NSF Engineering Research Center for Subsurface Sensing & Imaging Systems

Badri Roysam, D. Sc.,

Associate Director of CenSSIS ERC

Professor, Rensselaer Polytechnic Institute, Troy, NY.

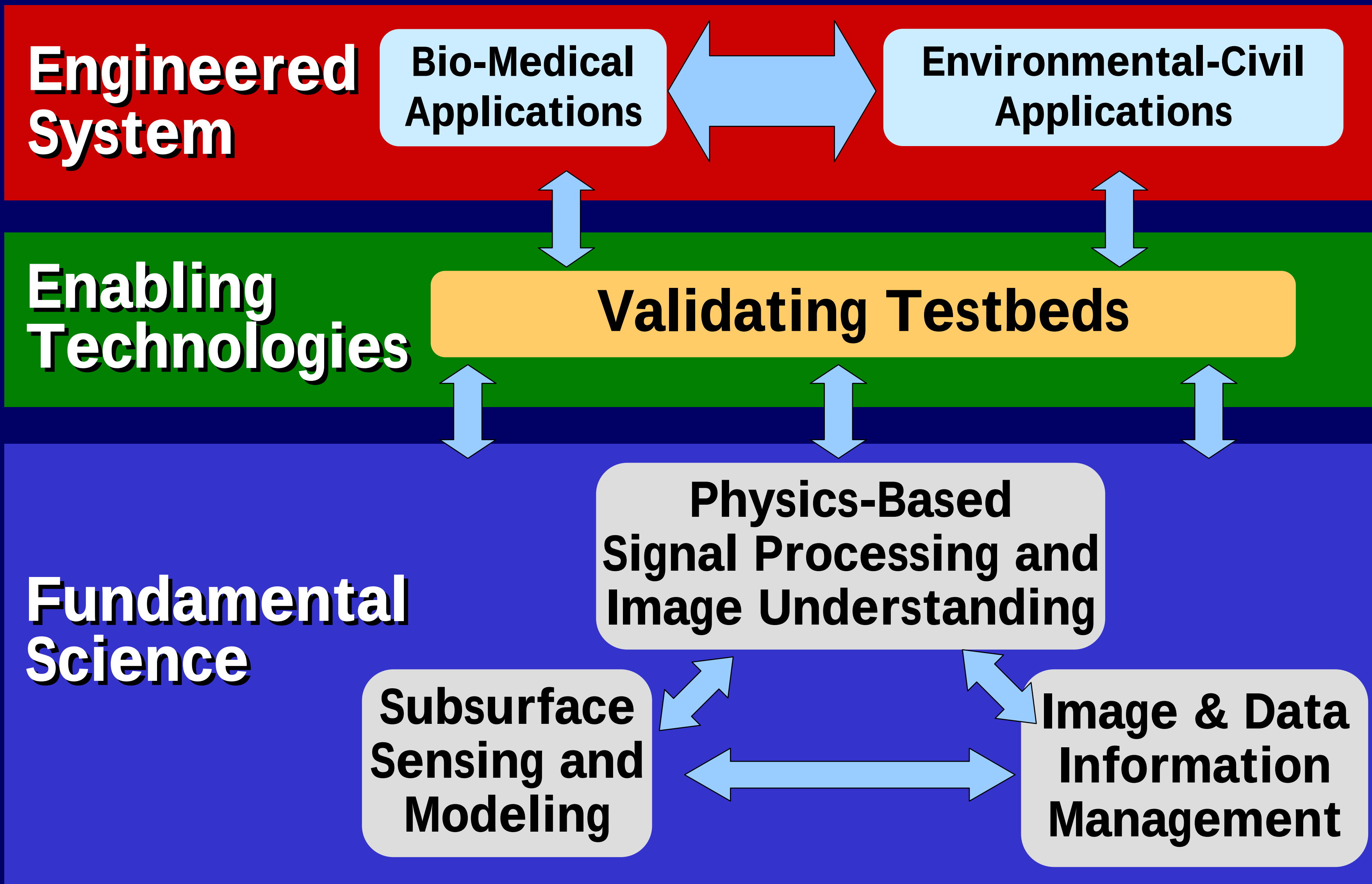
About the CenSSIS ERC

Established: 2000

Colleagues

- Rensselaer Polytechnic Institute
  - Richard Radke (PhD), Daniel Freedman (PhD), Charles Stewart (PhD), Gang Lin (PhD), Howard Tanenbaum (MD), Anna Majerovics (MD)
- Mass General Hospital
  - George T. Y. Chen (PhD), Evangelos Gragoudas (PhD), Noah Choi (MD), Eike Rietzel (PhD)
- Memorial Sloan Kettering
  - D. Michael Lovelock (PhD), Andrew Jackson (PhD)
- Woods Hole
  - Ali Can (PhD), Hanu Singh (PhD)
- Boston U.
  - Bahaa Saleh (PhD)

Overview of the CenSSIS Research Program

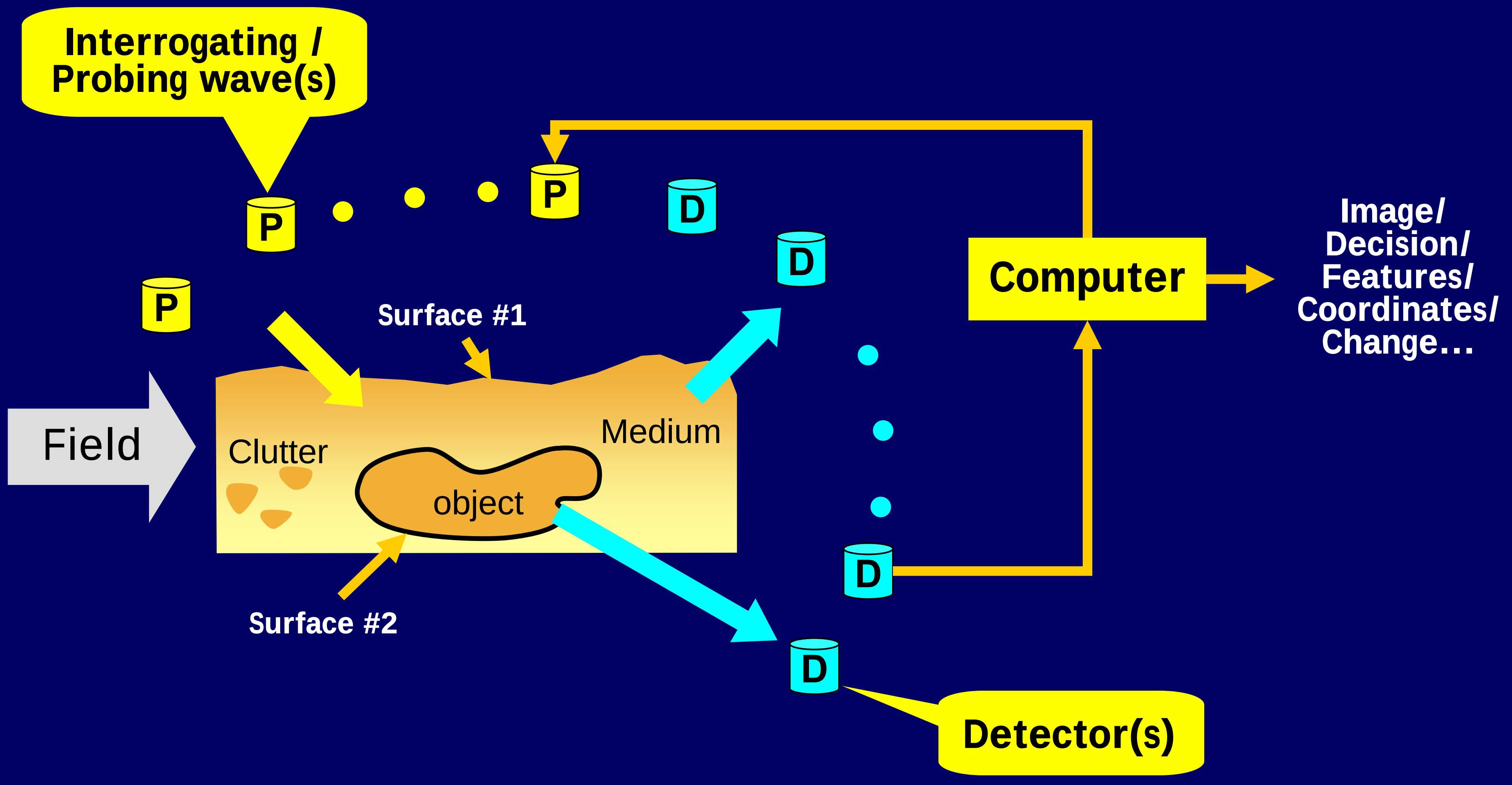


CenSSIS Themes

"Diverse Problems – Similar Solutions"

