Networking for Games

IMGD 4000

Introduction (1 of 2)

- Games are increasingly networked
  - Multi-player, connecting PCs and Game consoles (e.g., Counter-strike, Halo)
  - Single-player, pulling and pushing content to Web service (e.g., Lumosity)
- Emerging services play game in "cloud", sending rendered game down as video
  - (However, will not talk about this approach much)
- All require an understanding of networking (conversant), with enough knowledge to design and build network game (develop)

Introduction (2 of 2)

- For now, "networking" mostly means "Internet networking", so that will be our reference
- Other networking aspects that can be relevant for games includes:
  - Ad Hoc / Mesh networking
  - Short-range wireless (e.g., Bluetooth)
  - Network security (including cheating)
  - Mobile application (game) development (often networked)
- These, and other topics available in-depth from your friendly, neighborhood WPI course

(next slide)

Networking at WPI

- General, core networks:
  - CS 3516 – Computer Networks
    - Broad view of computer networks, top-down
  - CS 4516 – Advanced Computer Networks
    - In-depth computer networks, more "under the hood"
- Networks applied to specific domains
  - CS 4513 – Distributed Systems
  - CS 4518 – Mobile and Ubiquitous Computing
  - CS 4241 – Webware: Computational Technology for Network Information Systems
  - CS 4404 – Tools and Techniques in Computer Network Security
- Also grad courses
  - CS 513 – Introduction to Local and Wide Area Networks
  - CS 528 – Mobile and Ubiquitous Computing
  - CS 529 – Multimedia Networking
  - CS 530 – High-Performance Networks
  - CS 533 – Modeling and Performance Evaluation of Network and Computer Systems
  - CS 558 – Computer Network Security
  - CS 577 – Advanced Computer and Communications Networks

This deck → core networking applied to computer games.

The Internet from the Edge (1 of 2)

- Reasonable analogy → Postal Service
  - Letter in envelope
  - Find address of business in phonebook
  - Address on envelope
  - Put in Mailbox → *trust* that will reach destination
  - Don't know how envelope gets there
  - Delivery takes different amounts of time for each
    - Generally, further away longer (but not always)
  - Use external ways to confirm
    - (ex: Use phone, or resend letter until confirmation)

The Internet from the Edge (2 of 2)

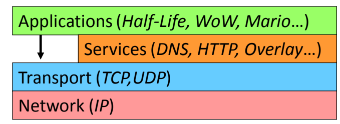
- Reasonable analogy → Postal Service
- Users view the Internet similarly → An opaque cloud
  - User application content is like *letter*
  - Putting content into packet for sending is like *envelope*
  - IP address is like *address* on envelope
  - Internet name service (DNS) to find address is like *phonebook*
  - Internet routing is like mail carrier delivery route
  - If don't get return letter, resend (packet) to make sure message is received
    - There are other ways to ensure delivery (e.g., repair) that we will not discuss

Outline

- Introduction (done)
- Basic Internet Architecture (next)
- Loss and Latency
- Latency Compensation Techniques
- Client-Server Synchronization

The Internet

- Many design decisions and end-user experiences for multi-player networked games derive from nature of Internet
  - "Best Effort" service
  - Internet naming and addressing
  - Transport protocols (TCP/UDP)
- Layered



Internet Provides "Best Effort" Service

- Few guarantees on timeliness
  - Can take milliseconds, 100's of milliseconds, or even seconds to deliver packet
- Few guarantees on arrival certainty
  - Sometimes packet doesn't arrive (loss)
  - Or arrives out of order (e.g., packet #3 arrives before packet #2)
  - Or can arrive twice (duplicates, uncommon but possible)
- Time to reach destination called latency
  - Lag typically latency + end-host (server and client) time
    - Often, players have hard time distinguishing

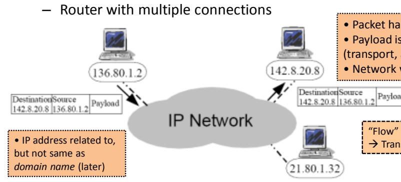
(More on loss and latency later)

