

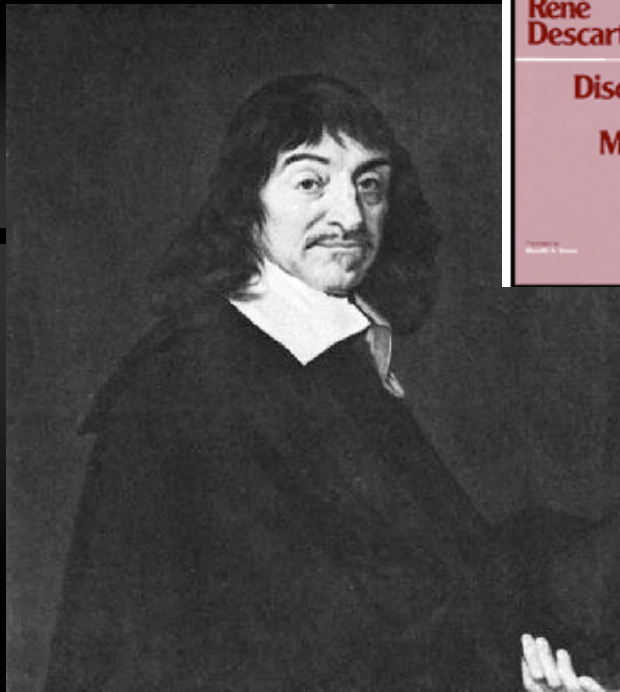


With pictures!!!

Virtual Acoustic Reflections

Gregory H. Wakefield
Interactive Systems Lab
CSE, PAT, OTO, EE:S

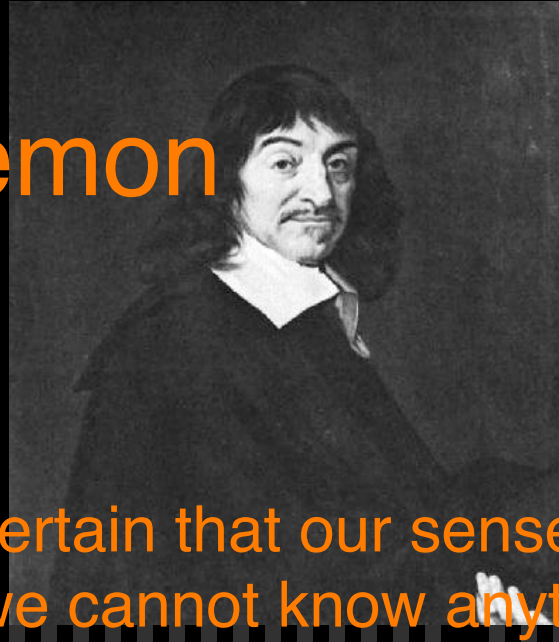
Cartesian Daemon



"I will suppose. . .that some evil demon of the utmost power and cunning has employed all his energies to deceive me." (17th century version)

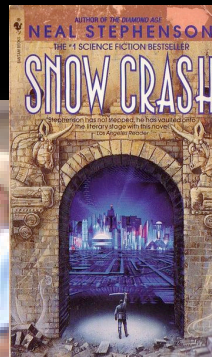
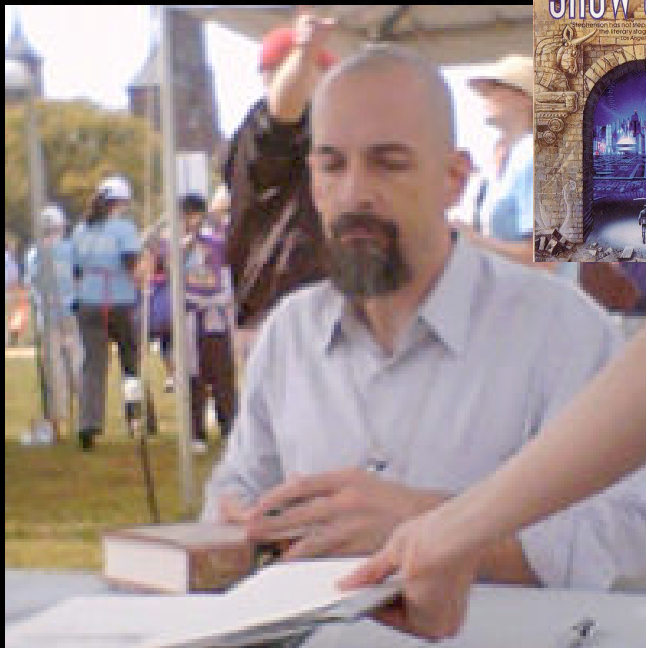
"I will suppose...that some mad scientist of the utmost power and cunning has placed my brain in a vat, and is cleverly stimulating my brain to deceive me otherwise." (20th century version)

Cartesian Daemon



- If we cannot be certain that our senses do not deceive us, then we cannot know anything with certainty.
- We cannot know whether or not our senses deceive us.
- Therefore, we cannot know anything about the world.

The latest Cartesian Daemon

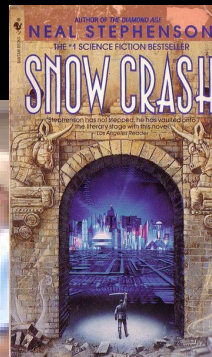
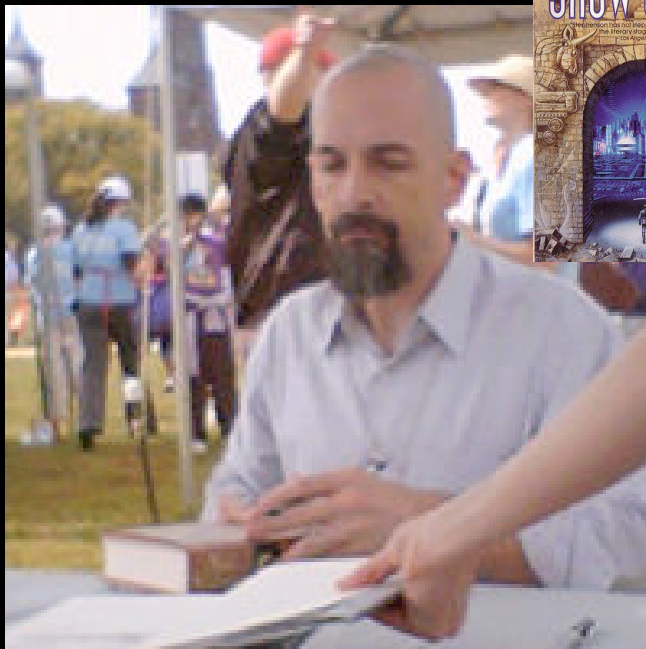


"I will suppose. . .that some evil demon of the utmost power and cunning has employed all his energies to deceive me."

"I will suppose...that some mad scientist of the utmost power and cunning has placed my brain in a vat, and is cleverly stimulating my brain to deceive me otherwise."

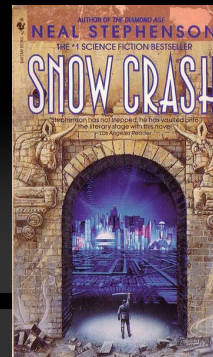
"I will suppose...that Bill Gates has placed me in a *metaverse* and has employed all his minions to deceive me."

Neal Stephenson (1959 -)



- Post-cyberpunk writer (see William Gibson)
- *Snow Crash* (1992)
 - Metaverse | Reality
 - Avatar embodiment

Well-engineered Games



- Epistemology
 - How does the world inform us of the world?
 - How do we “know what we know”?
 - Setting design criteria for VR, extended-reality, augmented reality, and interactive systems

Well-engineered Games



PERCEPTUAL PLUMBING

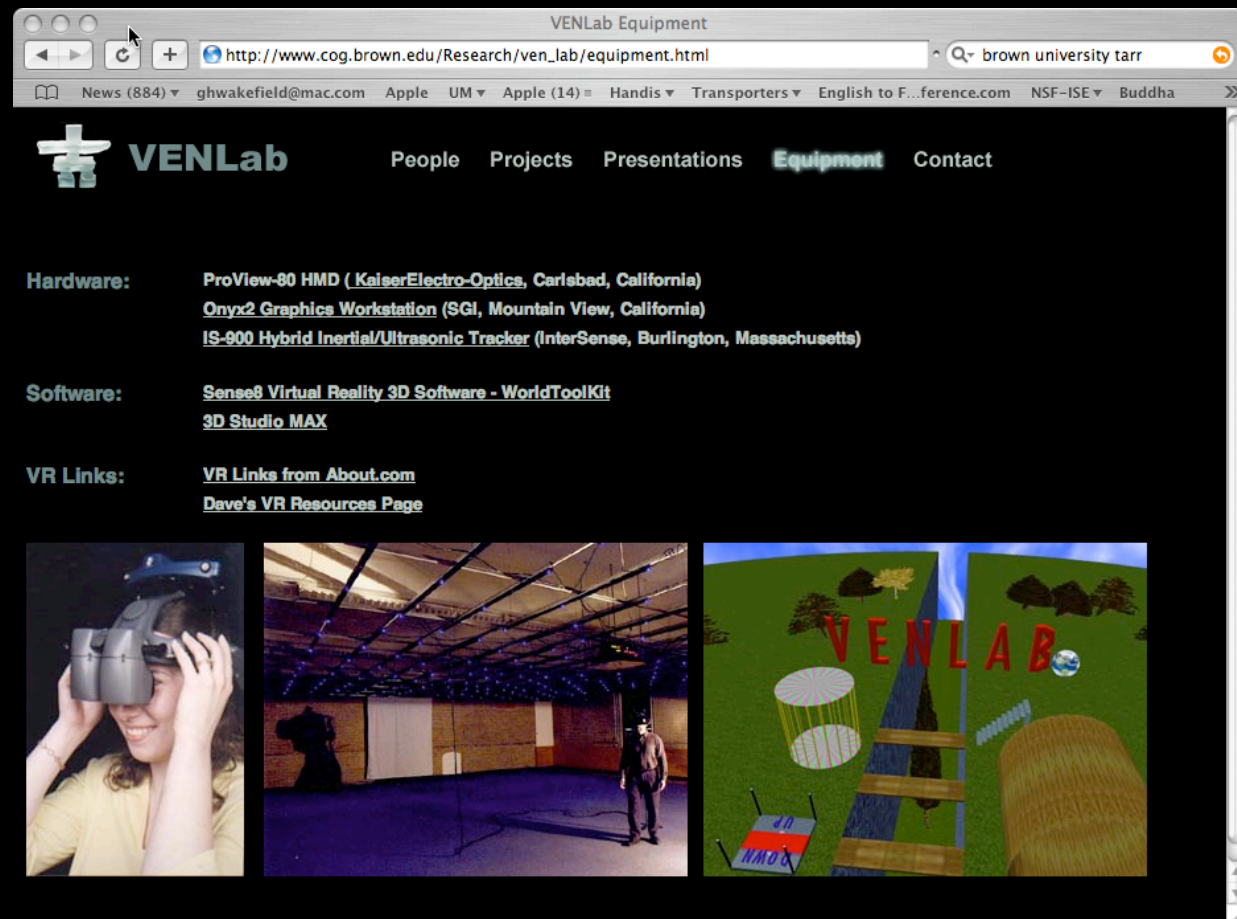
- Epistemology
 - How does the world inform us of the world?
 - How do we “know what we know”?
 - Setting design criteria for VR, extended-reality, augmented reality, and interactive systems

Rest of today...