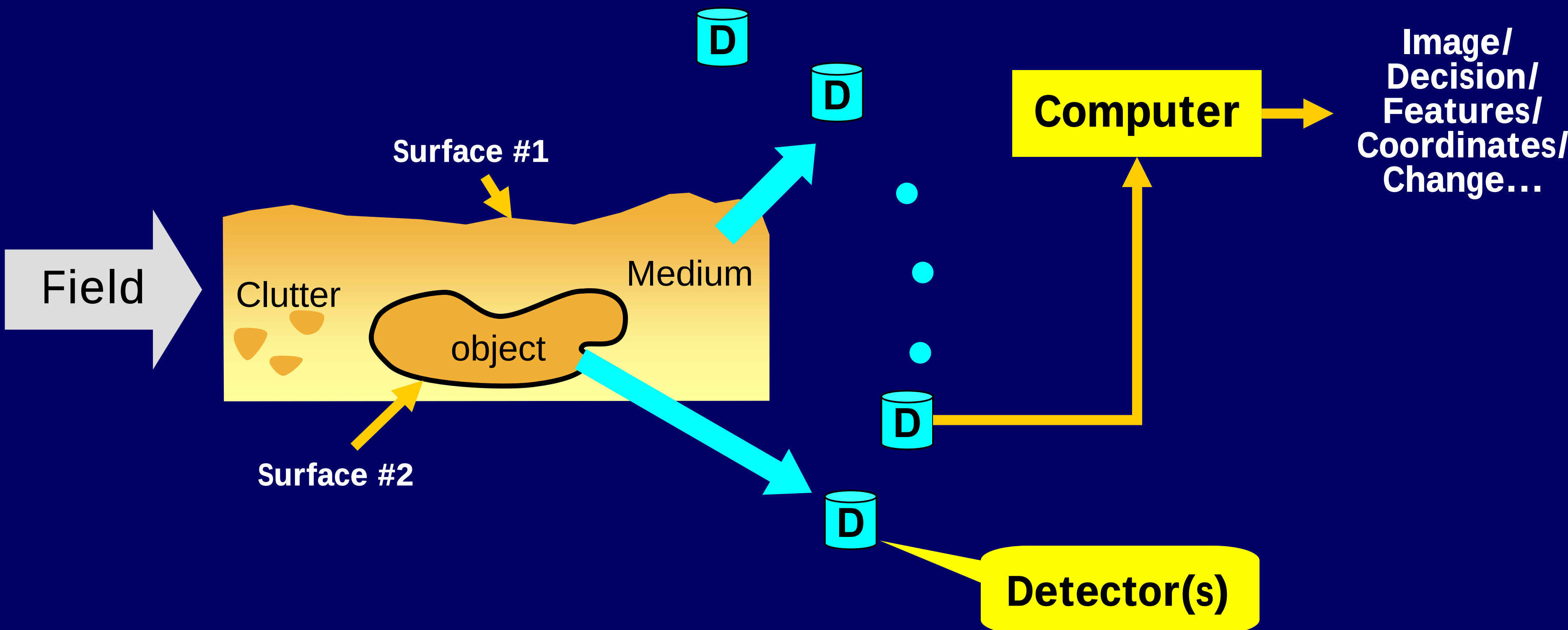
- A unified view of Subsurface Sensing & Imaging,
  - Optical, Electromagnetic and acoustic sensing modalities
  - Biomedical, biological, civil, industrial, and environmental applications
  - Emphasis on signal processing issues: Inverse problems, image reconstruction, image understanding, pattern recognition,…
- A taxonomy and framework for diverse SSI problems:
  - Physical, mathematical, and numerical models
  - Sensing and Imaging Architectures
  - Information Extraction Methods
    - LPM, MVT, MSD
    - Image & Change understanding
- Cross-application software toolboxes for rapid prototyping
- Hardware testbeds for multi-sensor fusion experiments

A Unifying View of Subsurface Sensing/Imaging Systems



The medium and object interact differently with the interrogating waves to generate detectable contrast.

Passive Subsurface Sensing/Imaging Systems



The medium and object emit differently to generate detectable contrast.

Many Choices for Imaging Systems

Excitation

Acoustic ↔ EM
Coherent ↔ Incoherent
Spatial Distribution
Spectral Distribution
(..RF↔THz↔IR-VIS-UV↔x-ray..)
Temporal Distribution
(CW ↔ Pulsed ↔ Modulated)
Polarized ↔ Unpolarized

Media/Target

- Emission
- Absorption
- Photoluminescence
  - Fluorescence,…
- Scattering
  - elastic ↔ inelastic
  - low ↔ high
  - linear ↔ non-linear
- Quantum effects:
  - entanglement
  - contrast agents
- Bulk Effects:
  - Reflection, refraction
  - Diffraction
  - Doppler
  - Polarization change
  - Dispersion
  - Phase change
  - Impedance

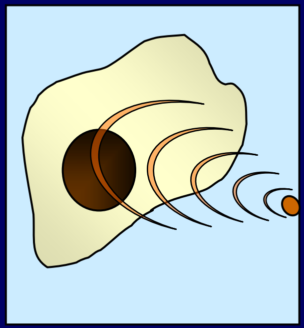
Influence field

Detection

Coherent ↔ Incoherent
Near-field ↔ Far-field
Time-resolved ↔ Integrating
Spectral ↔ Narrowband
Spatial Distribution
Spectral Distribution

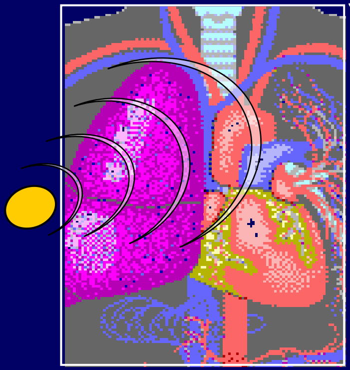
Scope of Center Activities

Sub-cellular Biology



100nm- 10 mm

Tissues & Organs

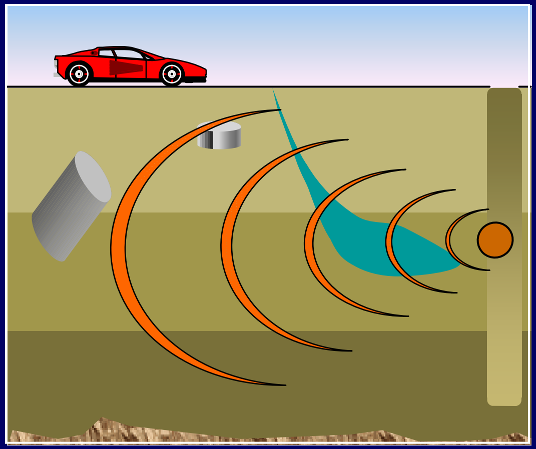


100 mm - 10 cm

Optics | **Ultrasound**

Radar | **Sonar**

Underground Diagnosis

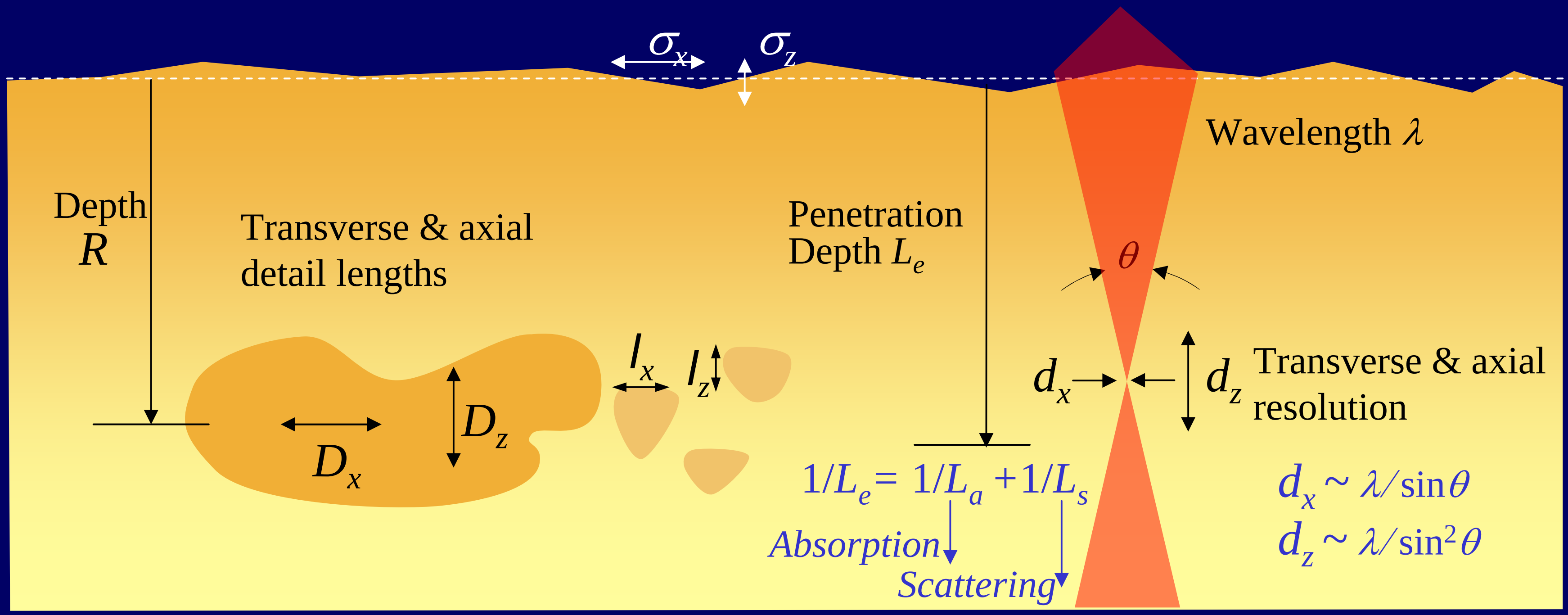


1 cm - 100 m

Underwater Exploration

10 cm - 1 km

Common General Considerations



Contrast Scales:

Object: $\Delta\alpha/\alpha_b$ or $\Delta k/k_b$

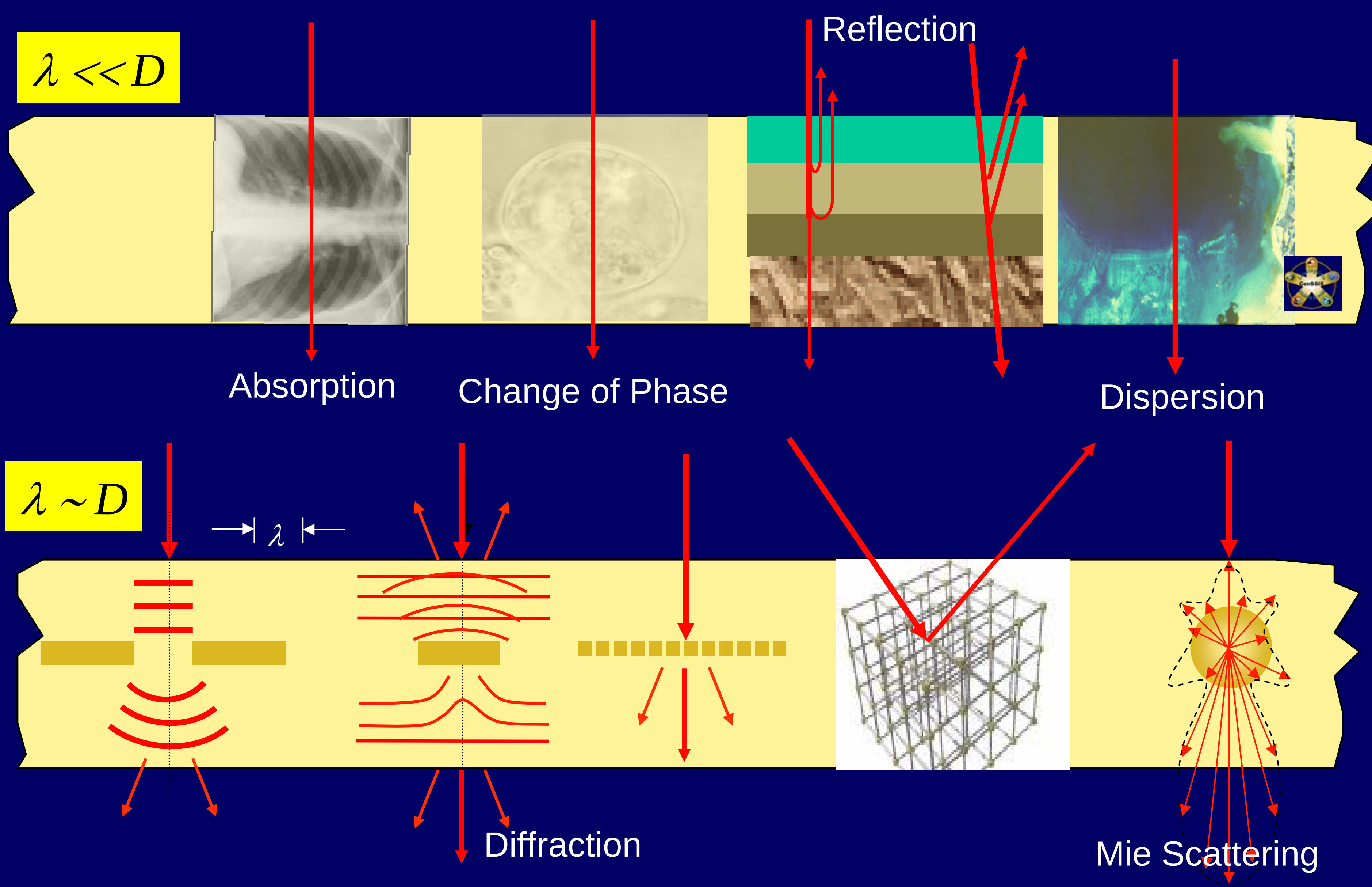
Surface: Impedance mismatch

- *Low contrast → Weak Scattering*
- *High contrast → Strong Scattering*

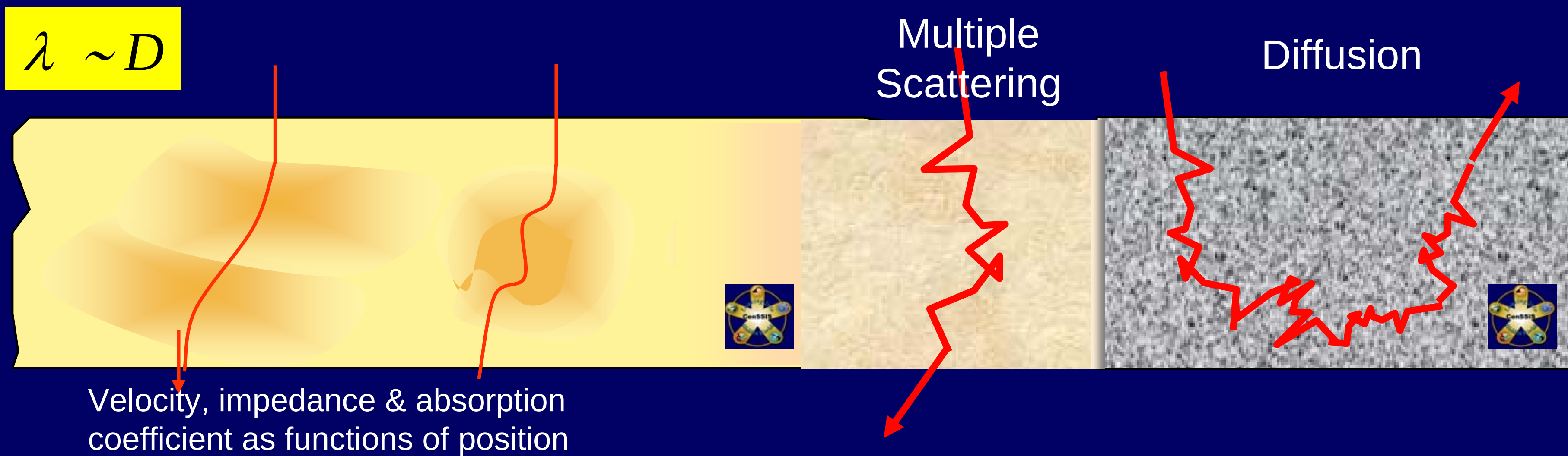
Spatial Scales:

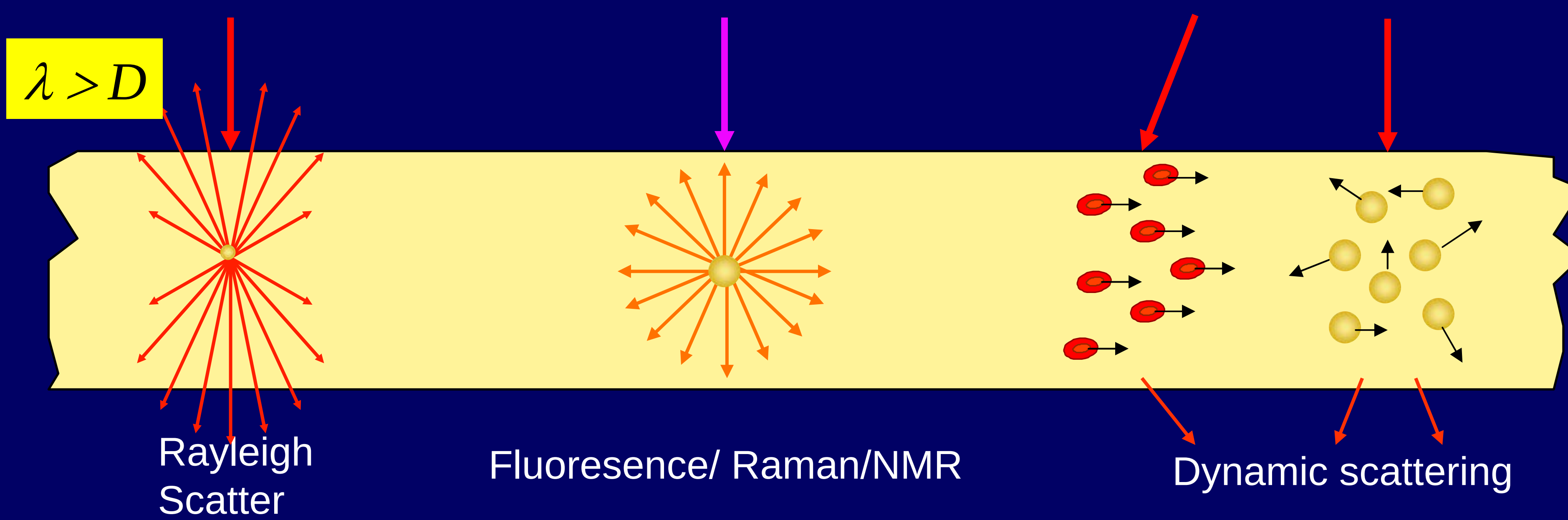
- $\lambda << D$
- $\lambda \sim D$
- $\lambda >> D$

Common Wave-media Interactions



Common Wave-Media Interactions

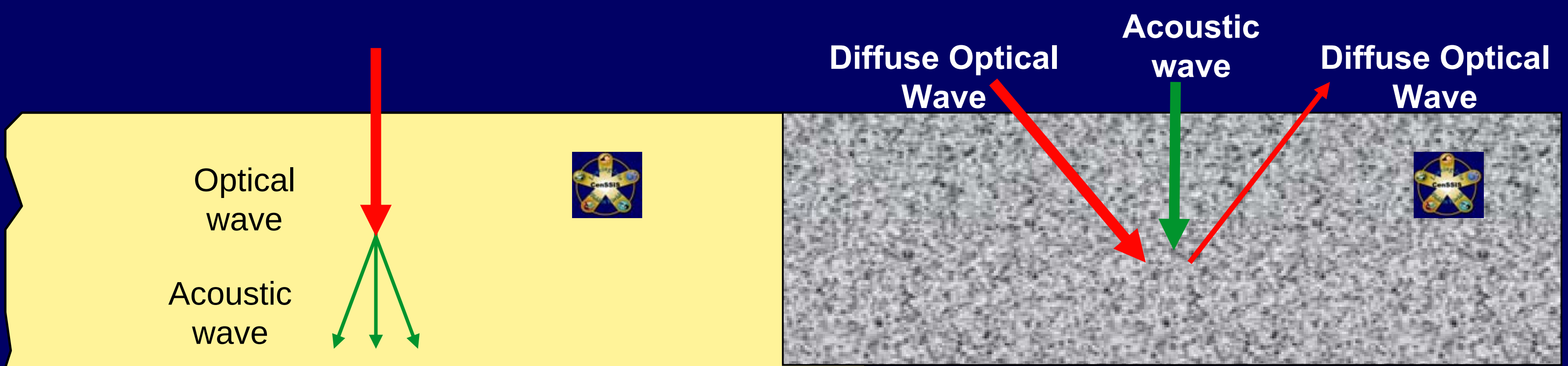




Nonlinear and Dual-Wave Interactions

Up-conversion: Harmonic imaging

Down-conversion: Sub-Harmonic imaging



Opto-Acoustic Imaging (OAI)

Acousto-Optic Imaging (API)

What Are The Fundamental Science Barriers?

Barrier 1	**Inadequate understanding of the physics of subsurface sensing and imaging**
Barrier 2	**Unreliable inversion methods for inhomogeneous and cluttered subsurface media**
Barrier 3	**Lack of robust, physics-based recognition and sensor fusion techniques**

What Barriers Prevent the Development of an Integrated Engineered System?