Endpoints and Addressing

- IPv4 numerical 32-bit (4 byte) values
  - Dotted quad form: `192.168.1.5` or `130.215.36.142`
  - In theory, 2^{32} (about 4 billion) addresses, but practically fewer since allocated in blocks
- Each Internet host has IP address
  - Client running game client
  - Server running game host
- Some have 2
  - Client with wireless and wired network (multi-homed)
  - Router with multiple connections

IPv6 has 2^{128} addresses (enough for 100 addresses for each atom on the earth surface), but not widely deployed in U.S.

- Packet has: source, destination
- Payload is upper layer (transport, application)
- Network worries about arrival



- IP address related to, but not same as *domain name* (later)

"Flow" determined by *port*, too
→ Transport layer (next)

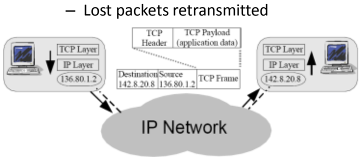
Transmission Control Protocol (TCP)

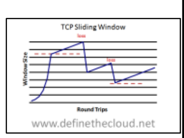
- Many applications sensitive to loss, not time
  - e.g., File transfer (.exe), email
  - Need reliable, ordered transfer of bytes
- Frames data → send as IP packets
- Provides connection
- Uses *window* for outstanding packets
  - Provides *flow control* and *congestion control*
  - Window grows with success, shrinks with loss
  - Lost packets retransmitted

Some games more sensitive to time
→Don't use TCP

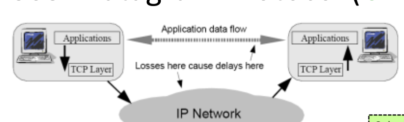
But many games do use TCP
→RTS, MMO

Generally, easier to use TCP for games!





User Datagram Protocol (UDP)

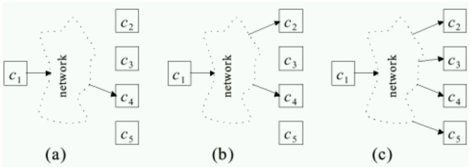


- Some applications sensitive to time
  - e.g., Voice over IP (VoIP)
  - Some games (e.g., First Person Shooter)
- Unreliable, connectionless
- No flow control (sender can go faster than receiver)
- No congestion control (sender can go faster than network)
  - Note: IP does ensure there are no bit errors (via Cyclic Redundancy Check, CRC)
- *Lightweight*, but *application must handle loss!*

Only use UDP if you know your application is sensitive to latency!

Otherwise, use TCP (see previous slide)

Unicast, Multicast, Broadcast



(a) Unicast, one send and one receive
- Wastes capacity when path shared

(c) Broadcast, one send and all receive
- Perhaps ok for LAN, but cannot do on Internet
- Wastes capacity when most don't need

(b) Multicast, one send and only subscribed receive
- Current Internet does not support
- Multicast can work for overlay networks (separate topic)

Note, UE4 provides a multicast networking feature. However, this is *not* true IP multicast, but rather replicated unicast to all clients.

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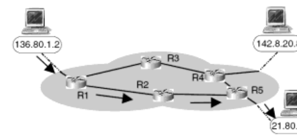
Connectivity

- Often edge most important
  - Game developer does not see internals
- But some aspects important for understanding network performance
  - Hierarchy
  - Routing
  - Link-layer



Independent choice for packet route based *solely* on destination address
- Not based on sender
- Not based on QoS

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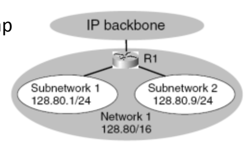
Connectivity – Hierarchy

- Routers designed for speed
  - Get packet to outgoing link asap
- Value + Prefix size
  - `128.80.0.0/16` → all w/`128.80` go to R1
  - R1 forwards more precisely to subnet
  - WPI has `130.215` with
    - `130.215.28` CS subnet
    - `130.215.36` CCC subnet (CCC1, …)
    - `130.215.16` ECE subnet…