- ✓ Examples of perceptual plumbers
 - ✓ Dominated by visual modality
- ✓ Auditory plumbing as a discipline
 - ✓ Modeling the listener in the environment
 - ✓ First-generation technologies
 - ✓ Current work
 - ✓ Caveats

VENLab (Brown University)

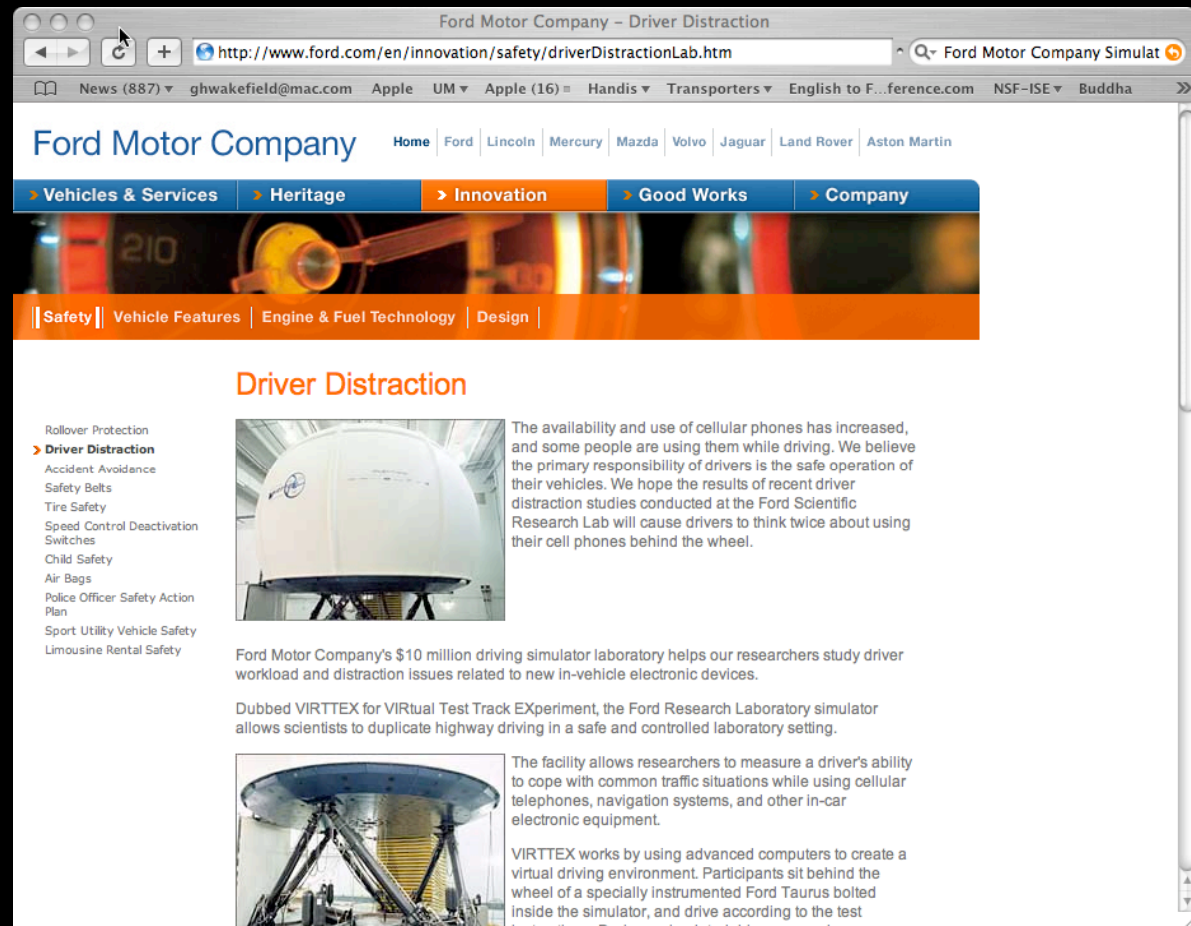


The screenshot shows a web browser window with the title "VENLab Equipment". The address bar contains the URL "http://www.cog.brown.edu/Research/ven_lab/equipment.html". The browser's address bar also shows a search for "brown university tarr". The page content includes a logo for VENLab, a navigation menu with "People", "Projects", "Presentations", "Equipment", and "Contact", and three sections of text:

- Hardware:**
 - [ProView-80 HMD \(KaiserElectro-Optics, Carlsbad, California\)](#)
 - [Onyx2 Graphics Workstation \(SGI, Mountain View, California\)](#)
 - [IS-900 Hybrid Inertial/Ultrasonic Tracker \(InterSense, Burlington, Massachusetts\)](#)
- Software:**
 - [Sense8 Virtual Reality 3D Software - WorldToolKit](#)
 - [3D Studio MAX](#)
- VR Links:**
 - [VR Links from About.com](#)
 - [Dave's VR Resources Page](#)

At the bottom of the page, there are three images: a woman wearing a VR headset, a person in a VR environment, and a 3D rendered scene with the text "VENLAB" and a globe.

Driver Distractor (Ford Motor Co.)



The screenshot shows a web browser window displaying the Ford Motor Company website. The address bar shows the URL: <http://www.ford.com/en/innovation/safety/driverDistractionLab.htm>. The page features a navigation menu with options like 'Vehicles & Services', 'Heritage', 'Innovation', 'Good Works', and 'Company'. The 'Innovation' tab is selected. Below the navigation, there is a section titled 'Driver Distraction' with a sub-menu on the left listing various safety topics. The main content area includes a large image of a driving simulator, a paragraph explaining the simulator's purpose, and another paragraph describing the VIRTTEX (Virtual Test Track Experiment) facility. A second image shows the VIRTTEX simulator in operation.

Ford Motor Company – Driver Distraction

News (887) ghwakefield@mac.com Apple UM Apple (16) Handis Transporters English to F...ference.com NSF-ISE Buddha

Ford Motor Company Home Ford Lincoln Mercury Mazda Volvo Jaguar Land Rover Aston Martin

Vehicles & Services Heritage Innovation Good Works Company

Safety Vehicle Features Engine & Fuel Technology Design

Driver Distraction

- Rollover Protection
- Driver Distraction**
- Accident Avoidance
- Safety Belts
- Tire Safety
- Speed Control Deactivation Switches
- Child Safety
- Air Bags
- Police Officer Safety Action Plan
- Sport Utility Vehicle Safety
- Limousine Rental Safety

The availability and use of cellular phones has increased, and some people are using them while driving. We believe the primary responsibility of drivers is the safe operation of their vehicles. We hope the results of recent driver distraction studies conducted at the Ford Scientific Research Lab will cause drivers to think twice about using their cell phones behind the wheel.

Ford Motor Company's \$10 million driving simulator laboratory helps our researchers study driver workload and distraction issues related to new in-vehicle electronic devices.

Dubbed VIRTTEX for VIRTUAL Test Track EXPERIMENT, the Ford Research Laboratory simulator allows scientists to duplicate highway driving in a safe and controlled laboratory setting.

The facility allows researchers to measure a driver's ability to cope with common traffic situations while using cellular telephones, navigation systems, and other in-car electronic equipment.

VIRTTEX works by using advanced computers to create a virtual driving environment. Participants sit behind the wheel of a specially instrumented Ford Taurus bolted inside the simulator, and drive according to the test instructions. During a simulated drive, researchers can

NRL/DoD

Human Performance Center, Seamless Product Information, Data Exchange and Repository

https://www.spider.hpc.navy.mil/index.cfm?RID=TTE_OT_1000026

NRL Spider

Human Performance Best Practices, Lessons Learned ISD Technologies Learning Topics Instructor Topics Management R&D

Human Performance Center

Quick Search

What's New
Calendar
Register
Search
Library
Organizations
Reports
Help
Log On

Training Technology Information Center

Human Performance Center HPC SPIDER

Virtual Reality (VR) and Augmented Reality (AR)

Technology Area

Description:

Virtual Reality (VR) can simulate not only dynamic visual information (which many training simulators do) but also simulate the immediate work environment typically mocked-up in a training simulator. Thus, the sensory feedback usually provided by a mocked-up work environment (e.g., instrumentation, controls, targeting devices, work surfaces) can all be simulated to create the feeling of being inside a computer-generated world.

Many define virtual reality (VR) as being multi-modal, that is being able to simulate sight, sound, smells, and touch simultaneously for a complete "immersion" experience. Joseph Psootka of the U.S. Army Research Institute defined immersion (1995) as "the sense of immediacy and control created by the feeling of "being there" or presence that comes from a changing visual display dependent on head and eye movements."

