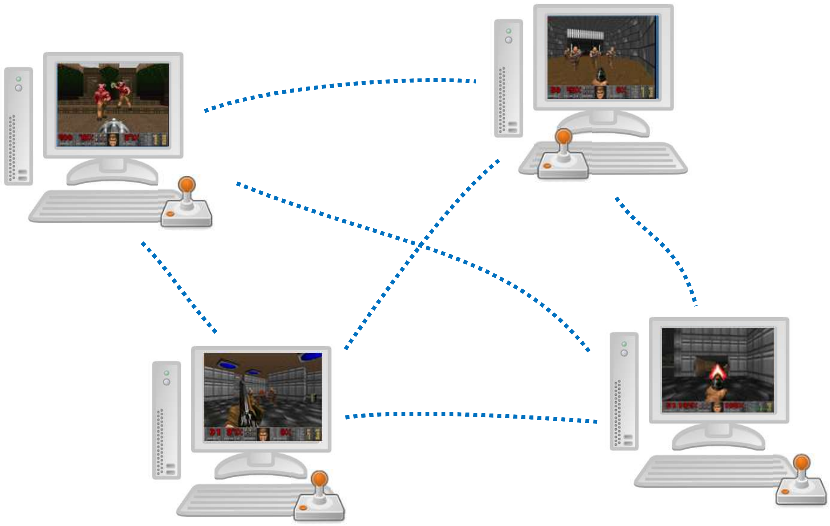
Model: Peer-to-peer
Network topology: complete



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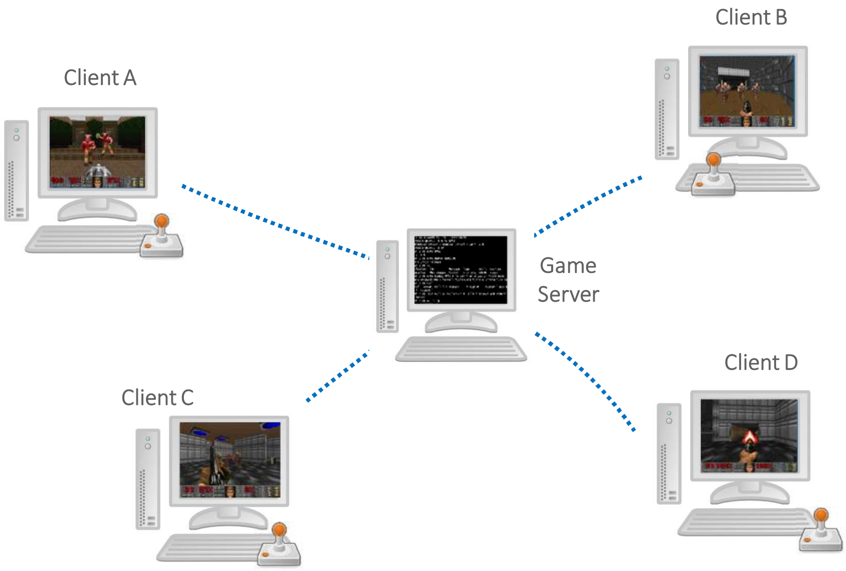
Model: Client / Server
Network topology: star



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Networking paradigms for games we will discuss

- Deterministic Lockstep on P2P
- Deterministic Lockstep
- Game-Status Snapshots
- Distributed Physics (just notes)
- Game-Status Snapshots with Client-Side predictions
- Cloud gaming

(Deterministic Lockstep through Cloud gaming: on client-server)

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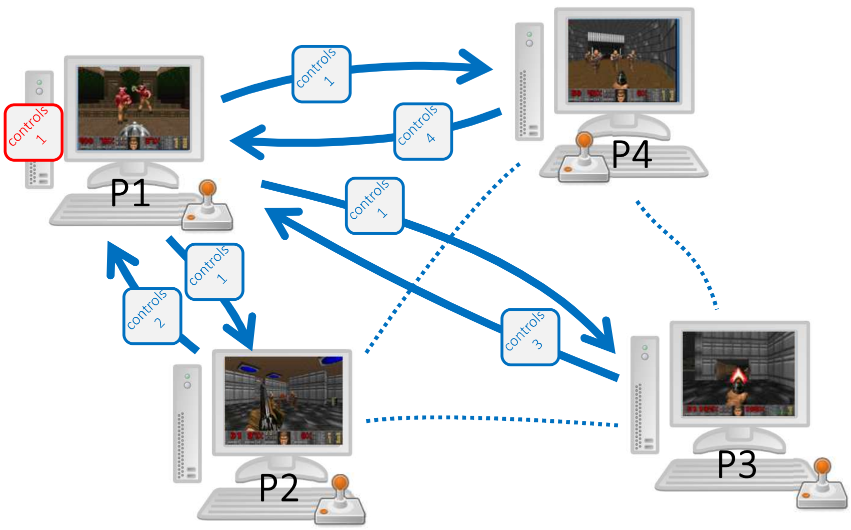
Deterministic Lockstep (on Peer-to-Peer)