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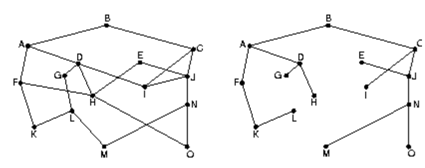
Connectivity – Routing

- Routers use dynamic routing
  - Discover topology
  - Pick "best" routes (want tree)
    - Typically shortest path (# hops, latency…)

Note: Local (internal to ISP) routing protocol different than among ISPs (ASes). The "cost" between ASes different than simply distance.



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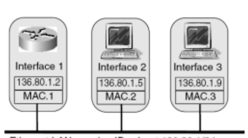
Connectivity – Link Layer

- Link layer conveys packets across LAN
  - Medium Access Control (MAC)
- IP address mapped to data link layer
  - Ethernet (IEEE 802.3), Wi-Fi (IEEE 802.11)
  - MAC address 48-bit. E.g., `00:0F:1F:81:41:6C`
  - MAC address specified by vendor on card
- IP to MAC assignment:
  - Fixed (e.g., register computer with netops)
  - Dynamic (assigned when boot)



Typically, network game won't care about link layer since usually fast. But …. wireless, particularly wide-area wireless (e.g, 4G) can have 10s or 100s and even 1000s of millseconds of latency!

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Miscellaneous

- Time-to-Live
  - Prevent loops (routers may have different shortest-path trees)
  - 8-bit value (0 to 255)
  - Decrement by one each hop
  - If zero, then discard
- Maximum Transmission Unit (MTU)
  - IP packet could be 64 KBytes
  - In practice, bound by Ethernet (prevalent standard)

  → 1500 byte payload, so 1460 bytes for application payload
  - If larger, then fragment into multiple IP packets
    - Re-assemble at end
    - If one lost, all lost!
- First Hop
  - Only know egress (e.g., first router)

`ifconfig` (Linux)
`ipconfig /all` (Windows)

For network games using UDP, keep data payloads smaller than MTU!

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Address Management Mini-Outline

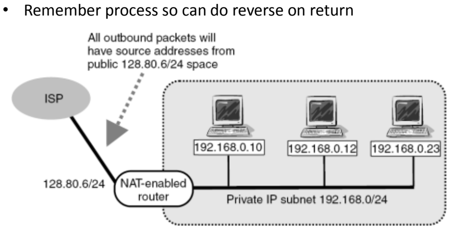
- Network Address Translation
- Dynamic Host Configuration Protocol
- Dynamic Name Service

Network Address Translation (NAT) (1 of 2)

- Used at boundary of ISP
  - Where internal private addresses use external publicly routable address
- Good if internal address not allocated
  - Ex: private networks
    - `10/8, 172.16/12, 192.168/16`
- Also, may help keep internal network secure (but not sufficient)

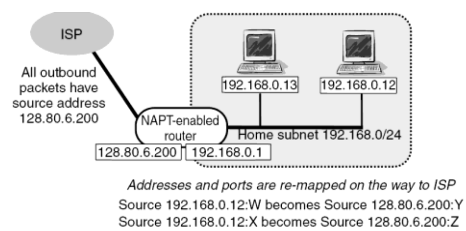
Network Address Translation (NAT) (2 of 2)

- Source hosts use private IP
- Forward to NAT router
- Swap private source address with public address (could be range)
  - 1-to-1 mapping between source hosts and public addresses
- Send to ISP for Internet routing
- Remember process so can do reverse on return



Network Address Port Translation (NAPT) (1 of 2)

- Have only 1 public address for multiple private addresses



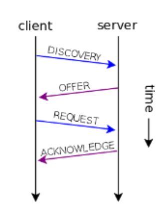
Network Address Port Translation (NAPT) (2 of 2)

- Good:
  - Easy to renumber (one number)
  - Only need one public address
- Bad: Breaks transparency (need to add functionality for each new protocol)
- Hard for outside hosts to access inside
  - Ex: what if two different *Unreal Tournament* servers inside?
  - Need non-standard ports that *clients* know about
    - Typically, local server register w/master server
      - Gives IP adress + Port where server is
  - Need to configure NAT box to forward ports

For network game, cannot rely upon reaching server behind NAT!