Virtual Reality technology typically involves powerful computers such as the Silicon Graphics, Incorporated (SGI) Onyx computers. It can also involve head-tracked systems, which sense the direction the user is looking and alter the image accordingly. There are limb-tracking systems which sense where the users' hands, fingers, or feet are in the virtual world. Other developments include, [natural language interfaces to virtual reality systems](#), and [haptic](#) or force-feedback interfaces.

A common VR device is a special glove or hand-held device that can sense the movement of the hands or even of individual fingers. The image of the hand then appears on the screen and moves as the real hand moves. A commonly used visual device is the head or helmet-mounted display. There are also

Second Life

The screenshot shows the Second Life website homepage during a grid maintenance outage. The top navigation bar includes the Second Life logo, the tagline "Your World. Your Imagination.", and links for "Resident Login" and "Join". Below the navigation bar is a search bar and a red banner with the text "GRID DOWN FOR MAINTENANCE" repeated four times. The main content area features a "LATEST STATUS" box on the left, a large image of a gorilla holding a bone in the center, and a "Headlines" section on the bottom left. The gorilla image has the text "The grid is down while we bang on things." overlaid on it. The "LATEST STATUS" box contains a message about a scheduled maintenance outage on December 13, 2006. The "Headlines" section lists three news items: "USA Today Marketers find a new place to set up shop...", "Time Out New York Life Imitates Art", and "Equity". The bottom of the page features three promotional banners: "A real guide for your virtual life" (Your Second Life is Ready), "YOU MIGHT BE A LINDEN!" (Work at Linden Lab), and "Second Life Videos" (Check out resident-created Second Life videos).

SECOND LIFE *Your World. Your Imagination.* [Resident Login](#) | [Join](#)

[WHAT IS SECOND LIFE?](#) | [SHOWCASE](#) | [BUSINESS PARTNERS](#) | [DEVELOPERS](#) | [COMMUNITY](#) | [BLOG](#) | [SUPPORT](#) Search Second Life

GRID DOWN FOR MAINTENANCE GRID DOWN FOR MAINTENANCE GRID DOWN FOR MAINTENANCE GRID DOWN FOR MAINTENANCE

LATEST STATUS:
December 13, 2006, 6:49 am Second Life is closed for scheduled maintenance from 7:00am-12:00noon PST (15:00-20:00 UTC). Visit <http://blog.secondlife.com> for further information.

For additional details about system upgrades, maintenance, outages, other known problems and more, please visit the [Official Linden Blog](#).

The grid is down while we bang on things.

Headlines [read more news...](#)

USA Today
[Marketers find a new place to set up shop...](#)

Time Out New York
[Life Imitates Art](#)

Equity

A real guide for your virtual life
Your Second Life is Ready
The Official Guide to Second Life is out. Learn more and order your copy

YOU MIGHT BE A LINDEN!
Work at Linden Lab
Where else can you help create a new world *and* have the time of your

Second Life Videos
Check out resident-created Second Life videos at our [media page](#).

Commercialization

The screenshot shows a web browser window displaying the 3001 AD website. The browser's address bar shows the URL <http://www.3001ad.com/>. The website's header features the 3001 AD logo and a navigation menu with links for COMPANY, INVESTOR INFORMATION, DISTRIBUTORS, MEMBER RELATIONS, PRODUCTS, BETA ZONE, PROFILES, CONTACT, SUPPORT, and HOME. The main content area is divided into several sections:

- The New Trimerion, Now Available for Home Gaming.** This section includes a call to action: "Click on the image to visit the dedicated site of the new Trimerion for an experience in 3D @ home." Below this is a large image of a woman wearing a VR headset, with a starburst graphic that says "click for 3D VIEW".
- 3001 AD @ the CES, Las Vegas** This section features the CES 2006 logo and text: "3001 AD at the Consumer Electronics Show in Las Vegas".
- Featured in RePlay Magazine.** This section shows a thumbnail of a magazine cover with the headline "VR COMES OF AGE" and the 3001 AD logo.

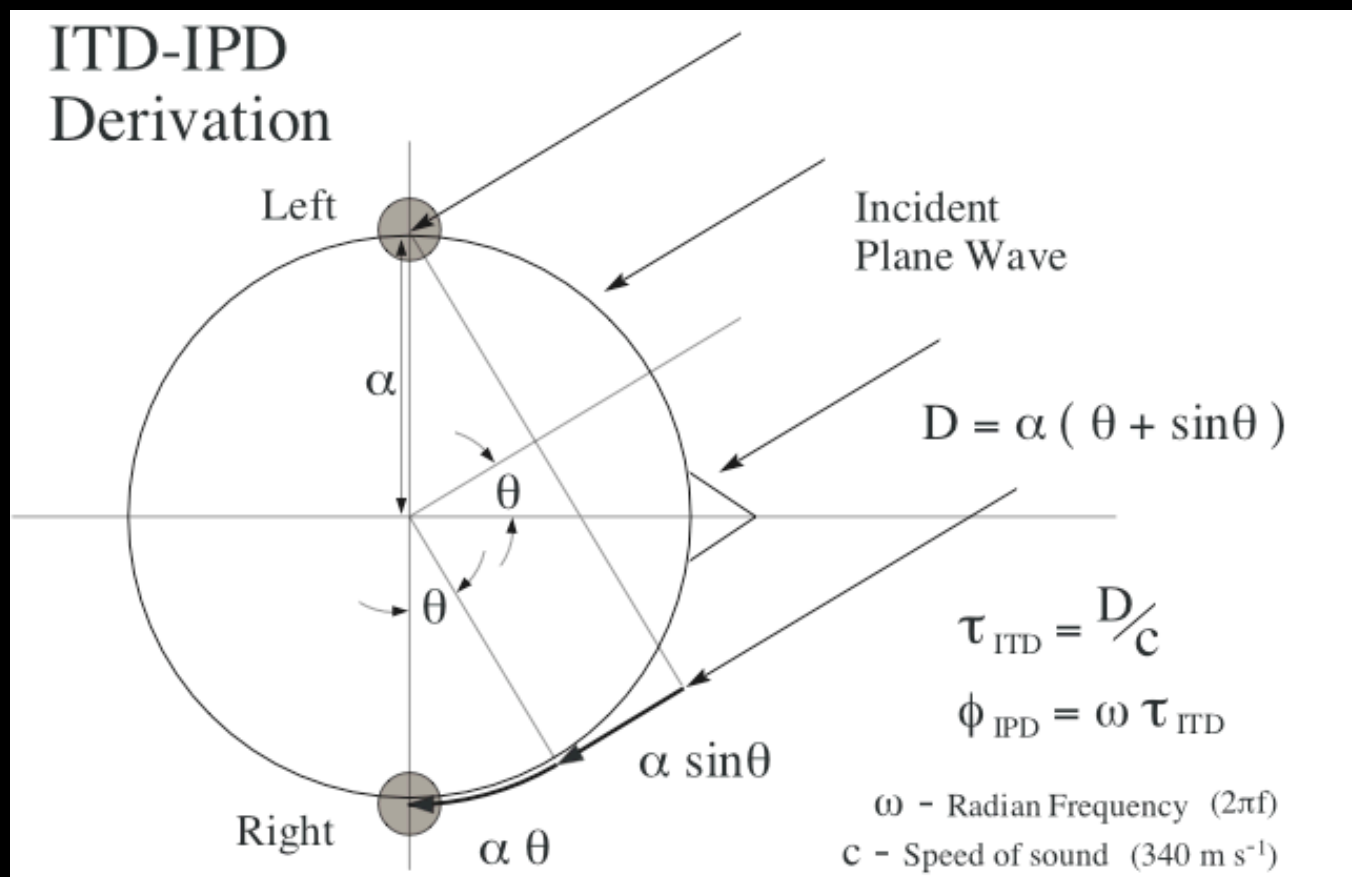
At the bottom of the page, there is a section titled "New 4-D Adventure film for the 2005 season" and a partial line of text: "3001 AD, the premiere provider of virtual".

What about the world of sound?