Barrier 4 — Lack of computationally efficient, realistic physical models

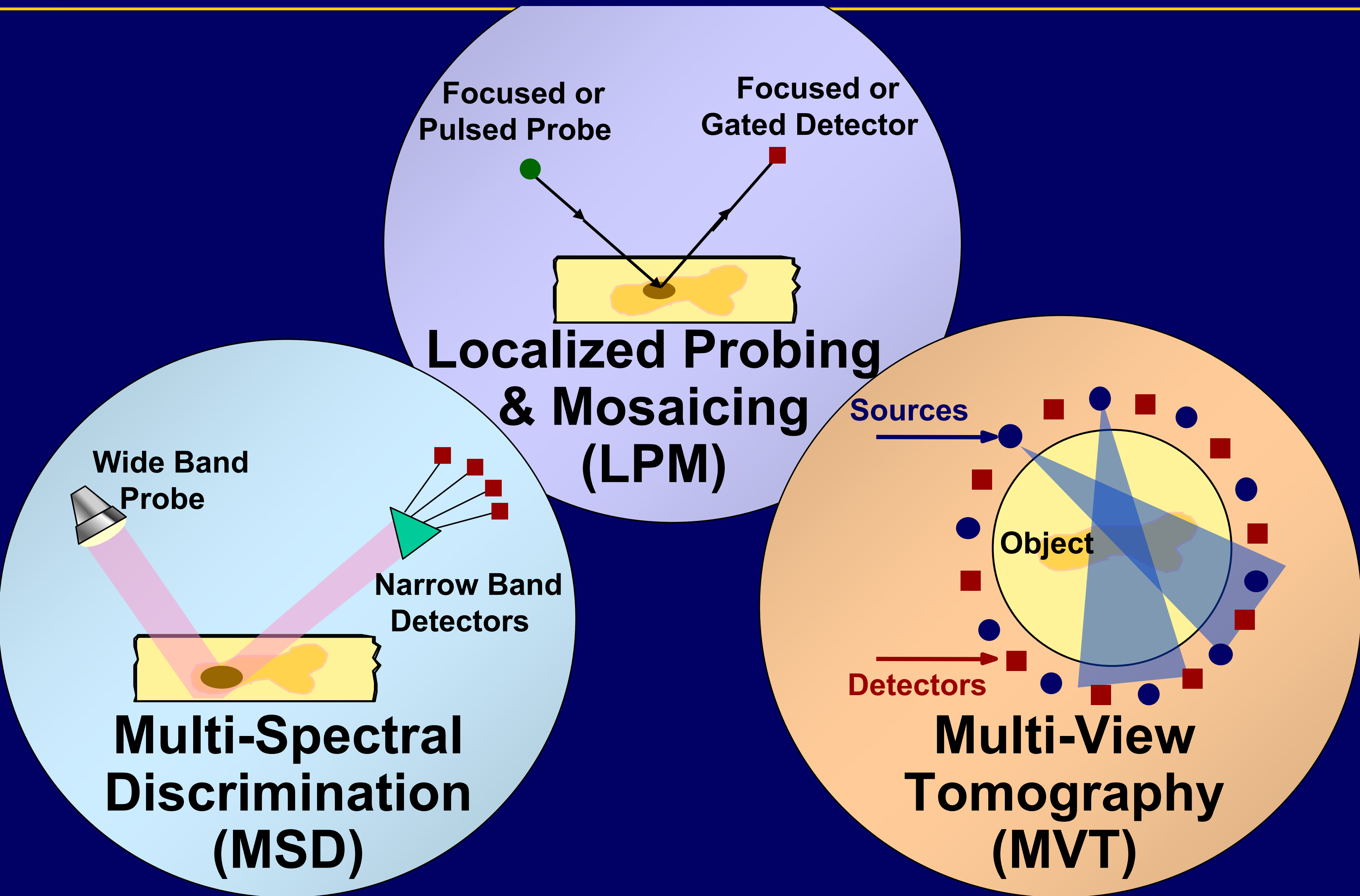
Barrier 5 — Lack of optimal end to end sensor design methods

Barrier 6 — Lack of rapid processing and management of large image databases

Barrier 7 — Lack of validated, integrated processing and computation tools

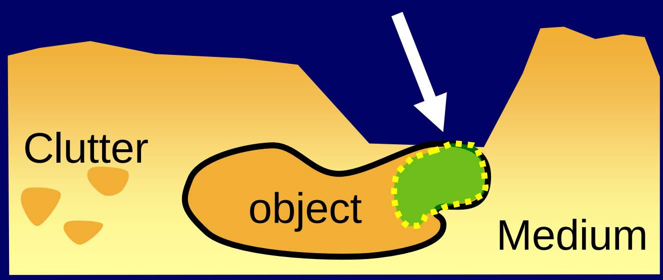
Barrier 8 — Lack of a unified framework for diverse sensing and imaging modalities

Principal Information Extraction Methods

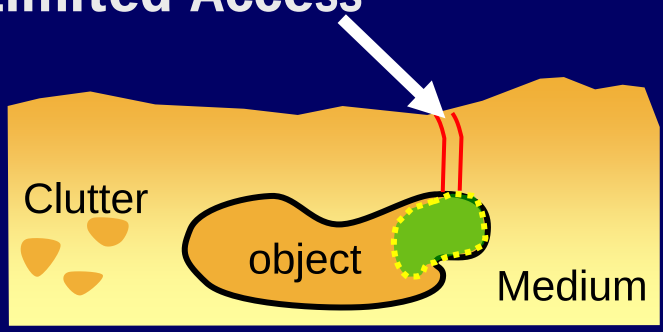


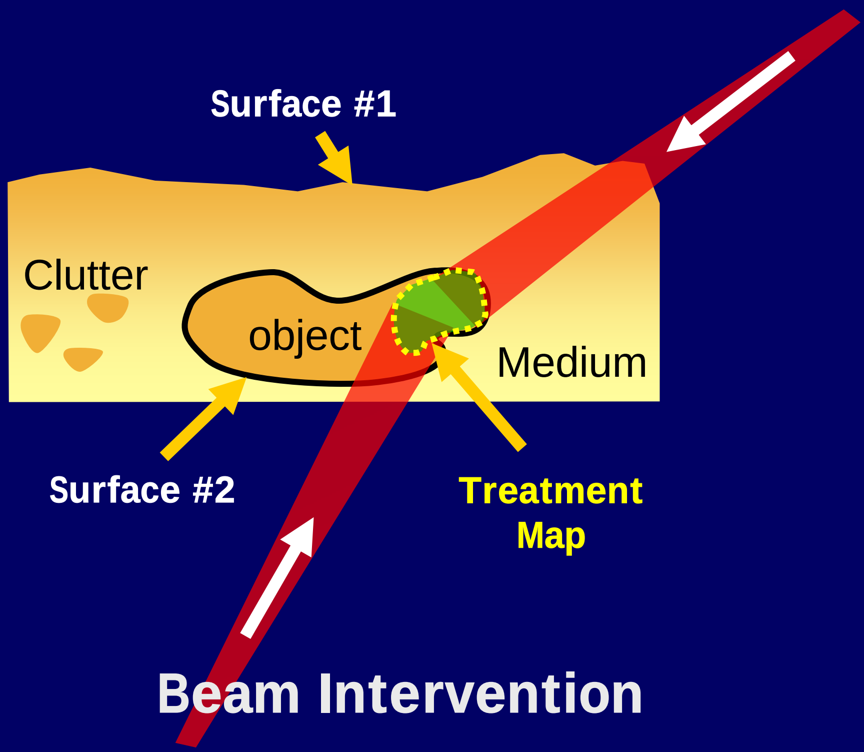
Subsurface Intervention Methods

Invasive Access



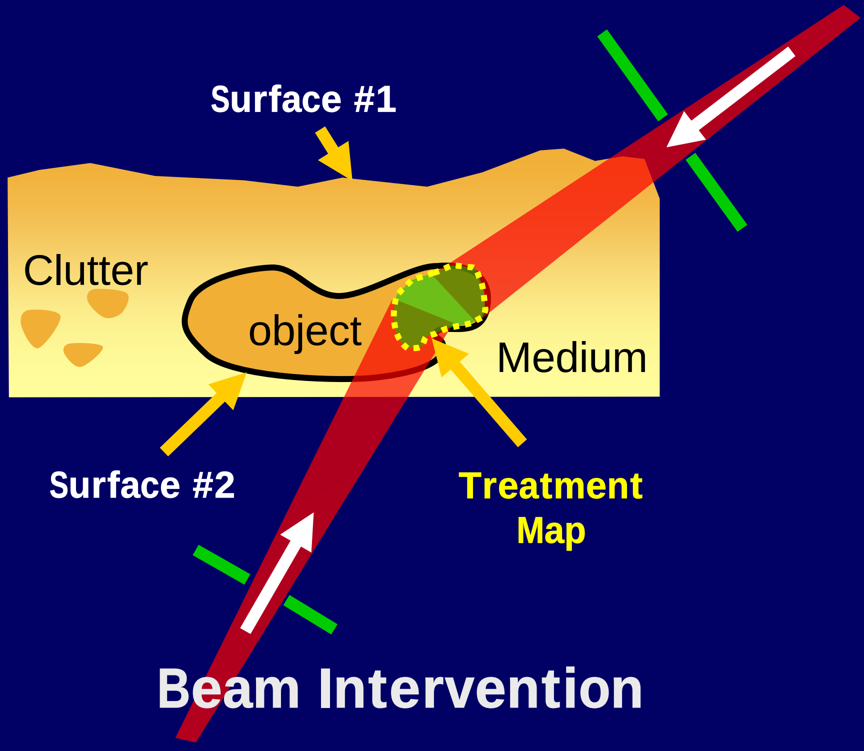
Limited Access





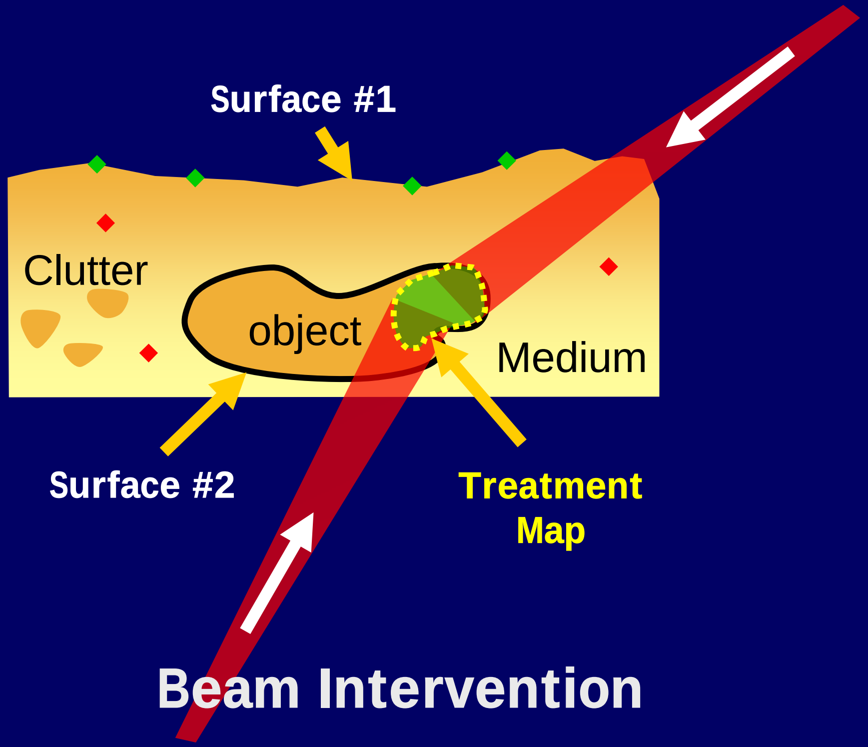
Beam Interventions

- **Common Beam Types:**
  - Optical (laser)
  - Acoustic (HIFU)
  - Radiation (x-ray, gamma ray, proton beam, …)
- **Common Objectives:**
  - Achieve desired spatial dose distribution:
    - Full coverage of pathology
    - Minimize dose to background
  - Motion and deformation compensation
  - Conforming the beam to the treatment map
  - Integrated approaches to diagnosis, planning, execution, and follow up
- **Examples**
  - Laser retinal surgery
  - Radiation treatment of intra-ocular tumors
  - Radiation treatment of cancer of lung, prostate, …