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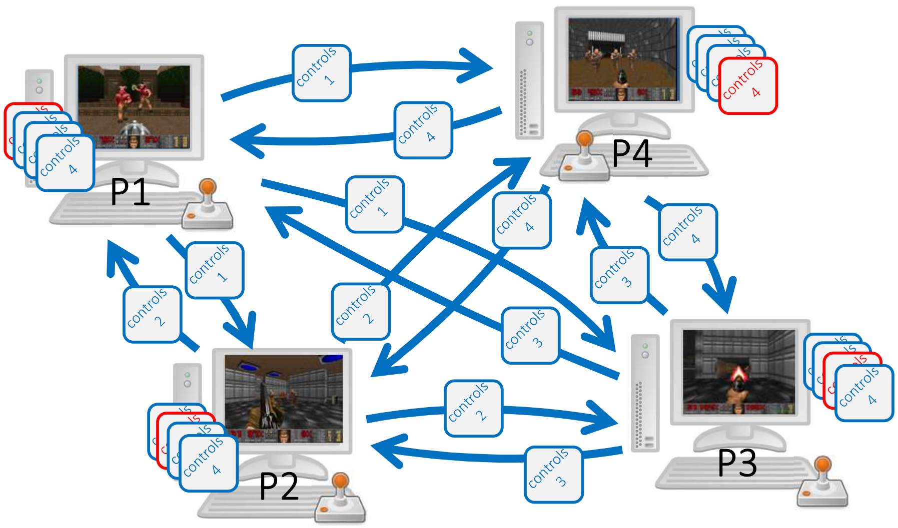
Deterministic Lockstep (on Peer-to-Peer)



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Deterministic Lockstep (on Peer-to-Peer)

- Game evolution = sequence of “turns”
  - e.g. physics steps (fixed *dt* !)
- Each node sends its current *controls* (inputs)
  - to everybody else
- After all controls are received, each node computes its own evolution
  - deterministically: same input → same result

even if independently computed

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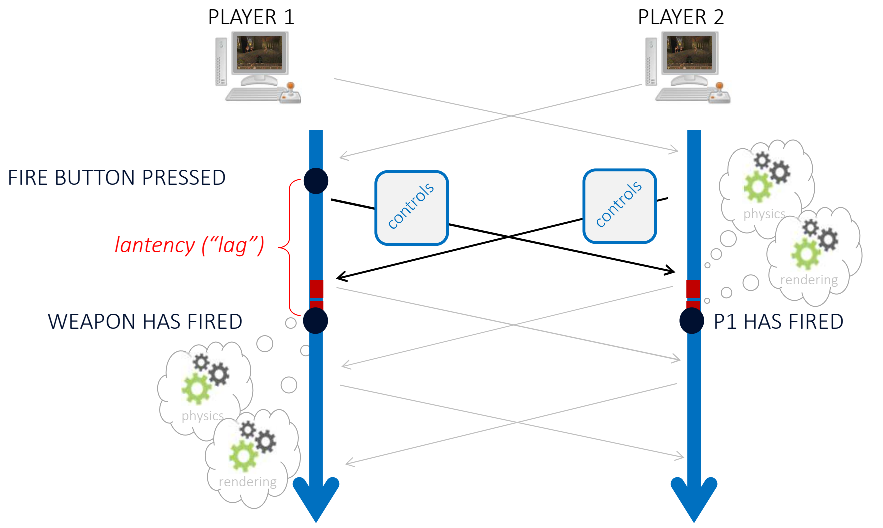
Deterministic Lockstep (on peer-to-peer network)



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Deterministic Lockstep: the good

- elegant and simple! ☺
- minimal bandwidth needed
  - only sent data = controls
    - compact! (e.g., a bitmask)
  - does not depend on complexity of virtual environment
- cheating: inherently limited
  - but a few ways to cheat are still possible, e.g.:
    - aim-bots (unlawful assist from AI)
    - x-rays (unlawful reveal of info to player)
- mixes well with:
  - non-cheating AI, replays, player performance recording…
- can use simple TCP connections
  - because we need 0% packet loss anyway (but…)

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Deterministic Lockstep:
can as well use TPC instead of UDP ?

- why yes:
  - TPC is simple to use
    - It takes care of everything
  - works well, when no packet loss
    - on loss, we need resend it anyway: let TPC do that
  - makes little sense to use UDP and then...
    try to re-implement all TPC over it
  - at the beginning of dev,
    UDP is a (premature) optimization
- why not:
  - to degrade better with packet loss
  - e.g.: use redundancy – instead of resend-on-failure
    - controls are small: send 100+ controls in every packet
    - keep resending until ack received

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Deterministic Lockstep

Starcraft Blizzard 1998-2015

- Common, e.g., in:
  - RTS
    - controls = orders
      - can be fairly complex
      - but game status = much more complex
  - *first generation* FPS
    - controls = [gaze dir + key status]

...why not anymore?