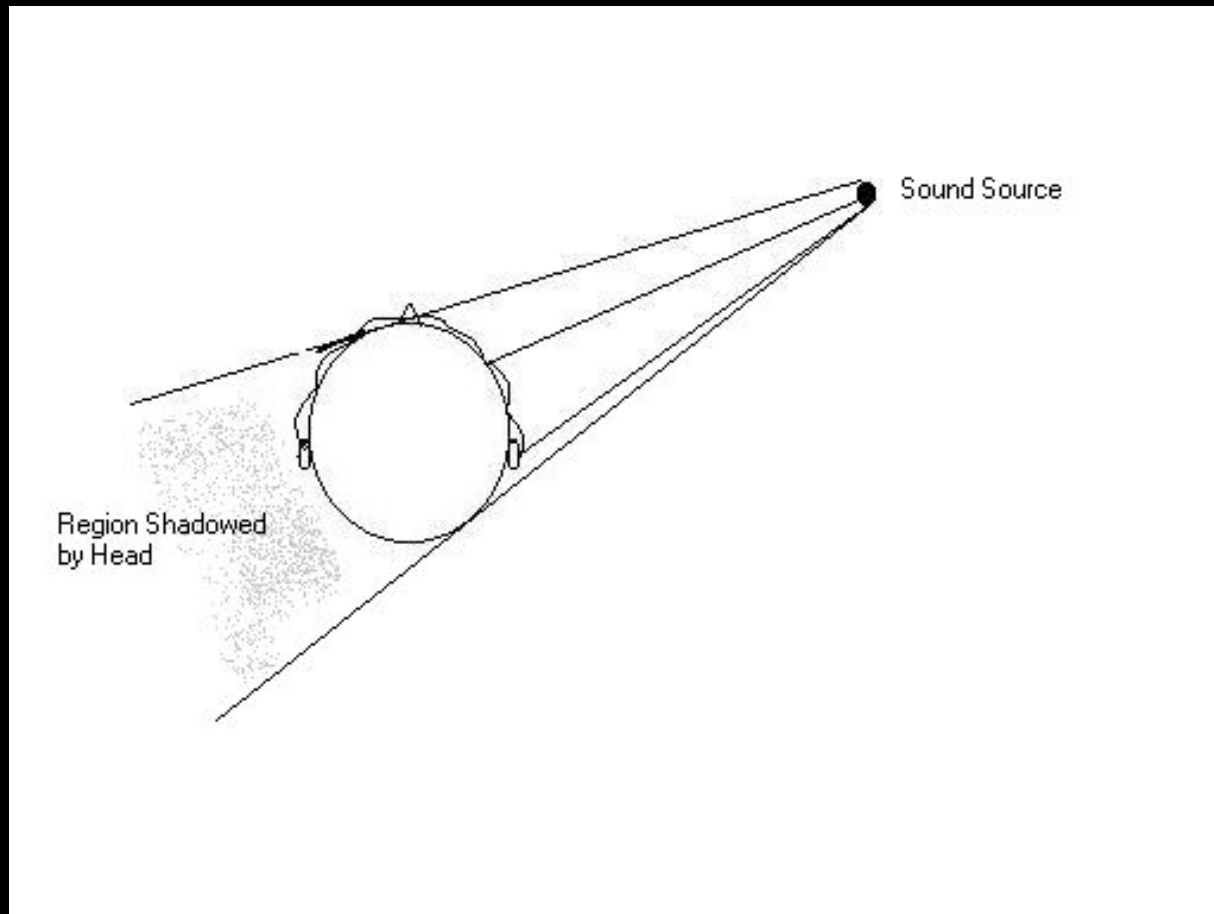


- ✓ Physics of Propagation
 - ✓ Line-of-sight vs. bending around corners
 - ✓ Sources + Transmission Medium (reflections)
- ✓ Perception of Propagation
 - ✓ Vision: Object as reflectance, source ignored
 - ✓ Auditory: Object as source, reflectance ignored
- ✓ Perception of Object
 - ✓ Vision: “Time independence + Spatial dependence”
 - ✓ Audition: “Spatial independence + Time dependence”

Modeling the Listener in the Environment



Modeling the Listener in the Environment



Modeling the Listener in the Environment

- ✓ Physics: Lord Rayleigh (1842-1919)
 - ✓ Difference in arrival times (Interaural Time Differences - ITD's)
 - ✓ Transient wave
 - ✓ Continuous wave - spatial aliasing
 - ✓ Level difference (Interaural Level Differences-ILD's)
 - ✓ Wavelength dependence
 - ✓ Duplex theory of auditory localization
 - ✓ Below 1-2 kHz, use ITD
 - ✓ Above 2-3 kHz, use ILD

First-Generation Auditory Plumbing

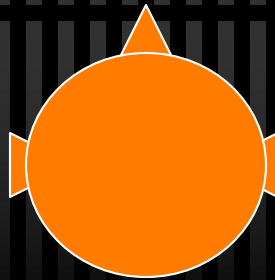
✓ Stereophony

- ✓ stereos = "solid" and phōnē = "sound"
- ✓ Adler (1881)
- ✓ Fletcher (Bell Labs, 1930's)
- ✓ Term coined: Western Electric (1937)
- ✓ Publicly demonstrated: Carnegie Hall (1940)

✓ Recording Techniques

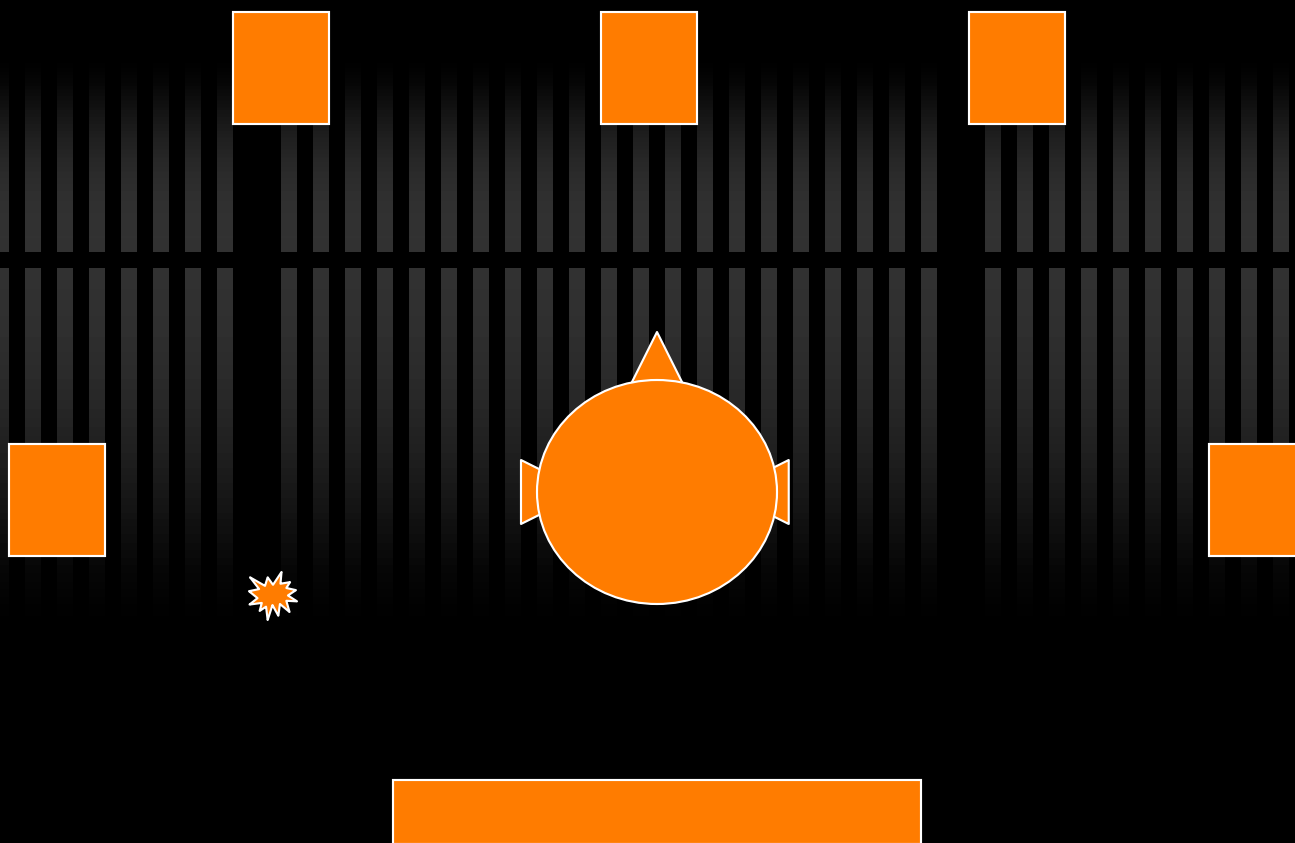
- ✓ X-Y (Intensity stereophony)
- ✓ A-B (Time-of-arrival stereophony)

Playback: Stereo Panning



Physics: Trading intensity and timing differences...

Surround Sound (5.1)



What about 3D Sound?

- ✓ Azimuth

- ✓ ITD, ILD cues

- ✓ Basis for stereophony and 5.1 sound

- ✓ Elevation

- ✓ ???

- ✓ Range

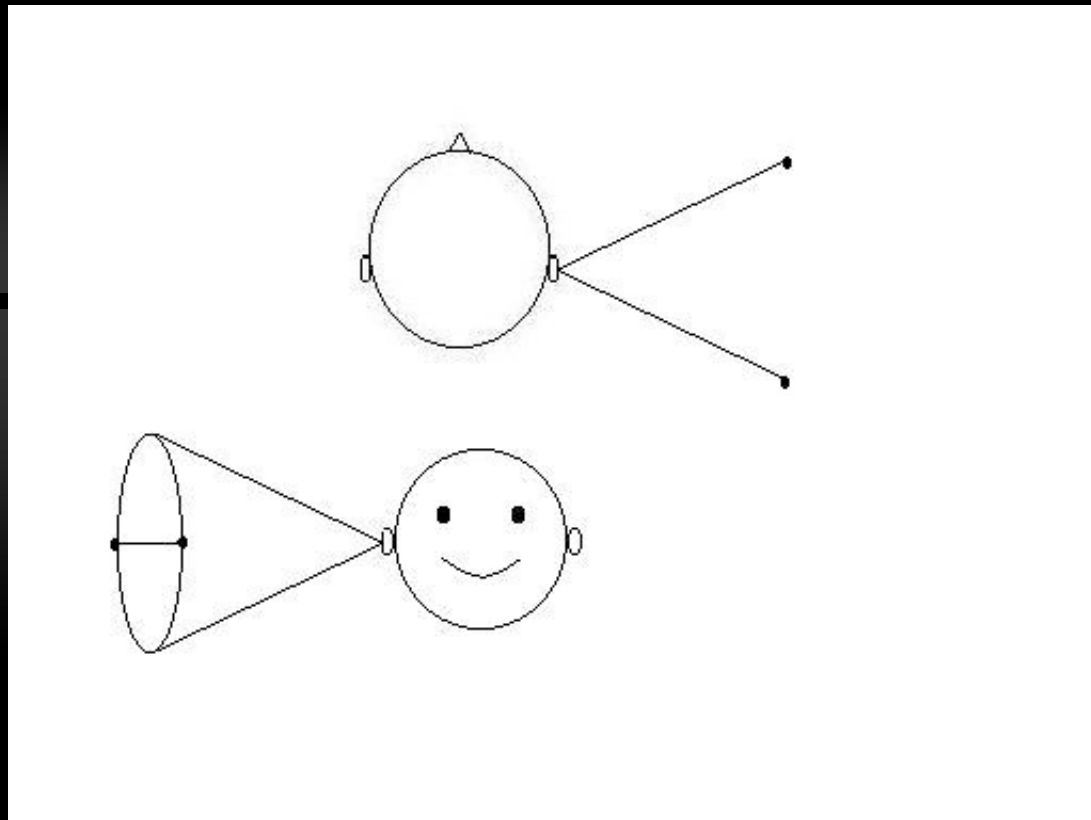
- ✓ ???