Beam Interventions (…contd)

- **Common issues:**
  - **Availability/otherwise of implantable marker targets**
  - **Relating several coordinate systems:**
    - **Imagery & coordinates of the surface and the subsurface**
    - **Marker targets**
    - **Imaging and Beam coordinate systems**
  - **Identification of delicate neighboring structures to be avoided**
  - **Achieving adequate spatio-temporal sampling of moving 3-D structures**
  - **Minimizing damage from imaging probes**

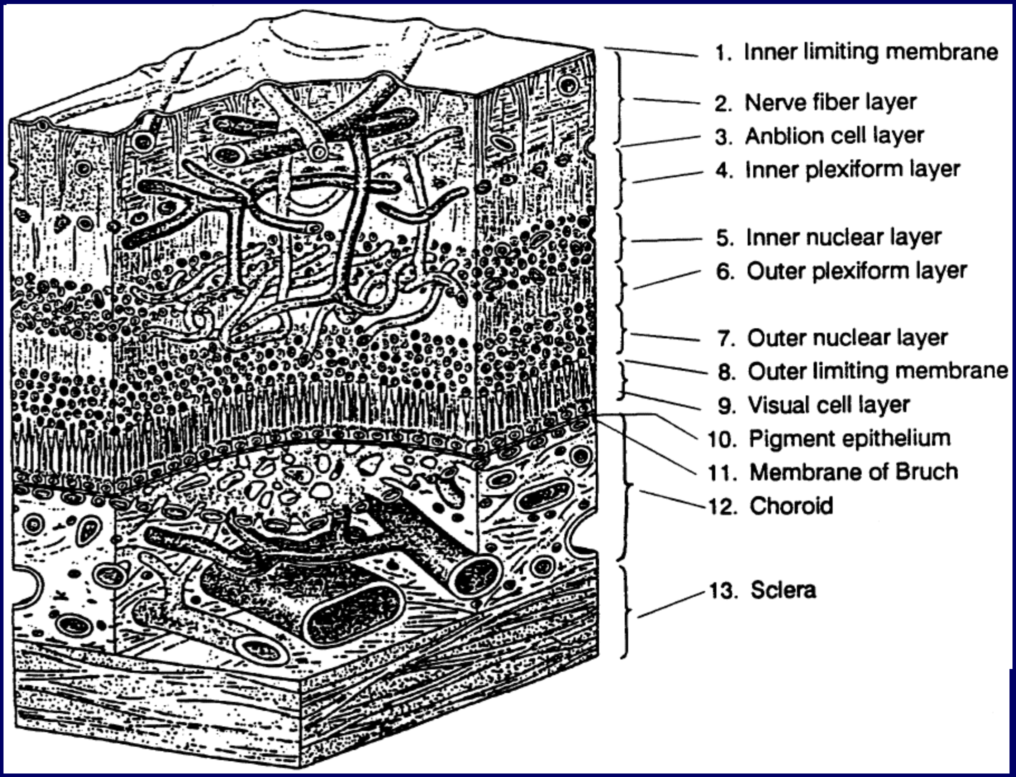


Before, During, and After Intervention

- **Before intervention**
  - Establishing a spatial reference map
    - Surface, subsurface, motions
  - Reliable detection of pathology
  - Accurate delineation of pathology & treatment map
  - Planning the intervention optimally
- **During intervention**
  - Precise knowledge and spatio-temporal control of dose
  - Maximize dose to pathology & minimize dose to other regions
  - Complete & stable visualization with context
  - Predictable real-time motion compensation & spatial referencing to map
  - Correction for patient pose and variable deformations
  - Responsibility and control
  - Spatial dosimetry
  - Alarms and safety cutoffs
  - Accounting for changes as they occur
- **After intervention**
  - Accurate assessment of changes inflicted by intervention
  - Updated planning for next intervention

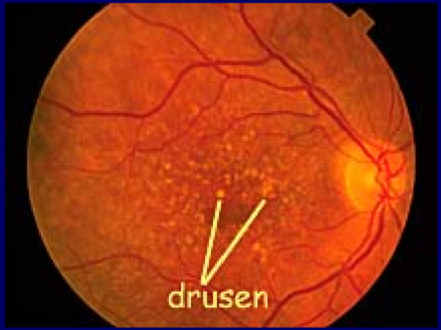
Human Eye and Retina

webvision.med.utah.edu



- Leading Causes of Blindness
  - Age-Related Macular Degeneration
  - Diabetic Retinopathy
  - Glaucoma
  - Retinopathy of Prematurity
- Laser Retinal Surgery = Best-available Treatment
- **Failure Rate ≈ 50%**