Command and Conquer EA / Westmany et al 1995..2012

Age of Empires Ensemble Studios et al, 1998..2015

Doom ID-soft, 1998

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Deterministic Lockstep (on peer-to-peer): the bad

- responsiveness:
  - input-to-response delay of 1 x delivery time (even locally!)
  - (you cannot act immediately even on your own local input)
- does not scale with number of players
  - quadratic number of packets
  - 2P ok, 100P not ok
- input rate = packet delivery rate
- delivery rate = as fast as the *slowest* connection allows
- if connection problems (anywhere): everybody freezes!
- joining ongoing games: difficult to implement
  - needs sends full game state to new player
- assumes full agreement on initial conditions
  - this is not problematic
- assumes complete determinism!
  - this can be problematic

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Determinism: what can break it

- Pseudo-Random? → not as problem
  - fully deterministic (just agree on the seed)
- Physics: many preclusions and traps
  - variable time step? bad
  - time budgeting? bad
  - hidden threats:
    order of processing of particles/constraints
- anything that depends on clock?
  → poison to determinism
- GPU computations? very dangerous
  - slightly different outcome on each GPU model
- floating point operations?
  - hidden dangers,
    different hardwired implementations
  - best to assume very little (**fixed point** is 100% safe)
- NOTE: 99.999% correct == not correct
  - virtual world is faithful to reality enough to be *chaotic* → butterfly effect:
    the tiniest local difference == expect completely different outcomes soon

The entire game system must be designed from the start with "determinism" in mind …

…and still, it difficult to get (and debug)

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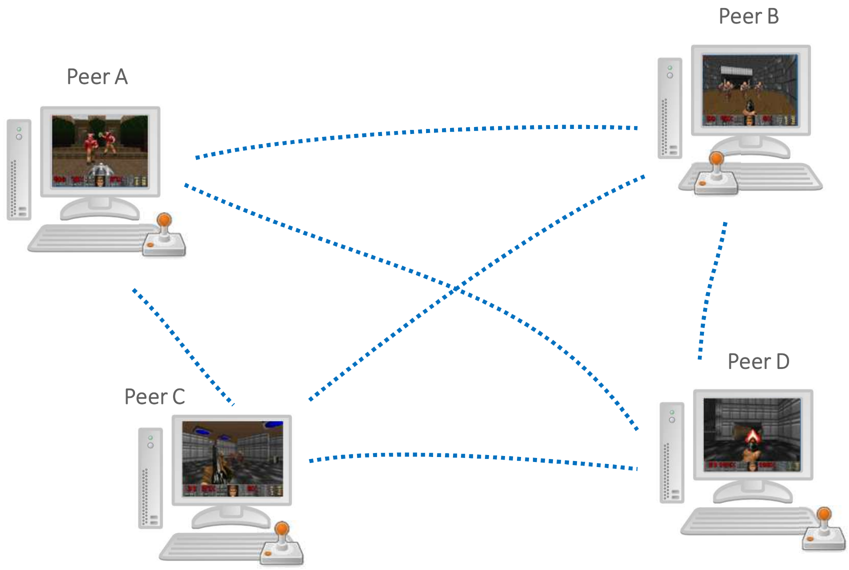
Model: Peer-to-Peer
Network topology: Fully Connected



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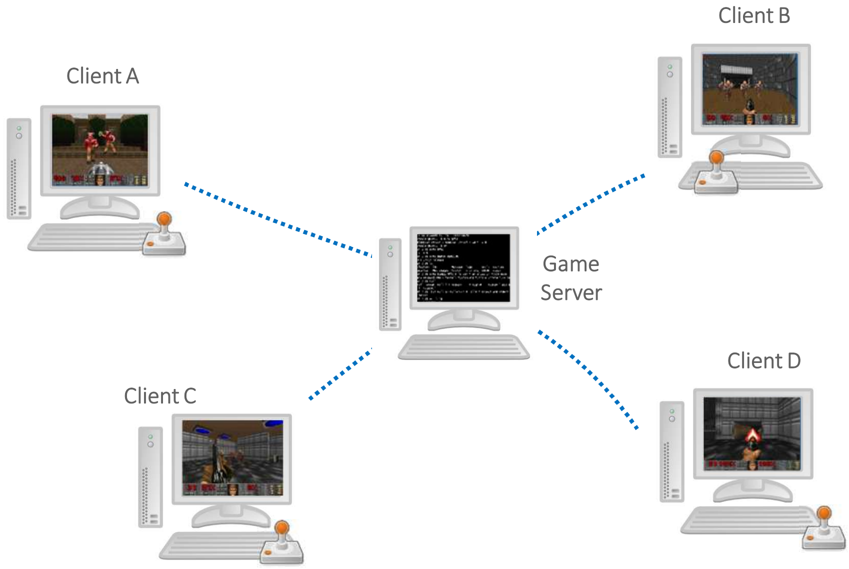
Model: Client / Server
Network topology: star



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Deterministic lockstep on Client-Server

- Server sits on the central node
- Protocol:
  - Each client sends his controls to server
  - Server collects all controls and sends them back to clients
- Advantage:
  - scalability:
    number of packets is linear (not quadratic)
- Cost:
  - responsiveness:
    latency = 2 × delivery time :-O
    hurts gameplay!
- Bonus: the server can now be made authoritative
  - Many new options available. For example…