Range: Bigger Fish to Fry

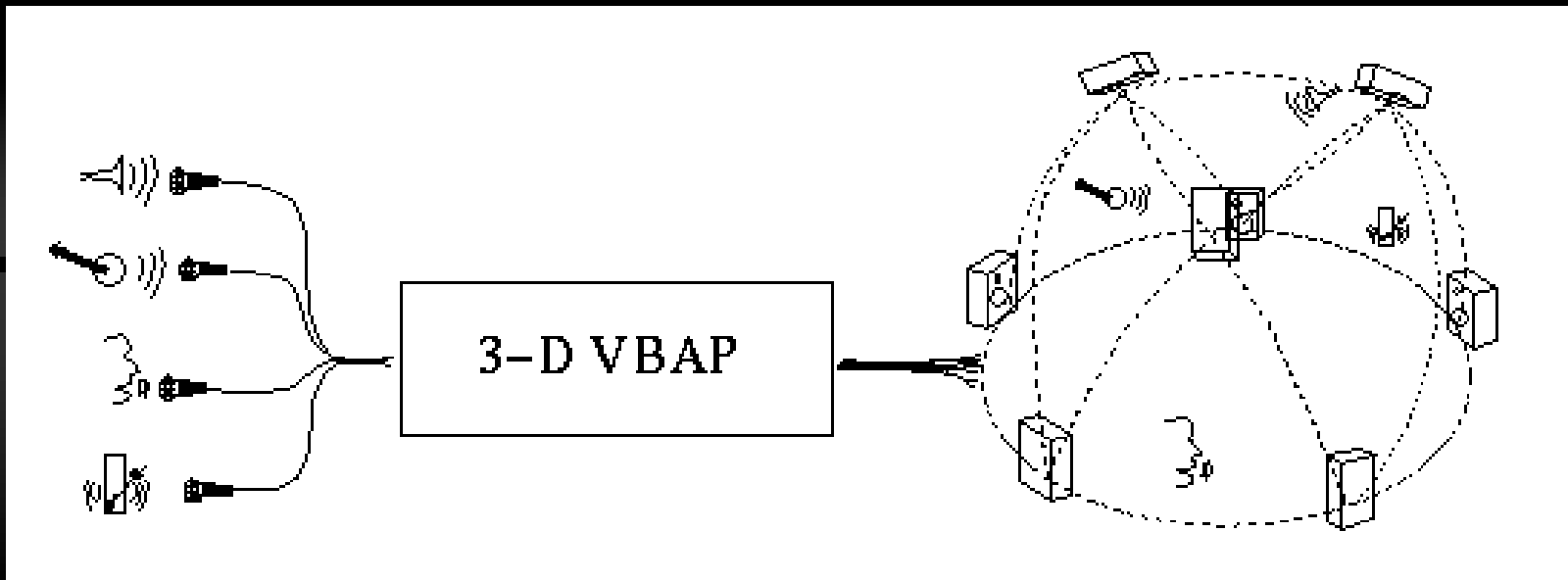


- ✓ Helmholtz: Unconscious Inference
- ✓ Range perception: very poor
 - ✓ Sound is close, near, far away
 - ✓ Simulation:
spectral coloration + reverberation

Elevation: Cone of Confusion



VBAP (Vector Based Amplitude Panning)



Solution: "M.1" in azimuth and elevation.
Ville Pulkki, D. Sc., HUT

3-D Commercialization



- ✓ Spatial diffusers
- ✓ THX
- ✓ VBAP

Costly commercial solutions...



- ✓ VR goggles vs.
- ✓ Large, acoustically balanced room +
Optimized, balanced loudspeakers +
Optimized, balanced amplifiers + ...
- ✓ And did we bother to talk about the
stereo hot-seat?

What about headphones?

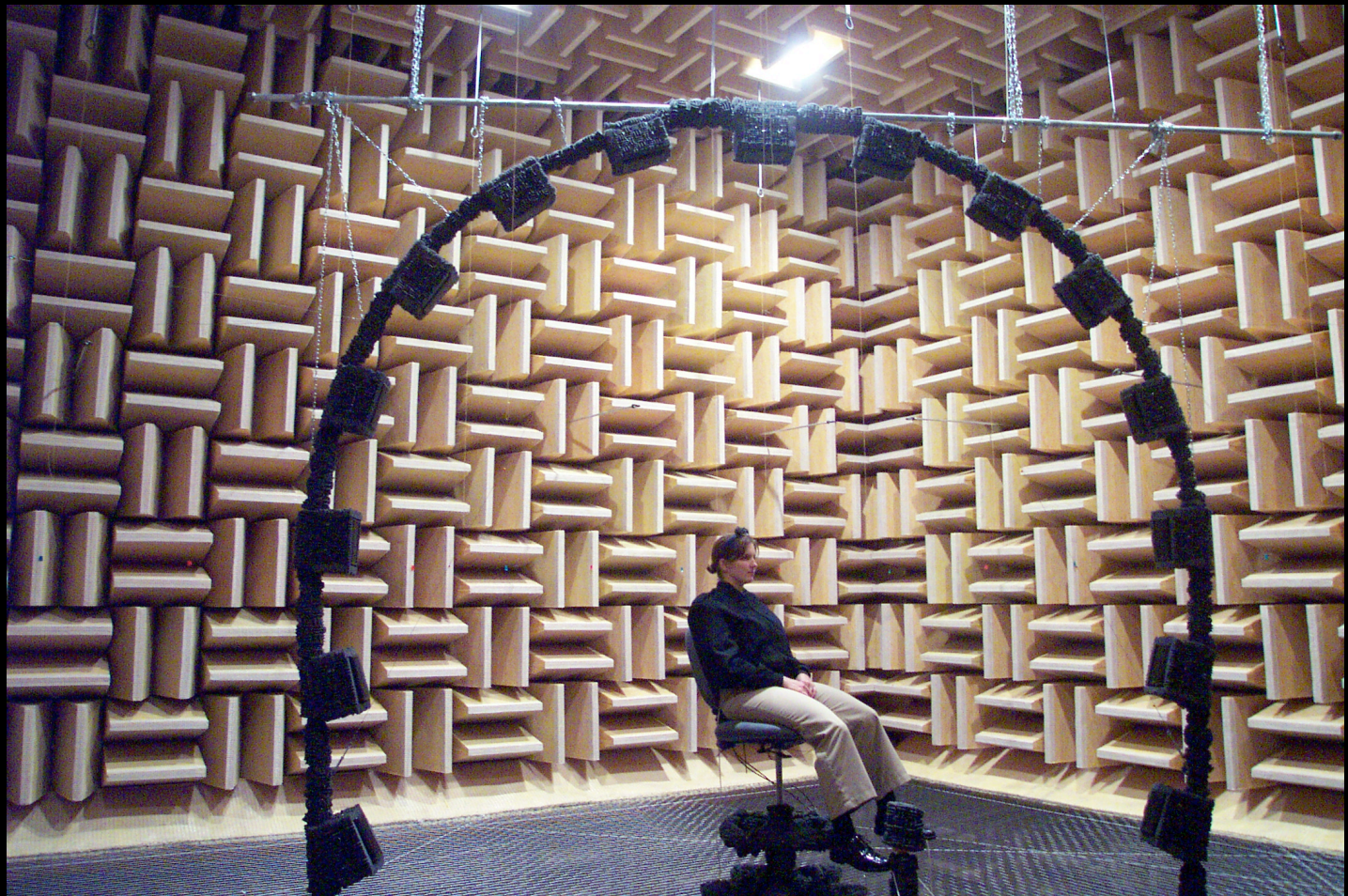


1. Characterize the spatial radiativity pattern of the listener's head
2. Synthesize sources at desired locations
3. Playback over headphones so that the acoustic signals at the listener's left and right ears are identical to those they would have received in the original listening environment

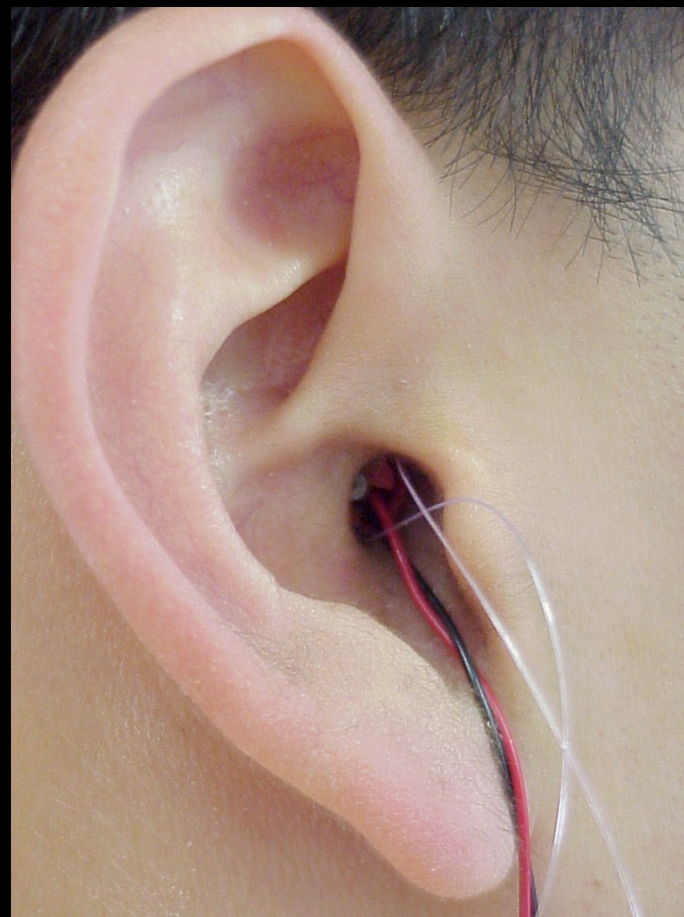
Measurement of Head-Related Transfer Functions