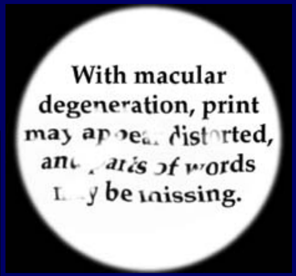
Macula.org



Early AMD

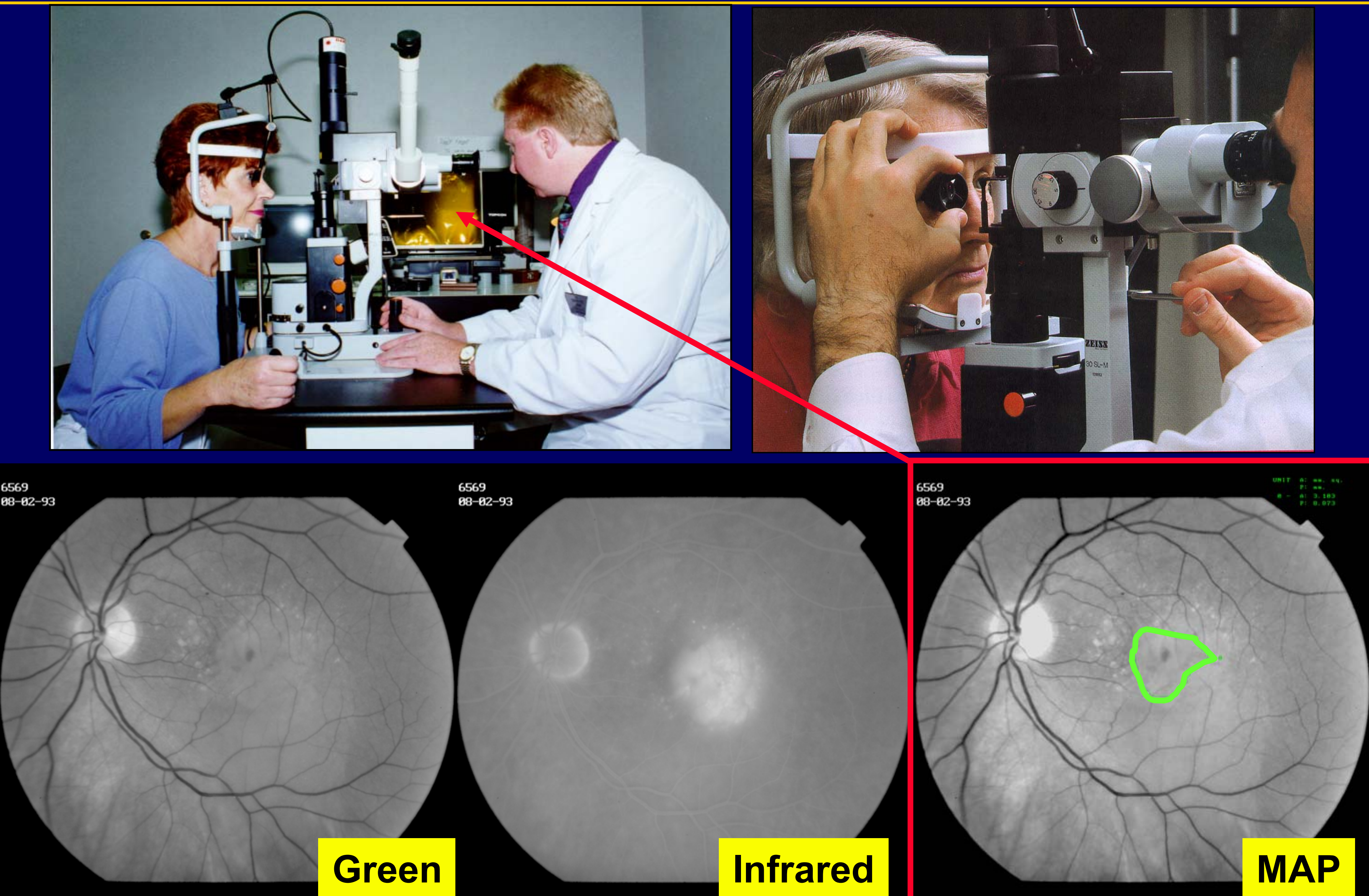
Dry AMD

Wet AMD



Scotoma

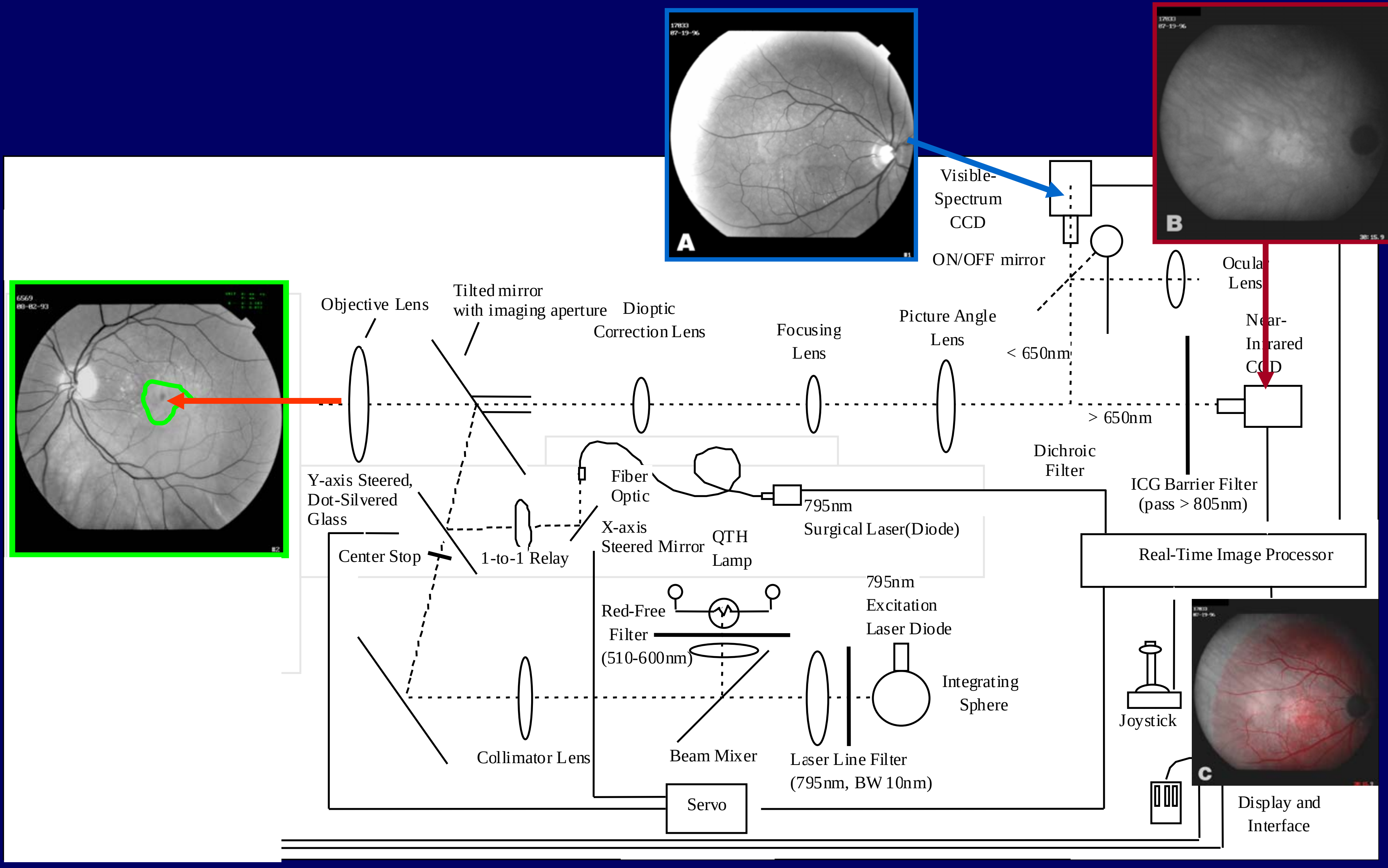
Current State of the Art



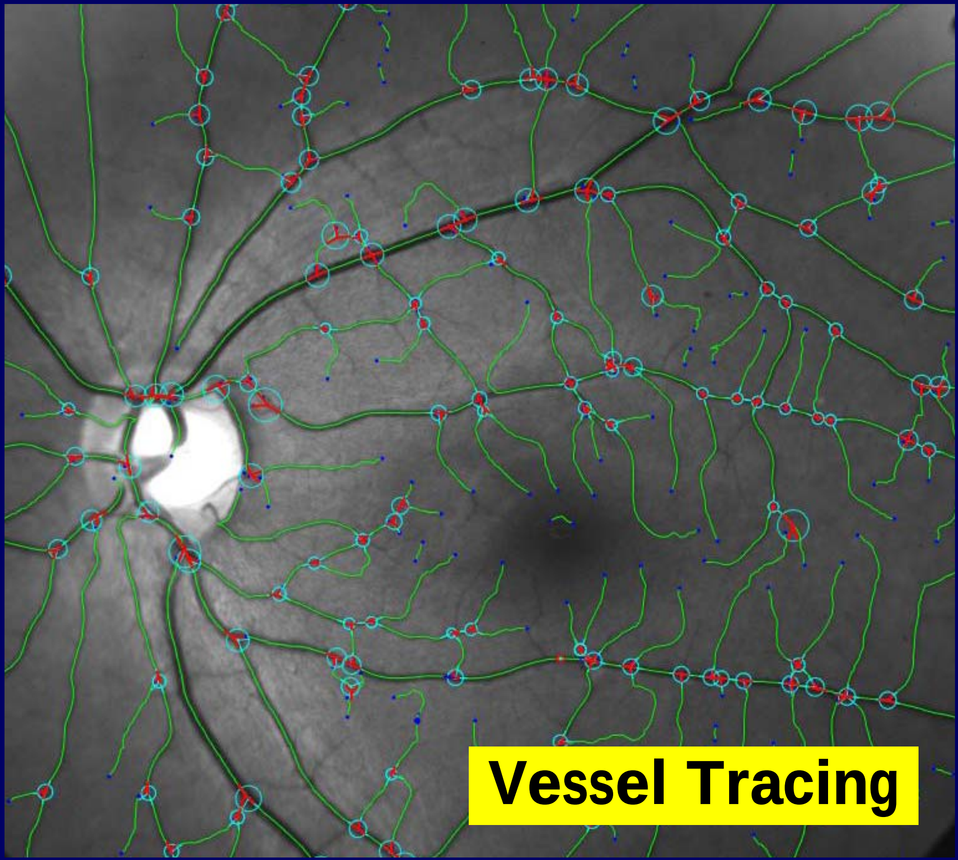
What can we engineers do to help?

- Develop an integrated solution
  - Optical hardware:
    - Multi-spectral imaging
    - Assisted laser guidance and safety shutoffs
  - Computer Software:
    - Establish a spatial map based on computer image analysis
    - Map-based spatial referencing and tracking for beam delivery
    - Tools to integrate with diagnosis, planning, and delivery
  - Computer Hardware:
    - Enable predictable real-time computing
    - Enable fast (parallel) computing