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"Server is the man" * (authoritative server)

- The server has the last word
- For example:
  - Packet loss from player 3?
    Server makes up controls for player 3
    (instead of waiting for them)
  - Note: server *defines* what player 3 eventually did,
    not player 3 itself!
  - i.e., clients take server's word even for its own actions
  - Packet loss affects one player only

* Tim Sweeney (Unreal)

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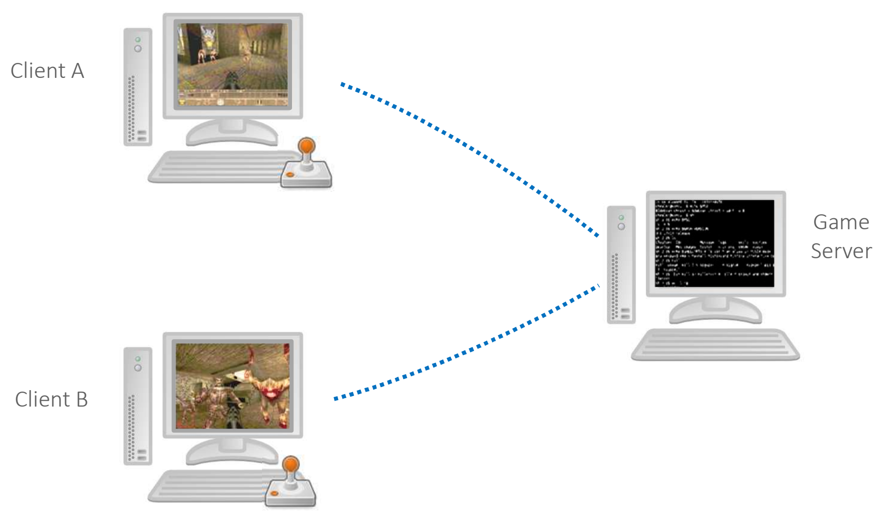
Client-Server



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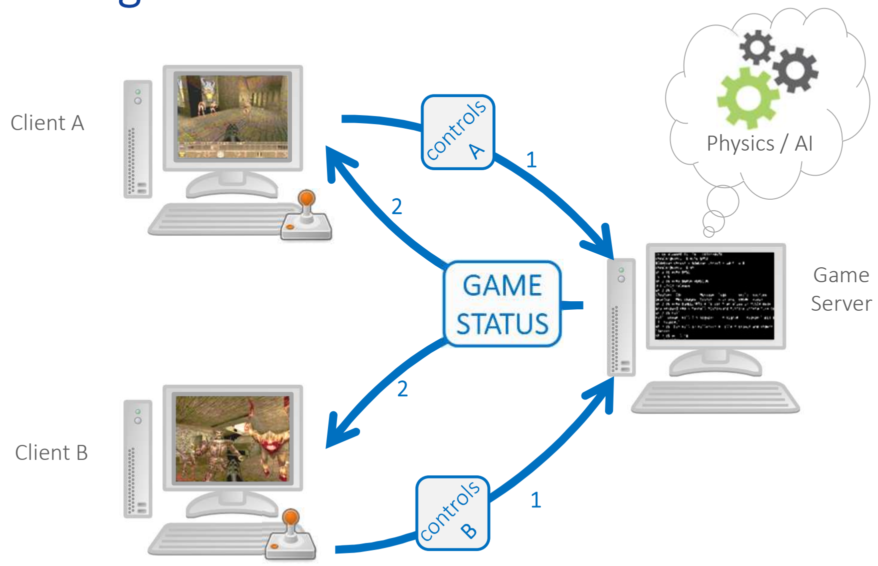
"Game-Status Snapshots" paradigm



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Quake – id Soft – 1996

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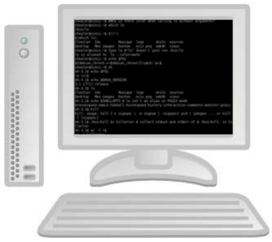
Game-Status Snapshots

- Client:
  - just a remote visualizer of the current status
    - status is “read only”
  - remote input collector
- Server:
  - computation of the evolving status
    - including physics
  - it’s where the “real game” runs



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Game-Status Snapshots

- Client:
  - connected: to server only
  - captures input
  - sends controls
  - receives game status
    - or relevant portions of it
  - renders it
    - using all relevant assets
- Server
  - connected: to all players
  - receives all controls
    - (missing? doesn’t matter)
  - updates game status
    - physical simulations, etc
  - sends current status
    - to all

Client: Physics, cosmetic effects only | Graphics | Sounds | UI

Server: Physics | AI | Scripts

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Game-Status Snapshots

- the gains:
  - determinism: no longer needs be assumed
  - joining ongoing games: trivial now
  - packet loss: bearable (hurts the player *only*)
    - to profit: UDP
  - slower connection: bearable (affects that player *only*)
- the losses:
  - packet size: a lot bigger!
    - optimizations, to counter this:
      - compress world status
      - send to each client only the portions which interest its player
  - responsiveness:
    from input to effect = delivery time :-(
    from input to visual = 2 x delivery time :-O

hurts gameplay!