Dynamic Host Configuration Protocol (DHCP)

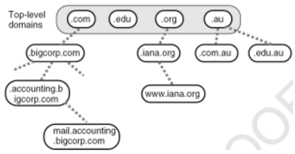
- Hosts need: IP address, subnet mask, IP address of at least one router
  - Use DHCP to get from LAN device
    - Typically with WLAN router, cable modem, …
- Client broadcasts DHCP discovery to port 67
  - Identifies its MAC address (e.g., 00:0a:95:9d:68:16)
- DHCP server responds w/IP + Mask + Router IP
- Client confirms, may request additional information (could be more than one DHCP server)
- Server ACKs



For network game, host may not have same IP address each time!

Domain Name System

- Map text names to IP address
  - Ex: `www.wpi.edu` mapped to `130.215.36.26`
  - Names more human-readable
- Minimal `<name>.tld` (top-level-domain)
  - tld: `.com, .gov, .edu`
  - tld: `.au, .fr, .uk`



- Hierarchy
  - Distributed name servers
  - Know first one, it knows upper level
  - Local responses cached
    - Local DNS, and at host

`nslookup, dig, host`

Initial latency may be high for first query (then cached by host)

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Outline

- Introduction (done)
- Basic Internet Architecture (done)
- Loss and Latency (next)
- Latency Compensation Techniques
- Client-Server Synchronization

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Loss and Latency

- Characteristics most identified with IP networks
  - Note, in other cases capacity, but not usually for network games
- **Loss** – packet does not arrive
  - Usually, fraction `#recv/#sent`, p → `[0:1]`
  - Note, often assumed independent but can be bursty (several lost in row)
- **Latency** – time to get from source to destination
  - Round trip time (RTT) often important since server response to game action
  - Often assumed (2 x latency), but network path can be asymmetric
  - Also jitter (or *latency jitter*) variation in latency (not discussed more here)
- How much does each matter? (later)
- Right now, sources for each

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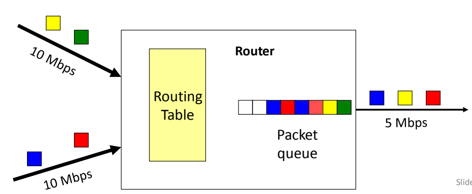
Sources of Loss

- Note, here we are considering only *IP* packet loss
  - Above IP, TCP will retransmit lost packets
  - Below IP, data link often retransmits or does repair (forward error correction)
- IP packet loss predominantly from congestion
  - Causes queue overflow (incoming packets dropped)
- Bit errors
  - More common on wireless
- Loss during route change (link/host unavailable)
- Often bursty!



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Sources of Latency

- Serialization – Time to transmit packet on link 1 bit at a time
- Propagation – Time for bits to travel from one host to another
- Queueing delay – Time spent in router queue waiting to be transmitted

- Typically
  - Propagation time fast (about speed of light)
  - Serialization time usually fast for high capacity links
  - Queuing delay can dominate, and exacerbated by long serialization times

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Latency Compensation Mini-Outline

- Motivation
- Prediction
- Time delay and Time warp
- Data compression
- Visual tricks
- Cheating

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Need for Latency Compensation

- Capacities are growing, but cannot solve all problems
- Still bursty, transient congestion (queues)
- Capacities uneven across all clients
  - And often asymmetric in downlink/uplink.
- Wireless Wide Area Networks (WWANs) growing (low, variable capacities, high latency)
- Propagation delays (~25 msec min across U.S.)

"There is an old network saying: 'Bandwidth problems can be cured with money. Latency problems are harder because the speed of light is fixed – you can't bribe God.' " —David Clark, MIT

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Is It Latency or Do You Just Suck?