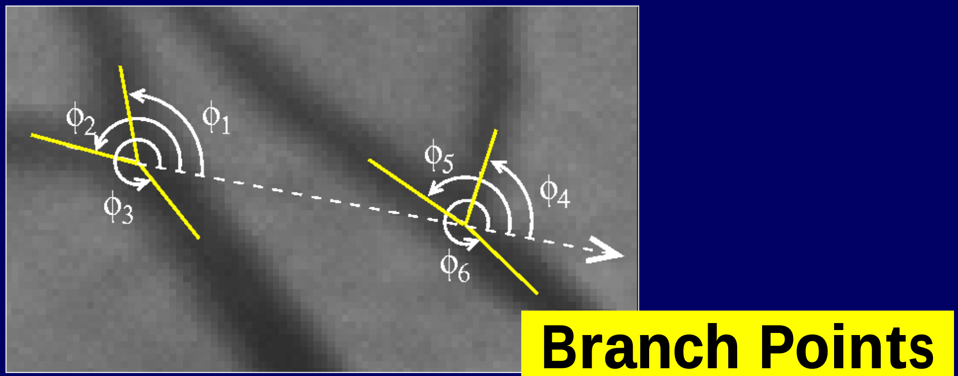
Towards a Smarter, Integrated System

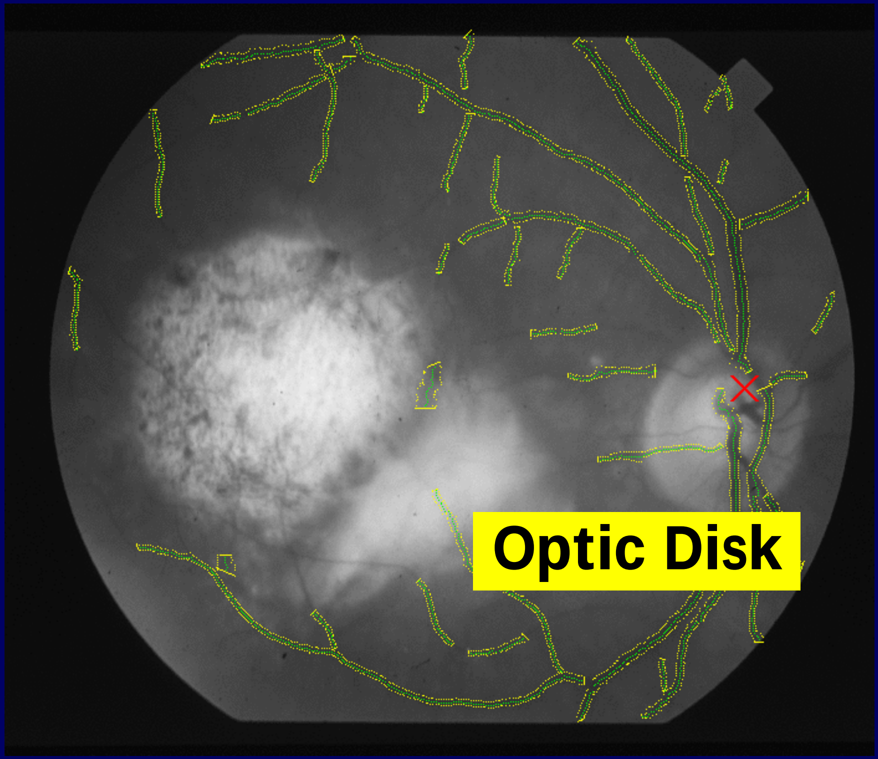


What it takes: Fast feature Extraction

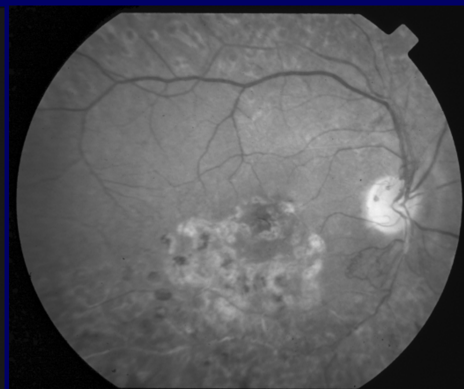


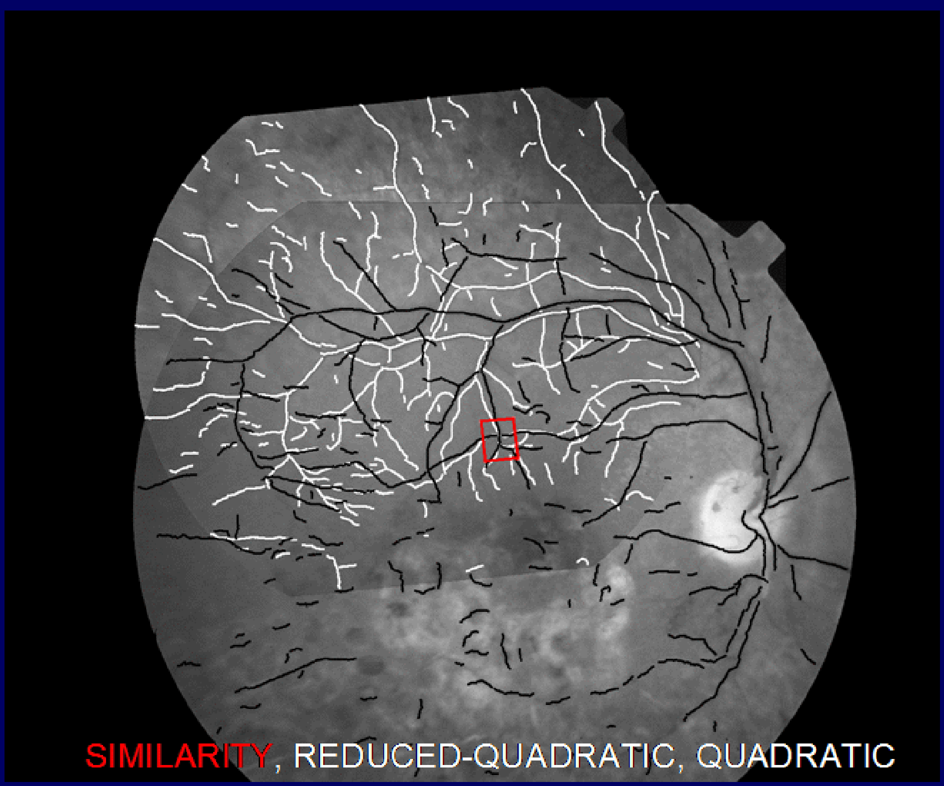
- Fast and automatic
- Sub-pixel traces and interest points
- Detailed vessel morphometry





What it takes: Precise Registration



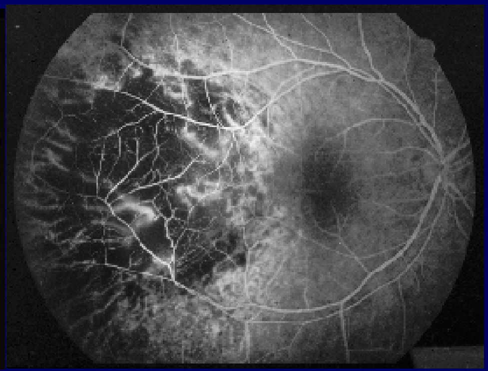


Main Ideas:

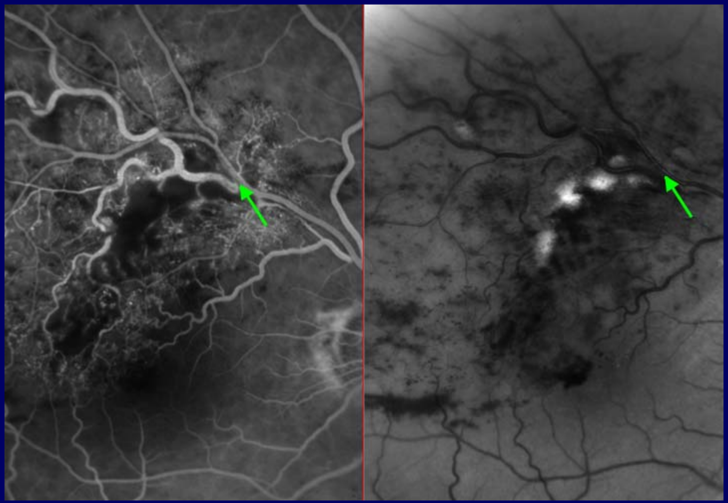
- 12-D model for the **curved retina** imaged by uncalibrated camera
- Dual-bootstrap registration:
  - Minimum initialization needed
  - Robust hierarchical estimation
  - Automatic model selection
  - Grow estimation zone based on uncertainty (view)
- Performance:
  - Large-scale Testing w/ 15,000 image pairs, 46 eyes covering 5 major diseases, up to 5 years apart
  - **99.5% success rate**