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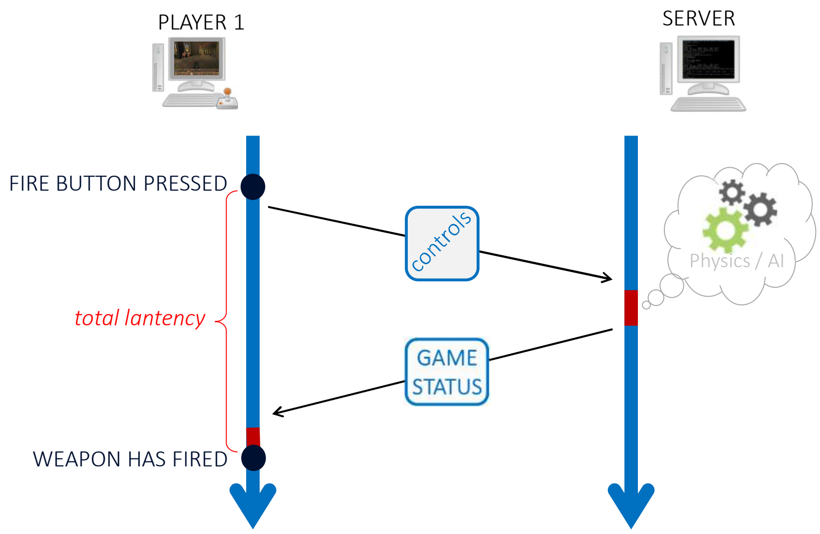
Game-Status Snapshots



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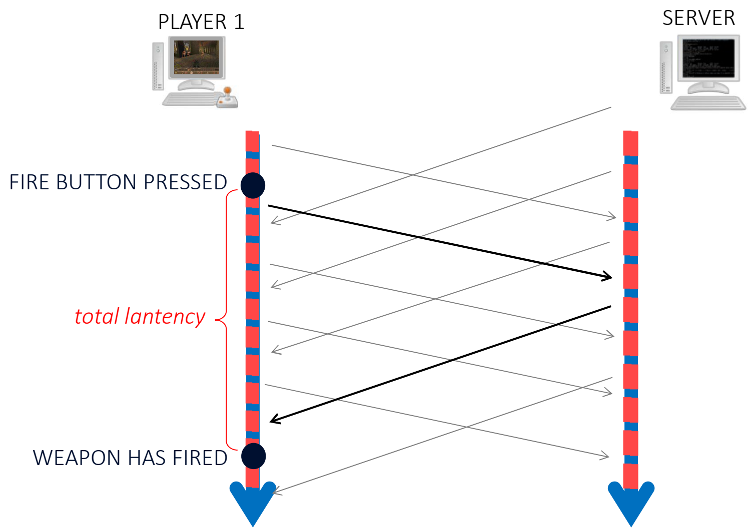
Game-Status Snapshots



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Game-Status Snapshots: with Interpolation: the idea

- World “Snapshot” contains:
  - data needed for 3D rendering:
    (position-orientation of objects, plus anything else needed)
- Problem:
  - large snapshot size! (even with optimizations)
  - ==> few FPS (in the physical simulation)
  - ==> “jerky” animations
- Solution 1: client-side interpolation
  - client keeps last two snapshots in memory
    - last received one + the previous one
  - interpolates between them,
    - client lags behind server by even more!
  - gain: smoothness (high FPS with low packet - rate)
  - loss: responsiveness (increased latency) oh noes!

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Game-Status Snapshots: with Extrapolation: the idea

- World "Snapshot" contains:
  - data needed for 3D rendering: (position-orientation of objects, plus anything else needed)
- Problem:
  - large snapshot size! (even with optimizations)
  - ==> few FPS (in the physical simulation)
  - ==> "jerky" animations
- Solution 2: client-side extrapolation
  - clients keeps last two snapshots in memory
    - last received one + the previous one
  - extrapolates between them, i.e., shows the expected "future"
    - i.e. it shows an attempted prediction to the next snapshot
    - NOTE: this prediction is often wrong: glitches.
  - gain: responsiveness
  - loss: accuracy - lots of glitches. :-(

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Partial Client-side Game Evolution (aka *distributed physics*): the idea

- Each client:
  - in charge for game evolution
    - including physics
  - communicates to others a reduced game-status snapshot (to server, or , in a P2P network, to each other peers)
    - describes only status of own player (e.g. positions + ori, its flying bullets)
  - receives other partial snapshots
  - merges everything up
    - (updates statuses of other players)
- Simple, zeroed latency
  - immediately responsive to local player controls
  - remote agents updated according to "what their client says"
- Problem: can still need determinism
  - (who keeps NPCs / environment in sync?)
- Problem: authoritative clients : prone to cheating!!!