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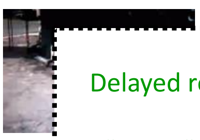
Is It Latency or Do You Just Suck?

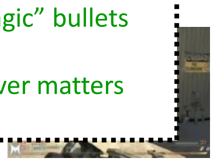


http://ww

Delayed response

"Magic" bullets

Server matters



http://www.youtube.com/watch?v=Bn1nBR5jOx8

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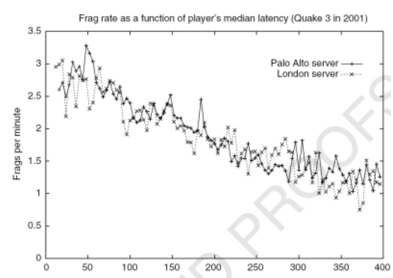
Latency and Playability (1 of 2)

- Affects player – subjective and objective (below)



But depends upon type of game!

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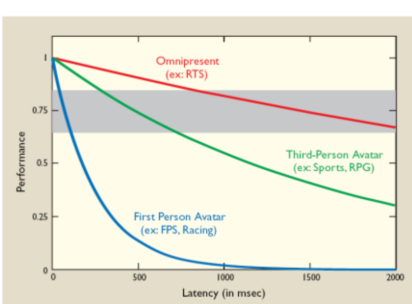
Latency and Playability (2 of 2)



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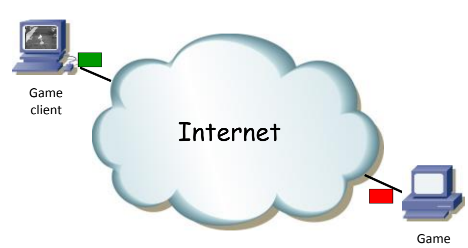
What is Network Latency for Games?



- *Latency* - time to get from source to destination
  - There and back (*round-trip time*)

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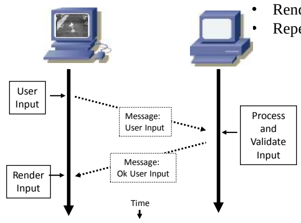
Basic Client-Server Game Architecture

- "Dumb" client
- Server keeps all state
- Validates all moves
- Client only updates when server says "ok"

Algorithm
- Sample user input
- Pack up data and send to server
- Receive updates from server and unpack
- Determine visible objects and game state
- Render scene
- Repeat



Latency affects *responsiveness*

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Latency Example (1 of 2)


Player is pressing left


Player is pressing up


Running back goes out of bounds

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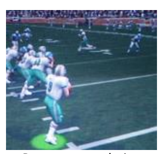
Latency Example (2 of 2)


Player is pressing "pass"


Pass starts rendering


Interception

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Outline

- Introduction (done)
- Basic Internet Architecture (done)
- Loss and Latency (done)
- Latency Compensation Techniques (next)
- Examples – Dragonfly and UE4

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Compensating for Latency – Prediction

- Broadly, two kinds of latency compensation:
  – Player prediction
  – Opponent prediction (often called "dead reckoning" but that name does little to help remember)

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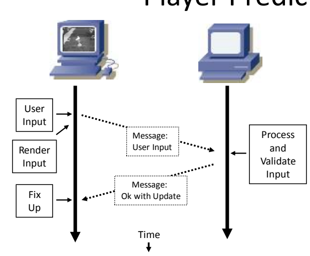
Compensating for Latency – Player Prediction



Prediction Algorithm
- Sample user input
- Pack up data and send to server
- Determine visible objects and game state
- Render scene
- Receive updates from server and unpack
- Fix up any discrepancies
- Repeat

Potentially, *tremendous* benefit. Render as if local, no latency. But, note, "fix up" step additional. Needed since server has master copy.