- Research history - short version of the list
 - NASA Ames - Wenzel/ Wightman and Kistler
 - Hartmann
 - Karjalainen (Finland, HUT)
 - Houtgast (Netherlands)
 - Wright-Patterson (Gilkey)
 - MIT/BU (Braidá, Durlach, Colburn, Kulkarni, Shinn-Cunningham)
 - Duda and Algazi
 - Middlebrooks (UFI/UM)
 - Wakefield, Adams, Cheng, Runkle, Blommer, Santoro, Buell (UM, NSMRL)
- Equipment and Measurement Issues

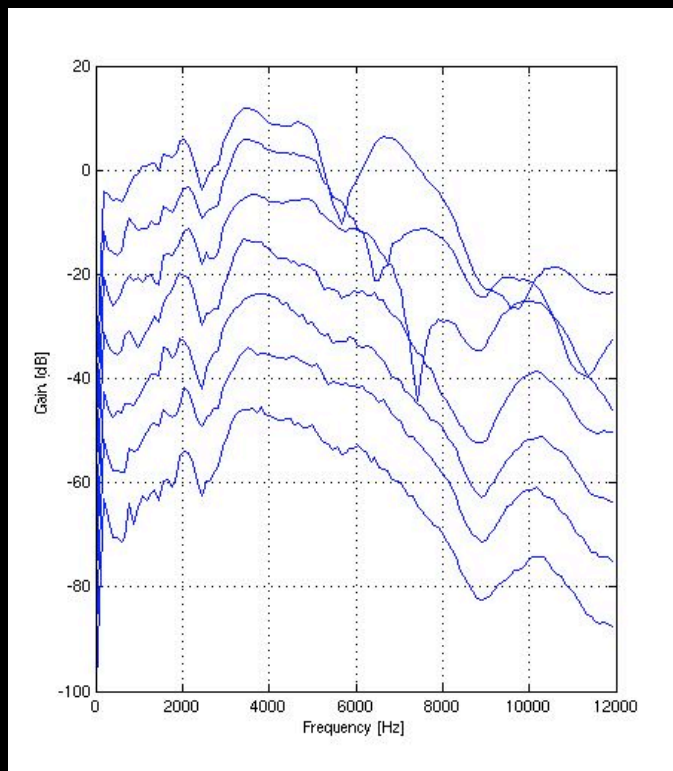
Anechoic Chamber/Loudspeaker System



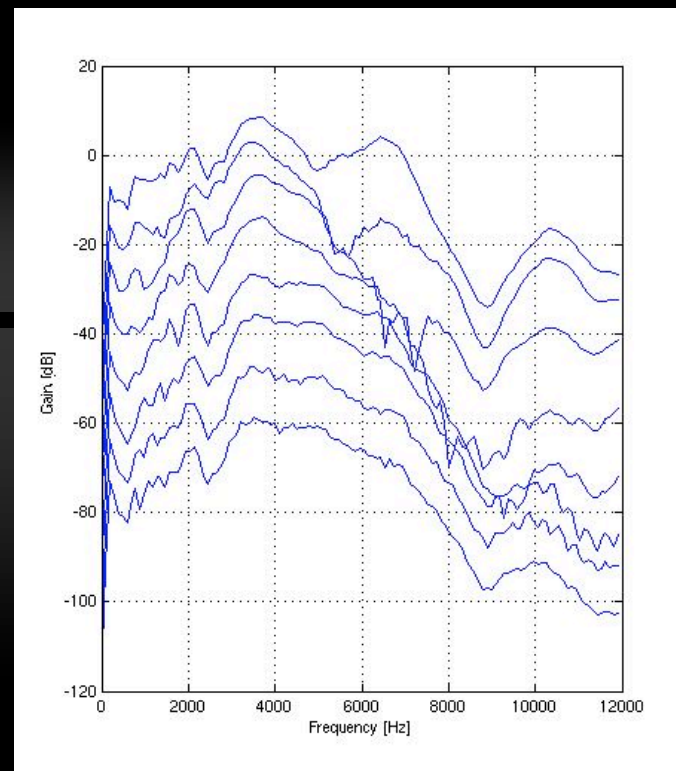
Probe-tube microphones



Results: Right Ear



90 deg (right)



0 deg (midline)

Typical data sets and costs

- ✓ 270-500 spatial locations
- ✓ Impulse responses: 150-300 samples
- ✓ 44100 samples/sec
- ✓ Rendering costs: 25 Mflops/source
- ✓ Low-order modeling: 2.5 Mflops/source
- ✓ PCA/Eigenfilter: 150 Mflops + 0.5 Mflop/source
- ✓ MIMO (Adams & Wakefield): 25-150 Mflops + fidelity criterion

Commercial Vendors



- ✓ AuSim (US)
 - ✓ Convolvotron w/specially-designed HRTFs
- ✓ Lake Technology (Australia)
 - ✓ Equalizer technologies
- ✓ Gaming “Near-field” systems

Want one?



- ✓ Azimuth performance with generic HRTFs: adequate
- ✓ Elevation performance with generic HRTFs: generally poor, particularly front-back confusions

Will there be a better one?



- ✓ Individualized HRTFs
 - ✓ Performance is never as good as free-field localization in anechoic chamber
 - ✓ Measurement error?
 - ✓ Rendering issues?
- ✓ Roughly 50% of population exhibit front-back confusions *even in free-field listening*
- ✓ Why? Role of head motion

Summary: Source Positioning



- ✓ Rendering azimuth and elevation of (point) source in anechoic environment
 - ✓ Azimuth (left-right)
 - ✓ Amplitude panning or timing disparity
 - ✓ Robust to differences among listeners
 - ✓ Robust to head motion
 - ✓ Elevation (including front-back)
 - ✓ Spectral coloration
 - ✓ Sensitive to differences among listeners
 - ✓ Sensitive to head motion

Additional rendering issues

- ✓ Rendering reflections
 - ✓ Computational explosion
 - ✓ Room-acoustic models
 - ✓ Auditory sensitivity spans 100 dB dynamic range: many many reflections later
 - ✓ Speed of sound (1 ms per foot): challenging filter design problem
 - ✓ Perceptual constraints: 4 regimes (rough!)
 - ✓ Binaural summation (< 1 ms)
 - ✓ Precedence (1-30 ms)
 - ✓ Early late-arrivals (10-100 ms)
 - ✓ Late arrivals (30 ms - 10's of seconds)

Additional rendering issues



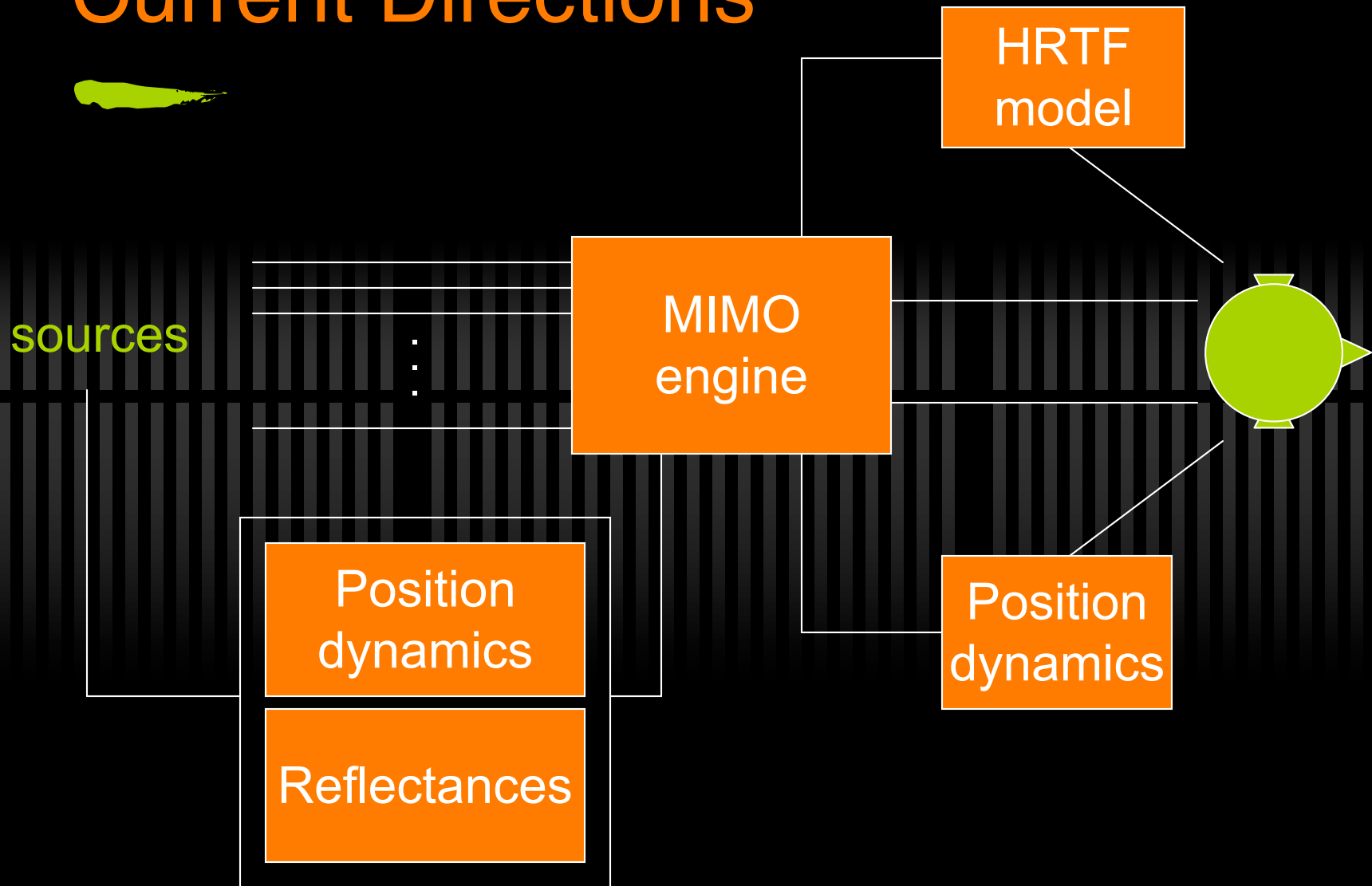
- ✓ Rendering motion
 - ✓ Head motion
 - ✓ Interpolation among HRTFs
 - ✓ Source motion
 - ✓ Doppler effects
 - ✓ Rotational vs. lineal