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Client-Side Prediction: the idea

- Client:
  - get Commands from local inputs
  - sends Commands to Server
  - computes game evolution (the prediction)
    - maybe “guessing” other players commands (which it ignores)
    - zero latency!
- Server:
  - receives Commands (from all clients)
  - computes game evolution (the “reality”)
    - server is authoritative
    - prevents many forms of cheating
  - sends Snapshot back (to all clients)
- Client:
  - receives Snapshot (the “real” game status)
  - corrects its prediction, *only if needed*

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Client-Side Prediction with corrections from the server

- The server-side “real” simulation lives *k msecs* in the past of the client-side “predicted” one
  - *k* = deliver time
  - remember: virtual time != real world time
- When server correction arrives to client, it refers to *2k msecs* ago (for the client)
- Q: how to correct… *the past*?

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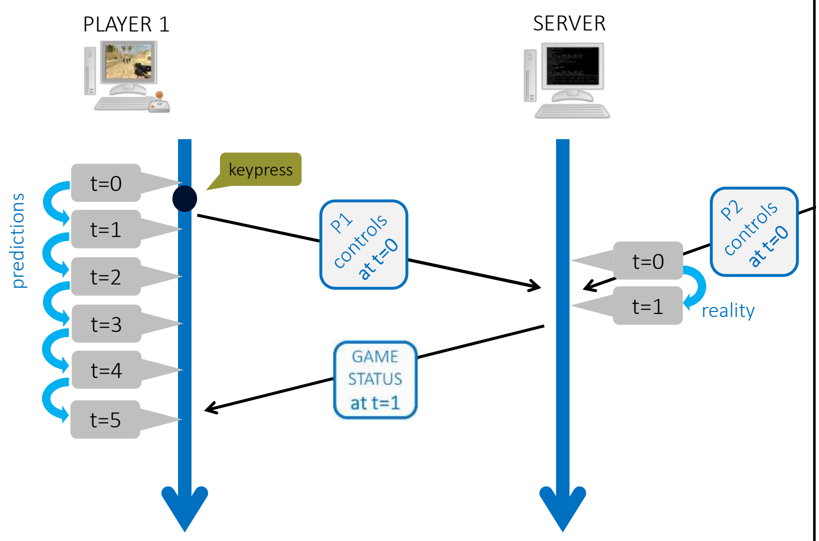
Client-Side Prediction



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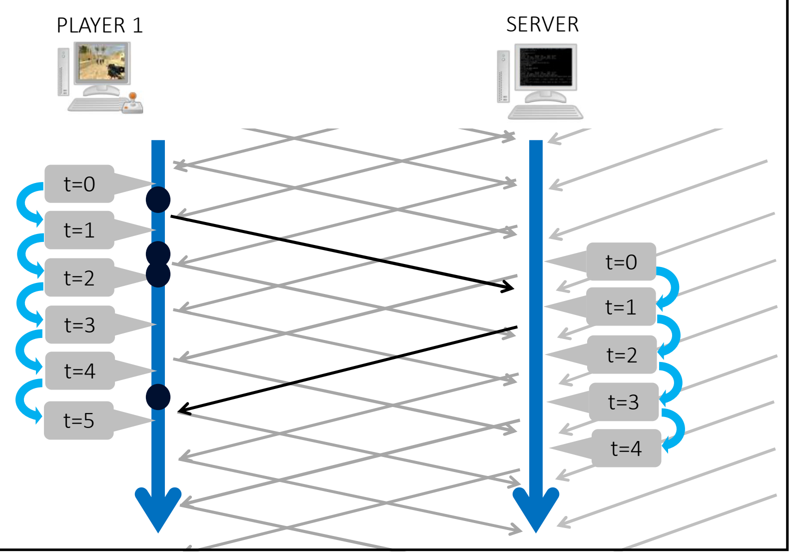
Client-Side Prediction



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Client-Side Prediction: correction from the server

- Q: How to correct… *the past*?
- A:
  - keep last *N* statuses in memory
    - including own controls
  - as the "real" status (the correction) of the past arrives from server…
  - …compare it with stored past status (at corresponding time):
    - does it match? nothing to do
    - does it mismatch? discard frame *and following ones*, rerun simulation to present (reusing stored controls)

optionally: within a tolerance

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Re-running physical simulation

- We just need to catch up with the present
- Physics and AI only
  - no graphics, no sound rendering, no cosmetic particle system…
- At full speed: can use larger dt if necessary
  - This only compromises accuracy a bit
- Must reuse same controls of own player and other's
  - Which are also cached
- Note: player is never shown these intermediate steps; only the final result
- The price to be paid: Glitches when going from current present to a different (corrected) present