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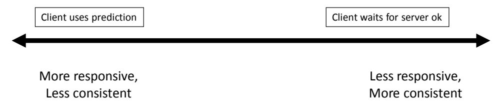
Example of State Inconsistency

- Predicted state differs from actual state

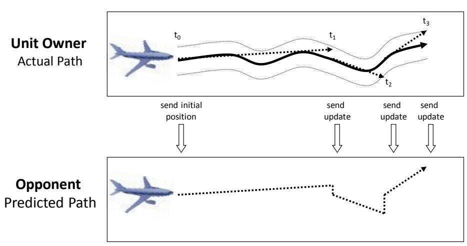
Prediction Tradeoffs

- Tension between responsiveness (latency compensation) and consistency



Compensating for Latency – Opponent Prediction

- Opponent sends position, velocity (maybe acceleration)
- Player predicts where opponent is



(User can see "Warp" or "Rubber band".)

Opponent Prediction Algorithms

Unit Owner

- *Sample* user input
- *Update* {location | velocity | acceleration} on basis of new input
- *Compute* predicted location on the basis of previous {location | velocity | acceleration}
- If (current location – predicted location) < threshold then
  - *Pack up* {location | velocity | acceleration} data
  - *Send* to each other opponent
- Repeat

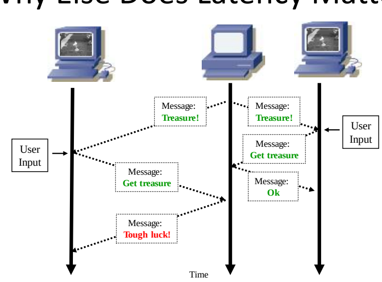
Opponent

- *Receive* new packet
- *Extract* state update information {location | velocity | acceleration}
- If seen unit before then
  - *Update* unit information
- else
  - *Add* unit information to list
- For each unit in list
  - *Update* predicted location
- *Render* frame
- Repeat

Opponent Prediction Notes

- Some predictions easy
  - Ex: falling object
- Other predictions harder
  - Ex: pixie that can teleport
- Some predictions game specific
  - Ex: Can predict "return to base" with pre-defined notion of what "return to base" is.
- Cost is having each host runs prediction algorithm for each opponent.
- Also, although is latency compensation method, can greatly reduce bitrate.
  - Predict self. Don't send updates unless needed.
  - Especially when objects relatively static.

Why Else Does Latency Matter?

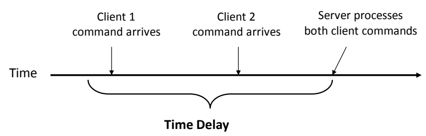


Latency affects *fairness*

Solution? Manipulate time
Time Delay
Time Warp

Compensating for Latency – Time Delay

- Server delays processing of events
  - Wait until all messages from clients arrive
- Server sends messages to more distant client first, delays messages to closer
  - Needs accurate estimate of RTT
- (Note, game plays at highest round trip time (RTT))



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Compensating for Latency – Time Warp

- In older FPS (e.g., Quake 3), player had to "lead" opponent to hit
  - Otherwise, opponent had moved
  - Even with "instant" weapon!
- Knowing latency roll-back (warp) to when action taken place
  - Usually assume ½ RTT

Time Warp Algorithm

- Receive packet from client
- Extract information (user input)
- elapsed time = current time – latency to client
- Rollback all events in reverse order to current time – elapsed time
- Execute user command
- Repeat all events in order, updating any clients affected
- Repeat

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Time Warp Example

- Client 100 ms behind Server
- Shots still hits (note blood)

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Time Warp Notes

- Inconsistency
  - Opponent targets player
  - Player moves around corner to hide
  - Time warps backward → hit
  - Bullets seem to "bend" around corner!
- Fortunately, player often does not notice
  - Doesn't see opponent
  - May be just wounded

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Compensating for Latency – Data Compression (1 of 2)

- Idea → less data, means less latency to get it there
  - So, reduce # or size of messages → reduce latency (serialization)
- Lossless (like zip)
- Opponent prediction
  - Don't send unless need update
- Delta compression (like opponent, but more general)
  - Don't send all data, just updates
- Interest management
  - Only send data to units that need to see it