Additional rendering issues

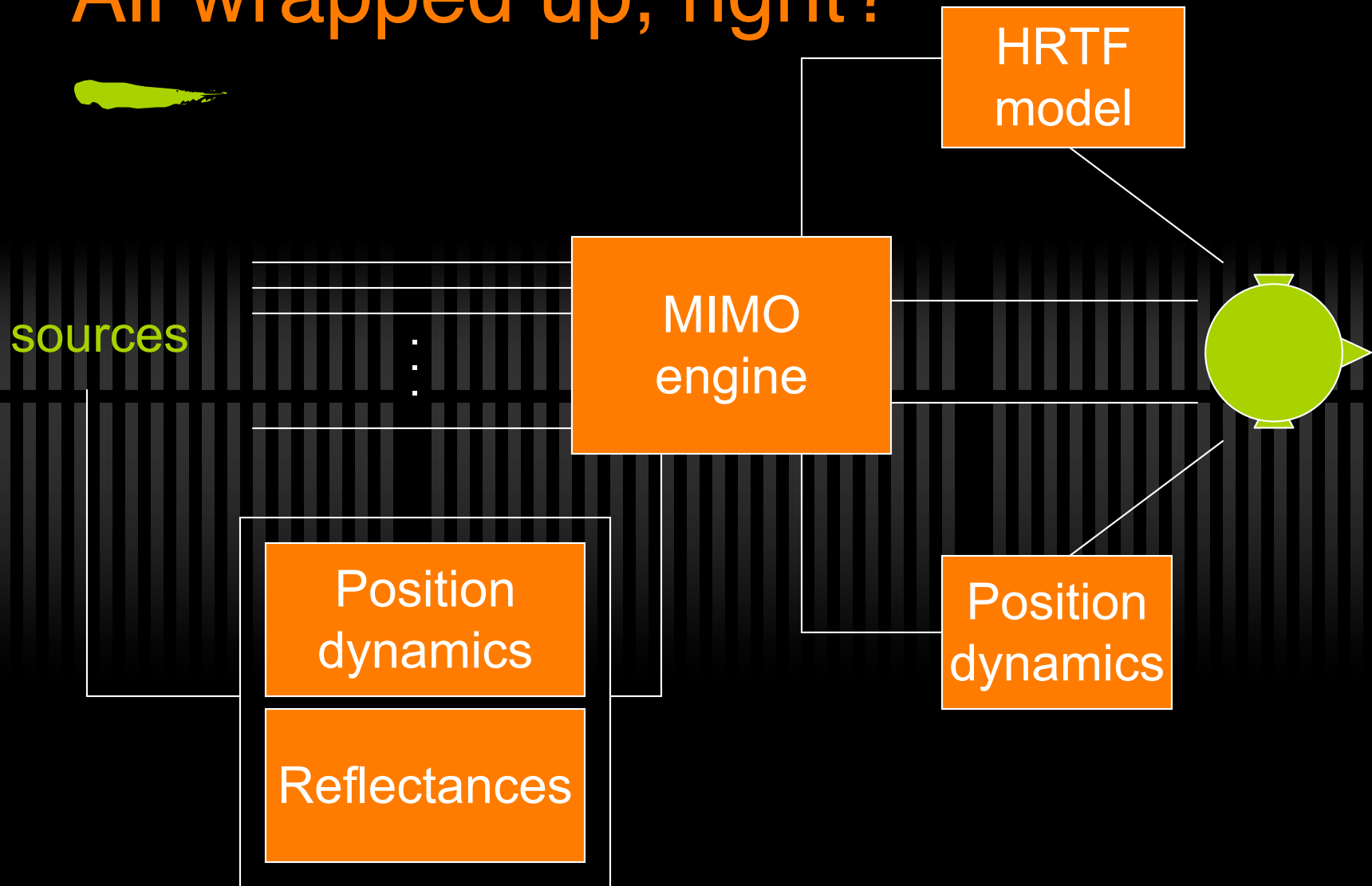


- ✓ Rendering spatial extent
 - ✓ Types of spatially extended sources
 - ✓ Flock of geese
 - ✓ Flow-noise in aircraft or automotive interiors
 - ✓ Non-uniform spatial radiativity patterns
 - ✓ ???

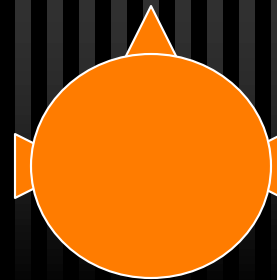
Current Directions



All wrapped up, right?

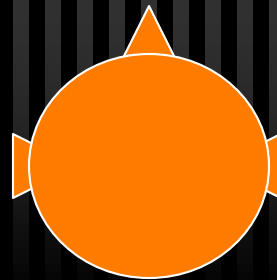


Caveat: The Single-Source Mindset



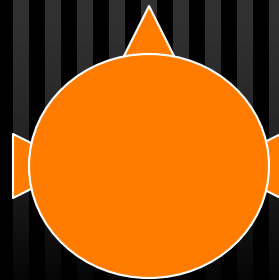
Where's the source?

Caveat: The Single-Source Mindset



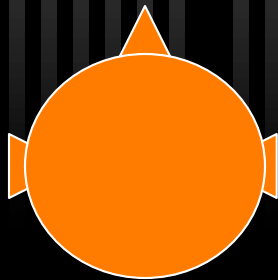
Where's the source?

Caveat: The Single-Source Mindset



Where are the sources?

Binaural phenomena



- ✓ Fusion
 - ✓ Multiple acoustic sources are fused into a single source
 - ✓ Source location dependent on relative timing of acoustic sources
 - ✓ Precedence effect
 - ✓ Reverb
 - ✓ Spectral effects
 - ✓ Franssen effect
 - ✓ Stereophony

Binaural phenomena

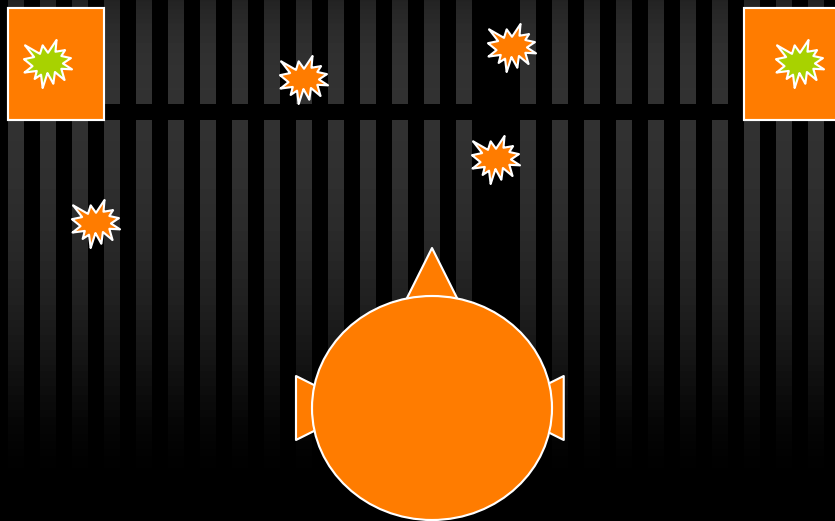


✓ Fission

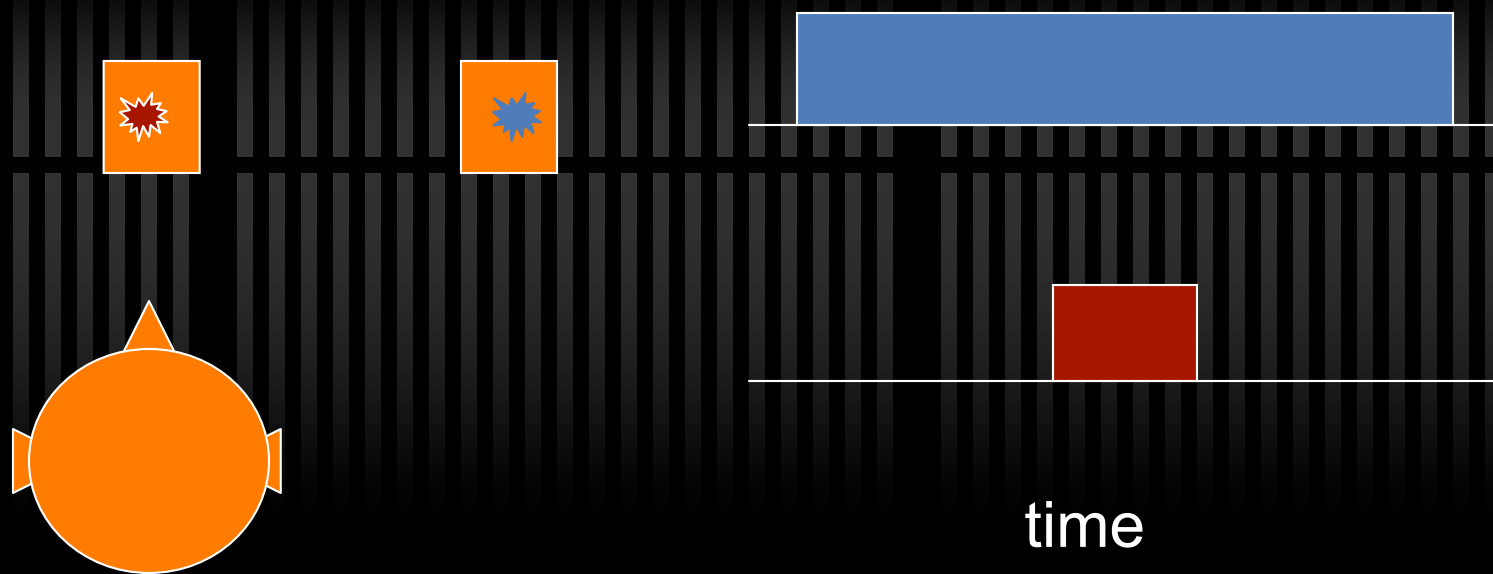
✓ Multiple acoustic sources may split into additional perceived sources