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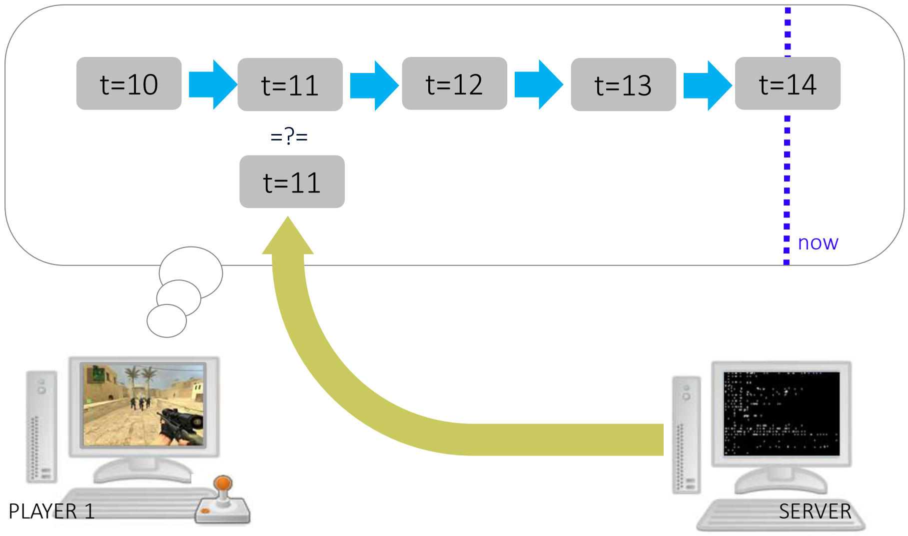
Client-Side Prediction: correcting the past



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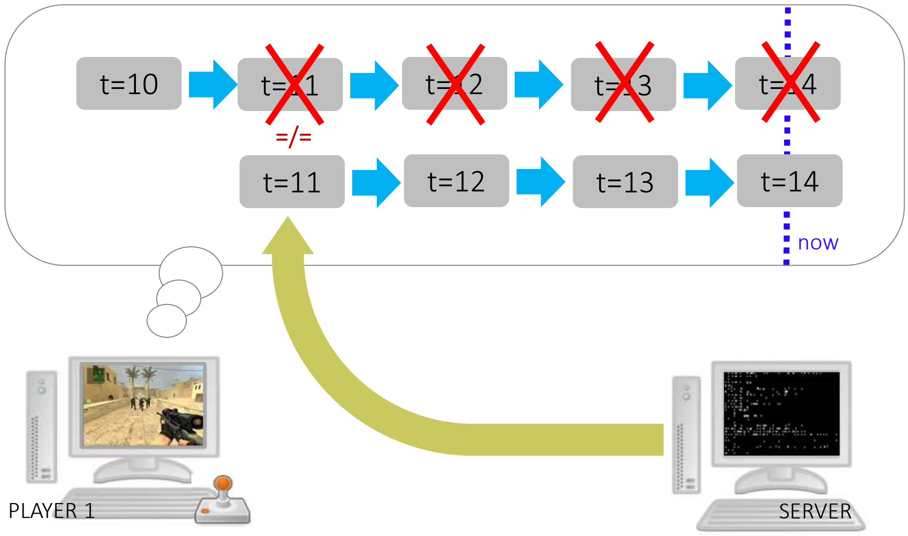
Client-Side Prediction: correcting the past



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Client-Side Prediction: what causes mispredictions?

- Lack of determinism
  - e.g., physics was approximated – "soft real time"
  - see above for more possible causes of this
  - (minor/rare issue)
- Didn't account that *own* controls were not received by server (in time)
  - server: "actually, back them, you didn't jump"
  - authoritative server – server *defines* the truth, (even when the client is in a better position to know)
  - (minor/rare issue)
- Didn't account for other players' controls
  - (the biggest issue)
- Note: none of the above breaks the game (hopefully)
  - it just causes minor / temporary glitches (maybe)

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Client-Side Prediction: optimizations 1/2

- reduce snapshots size
  (==> to increase packet frequency)
  - partial snapshots: refresh more often the parts which are most likely to be predicted wrong / or which changed
  - drastic space reductions!
  - but make sure that every part is eventually refreshed
- reduce correction computation
  (==> so to make corrections quicker)
  - partial physic steps: update only the parts affected by the error
  - use bigger dt (fewer steps to get to present)

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Client-Side Prediction: optimizations 2/2

- tentatively predict also unknown data
  (==> so to reduce correction frequency)
  - e.g. also predict other player's controls
  - easiest prediction: players do what they did last frame
- trigger correction only when status differ *enough*
  (==> so to reduce correction frequency)
  - e.g. when any spatial position difference > epsilon
  - tolerate small discrepancies
  - (warning: discrepancies tend to explode exponentially with virtual time – because Chaos)

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Client-Side Prediction: notes

- A snapshot = includes physical data
  - (not just for the 3D rendering, also to update physics)
  - can be small, when optimized!
- ☺ No latency: immediately react to local input
  - client proceeds right away with next frame
  - *when prediction is correct:* seamless illusion
  - *otherwise:* (minor?) glitches
- ☺ Determinism: not assumed
- ☺ Cheating: not easy (server is authoritative)

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Summary : rules of thumb

- How to choose the network layout
  - peer-to-peer :
    - ☺ reduced latency
    - ☹ quadratic number of packages (with number of players)
  - client-server :
    - ☹ doubled latency
    - ☺ linear number of packages (with number of players)
    - *REQUIRED*, for any solution with authoritative server
    - *REQUIRED*, for num players >> 4-6

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Summary : rules of thumb

- How to choose the network paradigm
  - Deterministic Lockstep, if ← RTS most common option !
    - determinism can be assumed
    - few players (up to 4-5)
    - fast + reliable connection (e.g., LAN)