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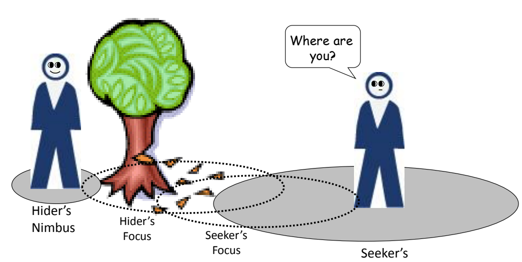
Interest Management



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Compensating for Latency – Data Compression (2 of 2)

- Peer-to-Peer (P2P)
  - Limit server congestion
  - Also, client1→server→client2 higher latency than client1→client2
  - But scales with *slowest* computer
  - But cheating especially problematic in P2P systems
- Update aggregation
  - Message Move A → Send C, Move B → Send C
  - Instead, Move A + Move B → Send C
  - Avoid packet overhead (if less than MTU)
  - Works well w/time delay

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Compensating for Latency – Visual Tricks

- Latency present, but hide from user
  - Give feeling of local response
- Ex: player pulls trigger, make sound and puff of smoke while waiting for confirmation of hit
- Ex: player tells boat to move, while waiting for confirmation raise sails, pull anchor
- Ex: player tells tank to move, while waiting, batten hatches, start engine

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Outline

- Introduction (done)
- Basic Internet Architecture (done)
- Loss and Latency (done)
- Latency Compensation Techniques (done)
- Client Server Synchronization (next)
  - By Example – Dragonfly and UE4

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Network Game Case Study – Saucer Shoot 2

Saucer Shoot for two players

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Dragonfly – Network Manager

```
class NetworkManager : public Manager {

 private:
  NetworkManager();.
  NetworkManager(NetworkManager const&);
  void operator=(NetworkManager const&);
  int sock;

 public:

  // Get the one and only instance of the NetworkManager.
  static NetworkManager &getInstance();

  // Start up NetworkManager.
  int startUp();

  // Shut down NetworkManager.
  void shutDown();

  // Accept only network events.
  // Returns false for other engine events.
  bool isValid(string event_type);

  …
```

Basic manager stuff

```
  // Block, waiting to accept network connection.
  int accept(string port = DRAGONFLY_PORT);

  // Make network connection.
  int connect(string host,
              string port = DRAGONFLY_PORT);

  // Close network connection.
  int close();

  // Send buffer to connected network.
  int send(void *buffer, int bytes);

  // Receive from connected network (no more than bytes).
  int receive(void *buffer, int bytes);

  // Check if network data.
  int isData();

  // Return true if network connected, else false.
  bool isConnected();

  // Return socket.
  int getSocket();
};
```

Network specific stuff

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Dragonfly – Network Events

```
#include "Event.h"

#define NETWORK_EVENT "__network__"

class EventNetwork : public Event {

 private:
  int bytes;   // Number of bytes available

 public:
  // Default constructor.
  EventNetwork();

  // Create object with initial bytes.
  EventNetwork(int initial_bytes);

  // Set number of bytes available.
  void setBytes(int new_bytes);

  // Get number of bytes available.
  int getBytes();
};
```

- Indicate network data is available
- And how much
- Bytes are actually still with network manager

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Client and Host Objects

- Host object (derived from Object) runs on server
- Client object (derived from Object) runs on client
- Host game started first, whereupon Host (using NetworkManager) readies computer for connection
- Client (also using NetworkManager) starts after and connects to Host
- Client gathers input normally, but also sends data to Host
- Host receives keystrokes sent by Client, generating network events to game objects (e.g., the Client Hero) to handle
- Each game loop, Host checks all game objects to see which ones are new and/or updated
  - Need to synchronize Objects between Host and Client … but how?

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How to Synchronize Client and Host (Server)?