✓ Source location dependent on relative timing of acoustic sources

✓ Stereophony

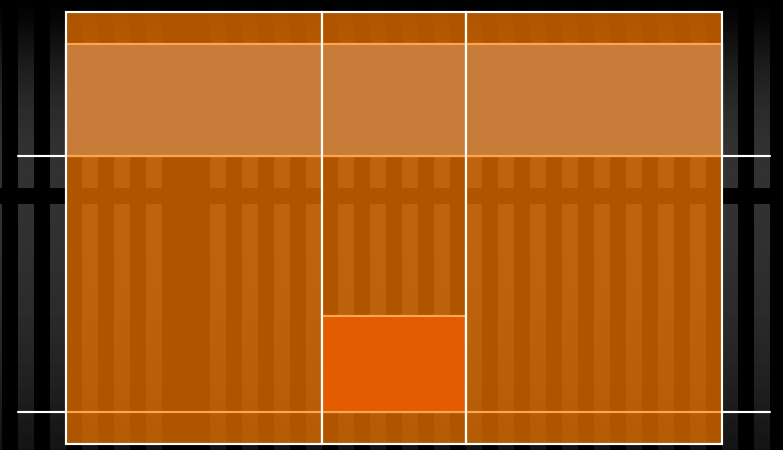
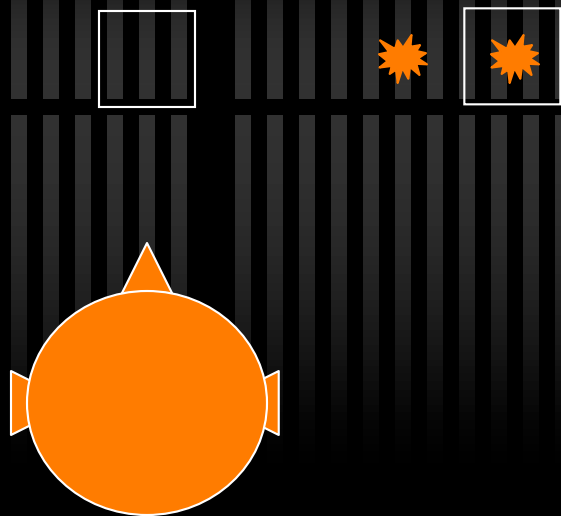


Binaural phenomena



What should you hear?

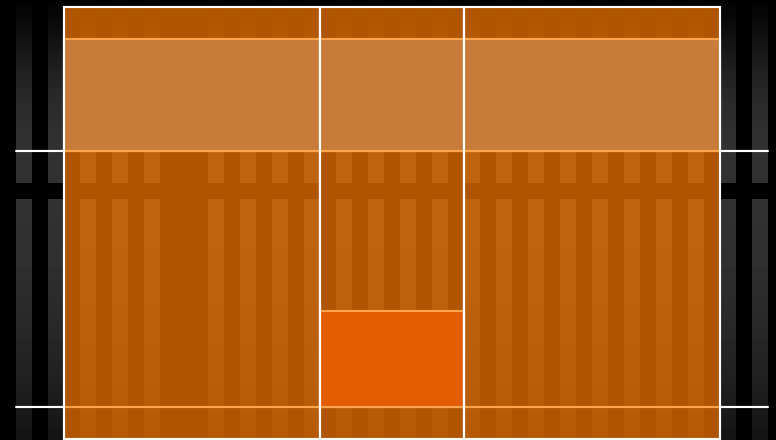
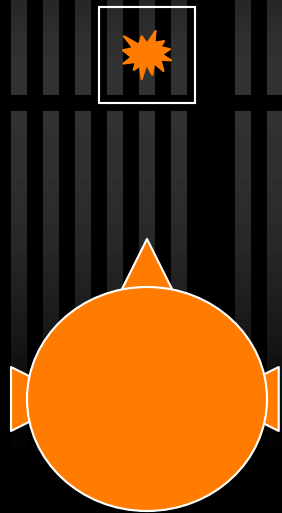
Fusion mechanism



time

What should you hear?

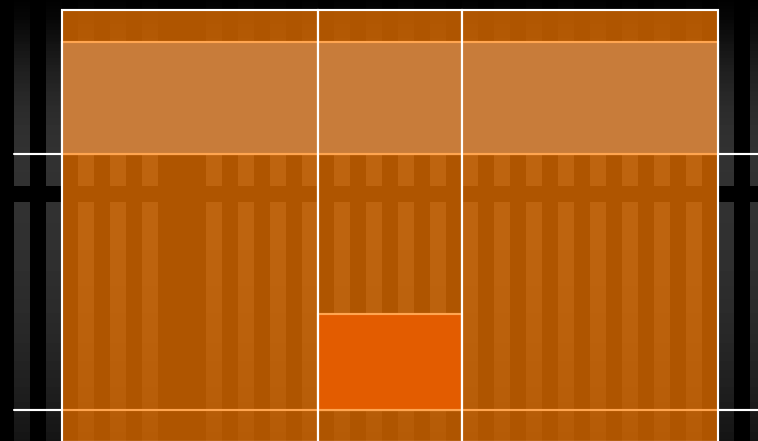
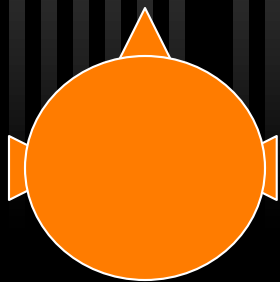
Fusion mechanism



time

What should you hear?

What you do hear

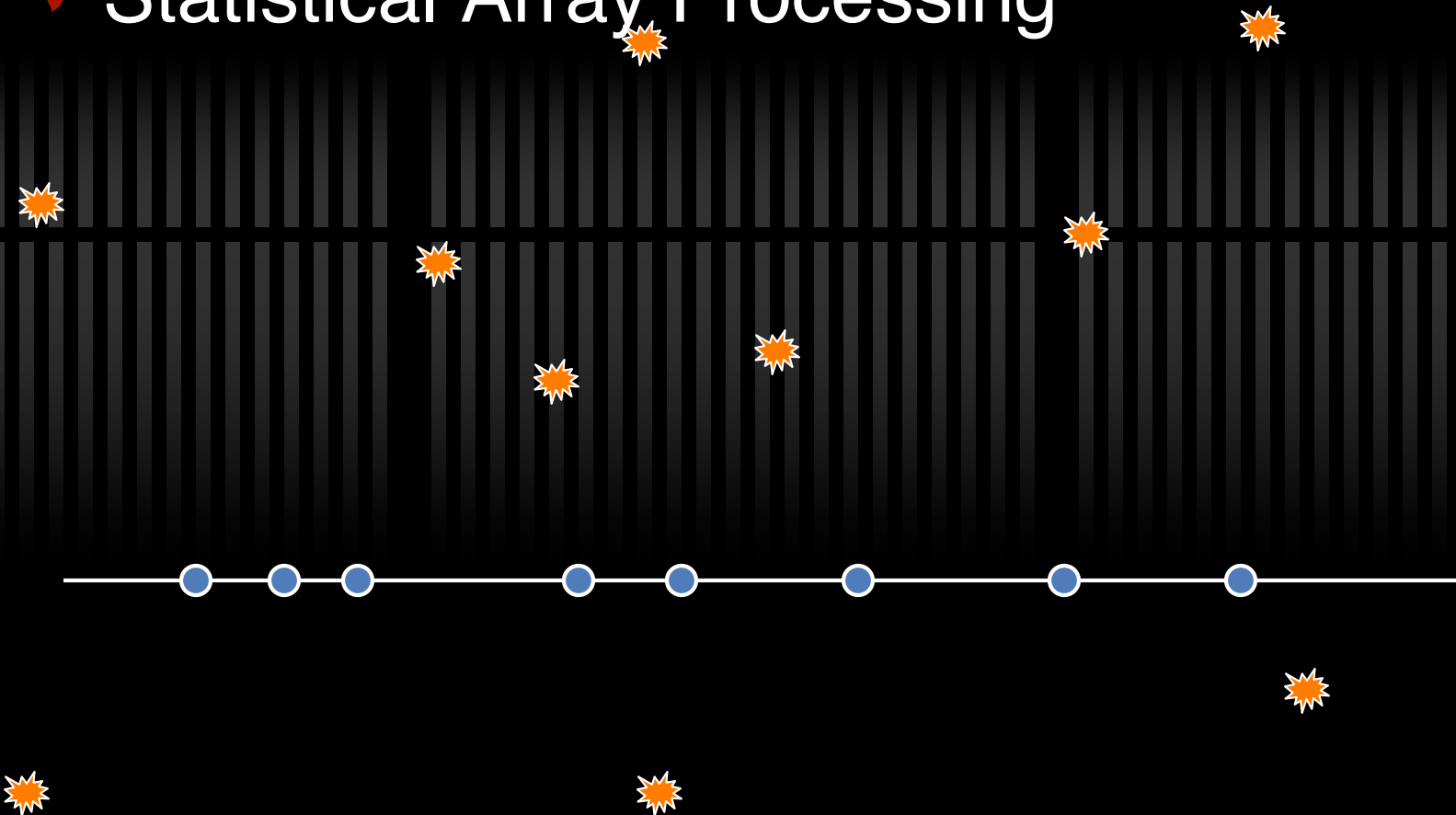


time

SAPS and Perception



✓ Statistical Array Processing



One-to-One vs. Many-to-One

- ✓ N sensors, M narrowband sources
 - ✓ $M \leq N$
 - ✓ One-to-one
 - ✓ Location is recoverable
 - ✓ $M > N$
 - ✓ Many-to-one
 - ✓ Additional constraints necessary to choose one solution

Mathematics of Spatial Hearing: Many-to-2

✓ Therefore, we should expect

✓ Fusion

✓ Fission

✓ And everything in between



Wrap-Up