    } *or*, slow paced game
  - Game-status Snapshots, if
    - game status not overly complex
    - a little latency can be tolerated
  - Client-side evolution, if
    - preventing cheating not important
  - Client-side prediction + server correction, if ← FPS most common option !
    - game status not overly complex

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Summary: classes of solutions

- Who computes game evolution? (incl. physics)
  - deterministic-lockstep : clients
    - there may be no server at all: peer-to-peer
    - independent computation, same result
  - game-status snapshots : server
    - clients are just visualizers
    - maybe with interpolation / extrapolation
  - (distributed physics : both clients and server)
    - clients in charge for own agent(s)
    - server in charge for env. / NPCs
  - client-side predictions : both clients and server
    - clients "predict" (just for local visualization purposes)
    - server "corrects" (it has the last word!)

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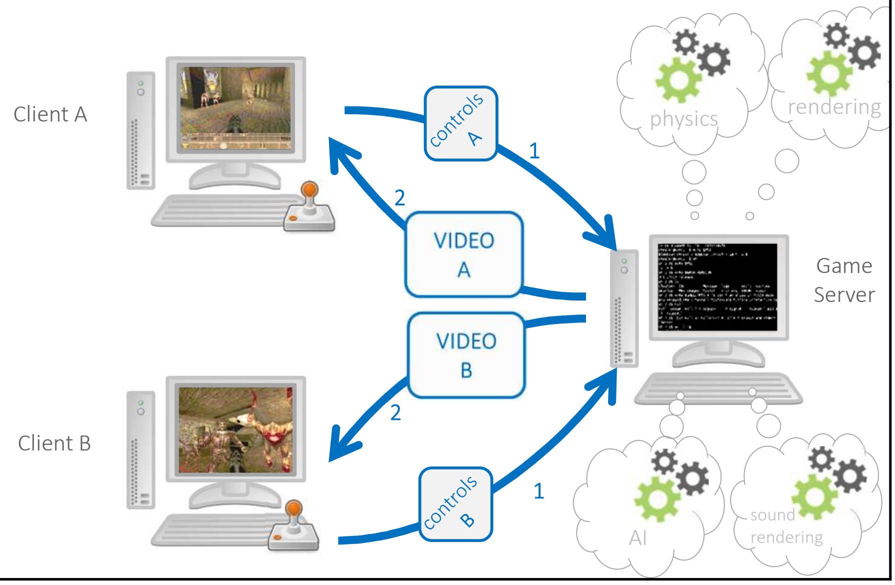
Cloud-gaming with video-streaming (aka game-on-demand)



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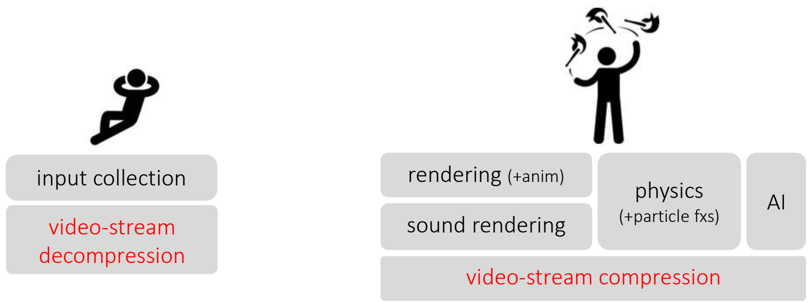
Cloud-gaming with video-streaming

- Client:
  - connected: to server only
  - captures + sends input
  - receives video + audio
  - decompresses video
- Server
  - connected: to all players
  - computes everything (for each player!)
  - compresses video + audio



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Cloud-gaming with video-streaming (aka game-on-demand)

- Compared to game snapshots technique…
- Server now does *everything*
  - 3D Physics + AI (same as with Game-Status snapshots)
  - 3D Rendering ("remote" rendering) (including animations, particle effects…)
  - 3D Sound rendering
  - Compresses and send 2D video

  ×N times! (once for each player)
- Client does almost nothing
  - Collects and sends inputs (controls)
  - Receives and decompresses 2D video

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Cloud-gaming with video-streaming (aka game-on-demand)

- Advantages: client is thin
  - client does almost nothing
  - client needs nothing (no asset, no storage)
  - needed capabilities are limited (pads, cellphones ok)
- Challenges:
  - Demanding in terms of bandwidth (high-res video + audio)
  - Demanding in terms of server workload
  - Latency!!! Impossible to reduce or to hide (by prediction), plus compression by server, plus decompression by client
    - Luckily, video-on-demand technologies can be reused
  - Video resolution, FPS: now become problematic

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Cloud-gaming (aka gaming-on-demand)

- A heavily invested-on, fast-growing approach to 3D game networking
- Latency = maybe 80-120 ms
  - Is this acceptable?
- Bandwidth = maybe 5-50 mbits/s
- Will it become an established platform for 3D games?

STADIA (Google)

GEFORCE NOW (nVidia)

X CLOUD (Microsoft)

PlayStation Now (Sony)

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