- Many decisions for multiplayer game
  - How are player actions transmitted to server?
  - What Objects are synchronized and how often?
  - How are inconsistencies between client and server game states resolved?
- Key aspect – how to “send” Object from one computer to another

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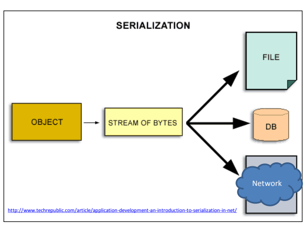
Serializing Objects

- Convert Object attributes to byte stream for storage or transmission

Also known as “marshalling”



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Serializing (Marshalling) Objects

Object class extensions to support marshalling

```
// Serialize Object attributes to single string (json-like).
// e.g., "id:110,is_active:true, ...
// Only modified attributes are serialized (unless all is true).
virtual string serialize(bool all = false);

// Deserialize string to become Object attributes.
virtual int deserialize(string s);

// Return true if attribute modified since last serialize.
bool isModified(enum ObjectAttribute attribute);
```

e.g.,

```
id:0,is_active:true,is_visible:true,event_count:0,box-corner-x:0,
box-corner-y:0,box-horizontal:1,box-vertical:1,pos-x:0,pos-y:0,
type:Object,sprite_name:,sprite_center:true,sprite_transparency:0,
sprite_index:0,sprite_slowdown:1,sprite_slowdown_count:0,altitude:2,
solidness:0,no_soft:false,x_velocity:0,x_velocity_countdown:0,
y_velocity:0, y_velocity_countdown:0,
```

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Synchronizing Objects (1 of 2)

- Only synchronize important objects and events (e.g., Hero destruction vs. Stars moving)

Synchronize	Don't Synchronize
Saucer creation/destruction	Stars
Bullet creation/destruction	Object movement that velocity handles
Hero creation/destruction	Explosions
Points increase	Reticle
Above Object position changes	

Synchronizing Objects (2 of 2)

- Have configuration for game (host | client)
  - Can keep same codebase for Hero, Bullet, Points…
- Generally, only Host creates/destroys
  - Except for Explosion
- Generally, Host and Client move and animate
  - Except for Client Hero (see below)
- Client Player input
  - Could update Hero location and synchronize
    - But if not allowed, need to “roll back” state
  - Instead, send keystrokes to server
    - Let server move all Objects and send to client

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Multi-player Networking

- Client-Server
  - Authoritative server, makes all decisions
- Replicate objects, variables, functions
  - Replicated Actors are main “workhorse” server uses to synchronize
  - Server gathers attributes that change, send to client
- Not all objects, variables, functions need to be replicated
  - E.g., objects that compute AI behavior on server → only when move Actor
  - E.g., only replicate functions that result in client seeing/hearing

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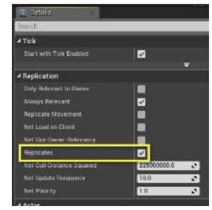
Replication

- When replicated object created/modified/destroyed on server, sent to clients
- When replicated object created/modified on client, not sent
  - Can be used for “cosmetic” objects that don’t effect gameplay
- Client sends information via “run on server” functionality



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Remote Procedure Calls (RPC)

- RPCs are functions called locally (they look like “normal” functions), but are executed on server
- Allow client/server to send messages to each other
- Used for playing sounds, spawning particles
- Also, client invokes via “run on server” function

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Reliability

- Any replicated event can be reliable or unreliable
- Reliable
  - Guaranteed to be called, resent if error, delayed when bandwidth saturated
    - E.g., use for starting game
- Unreliable
  - Attempt to call, but not resent if error, dropped if bandwidth saturated
    - E.g., use for player movement
- NetMulticast – send to all clients (not true multicast)
  - E.g., send notice of player death

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Summary

- Networking increasingly important for games
  - The network *is* the computer
  - Many games come with multi-player, online play, downloads, player communities
- Internet influences design of game architecture
  - Need to live with “best effort” service
- Choice of solution depends upon action within game
  - Transport protocol
  - Latency compensation
  - Client-server architectures dominate
- Game developers need to carefully consider design of object synchronization

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