What it takes: Cross-Modality Mapping

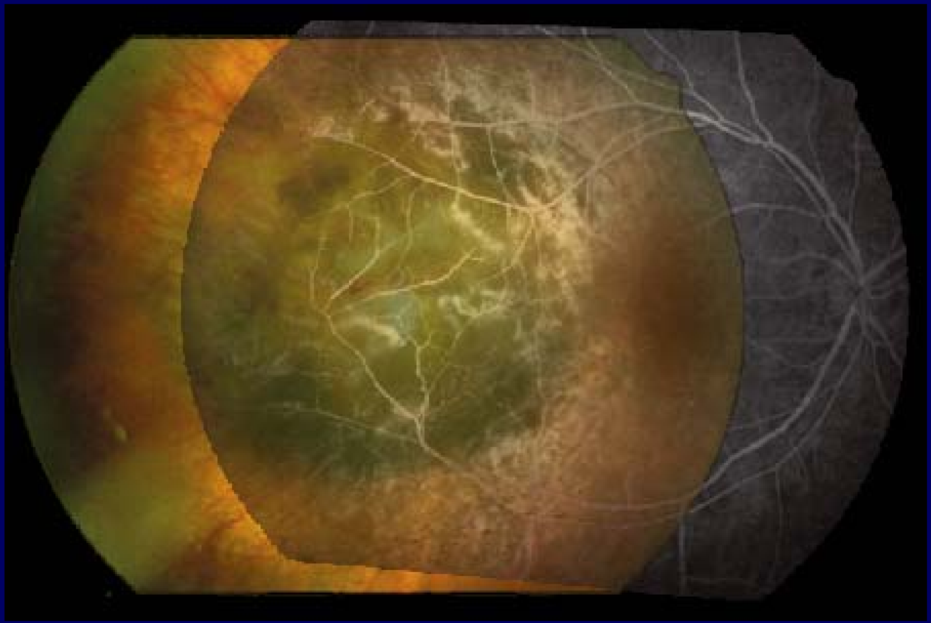
Visible



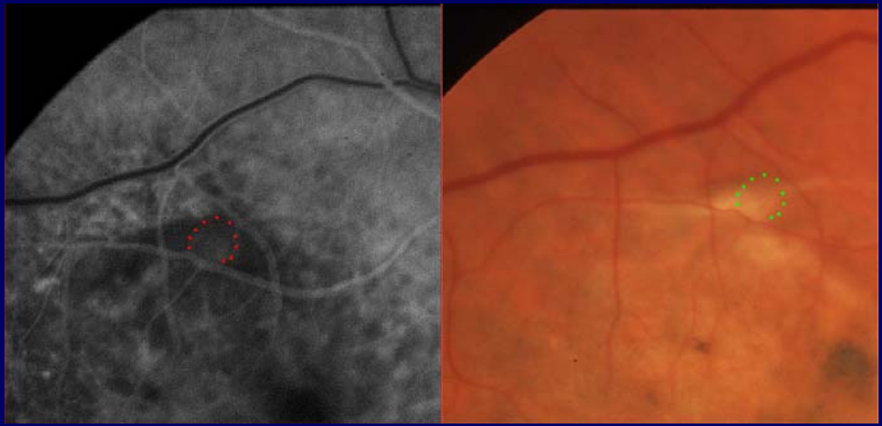
Fluorescein



Vein occlusion



Melanoma Example

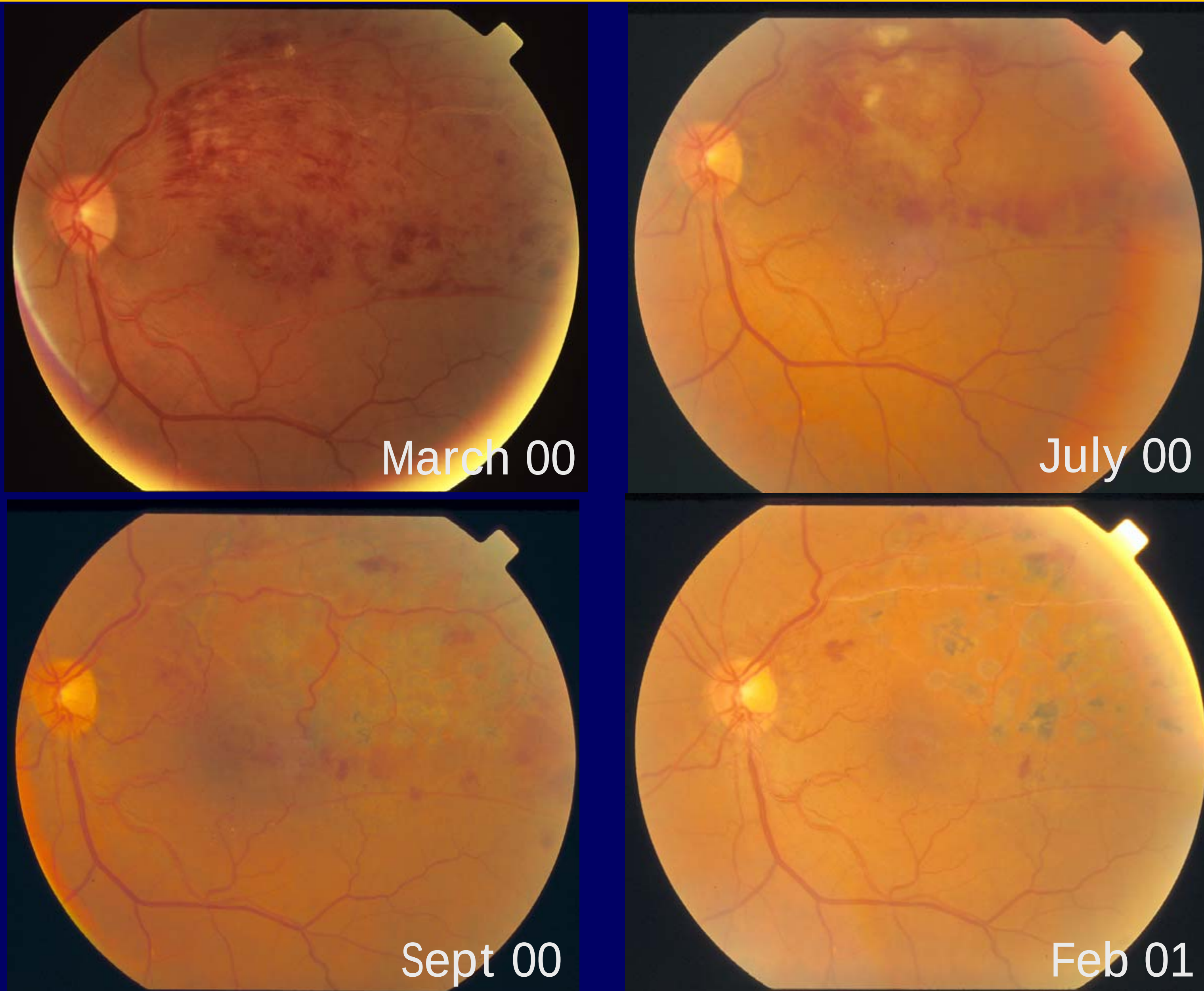


Wet AMD

More Precise Mapping

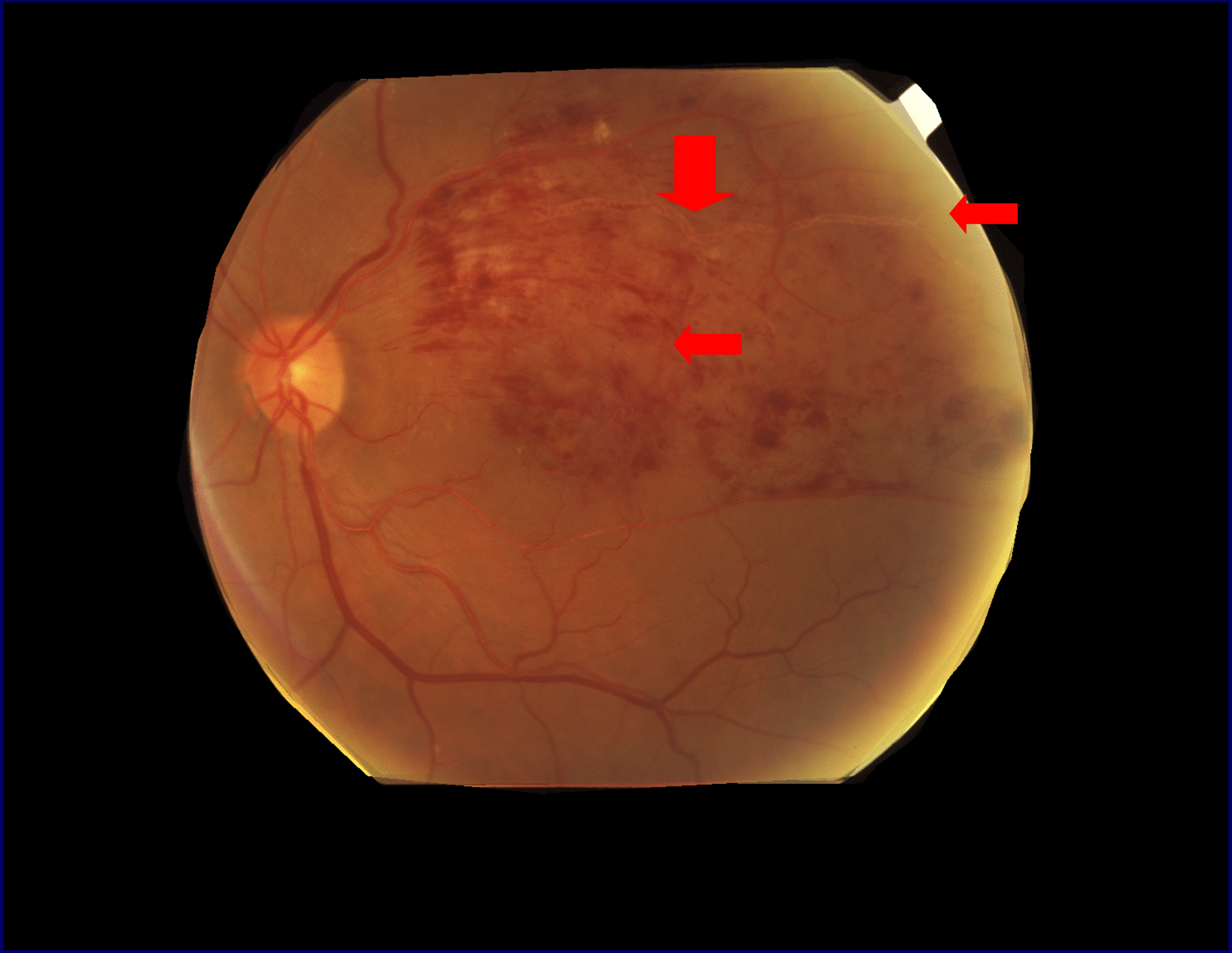
Mapping Changes

BRVO w/ macular edema, neovascularization,...

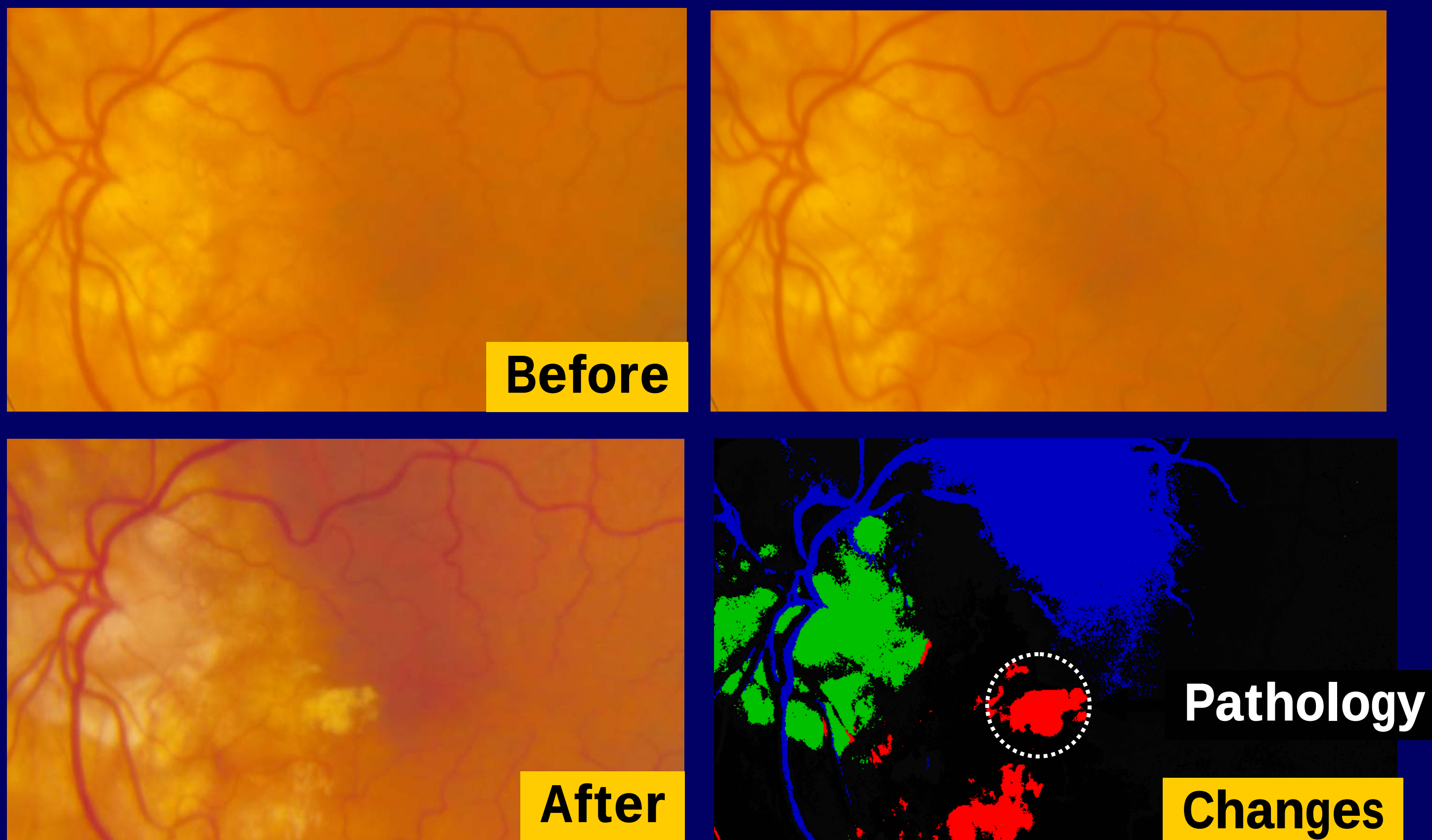


Data courtesy: Dr. A. Majerovics

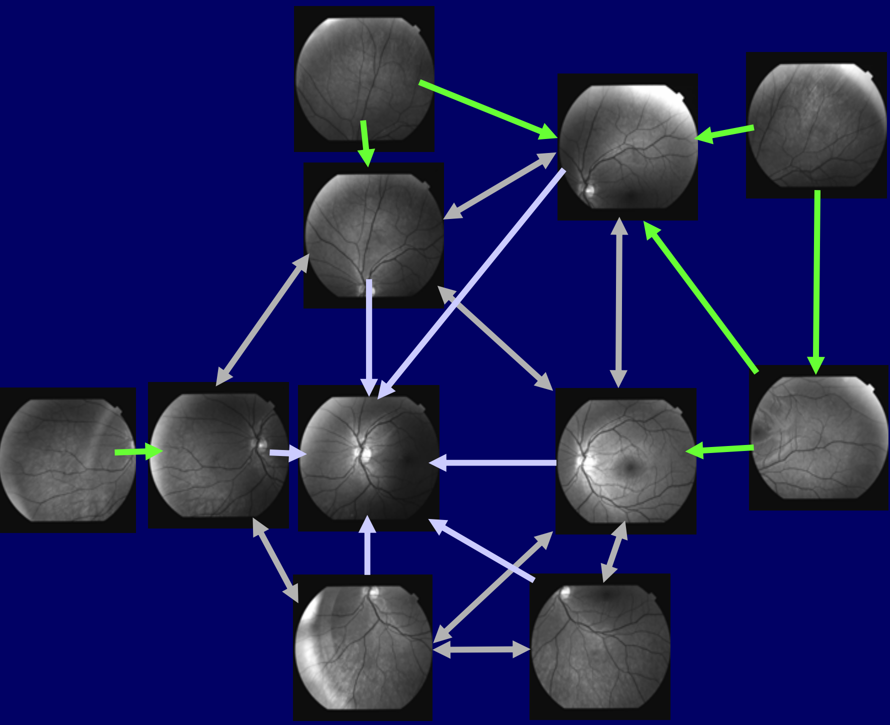
Registered Movie

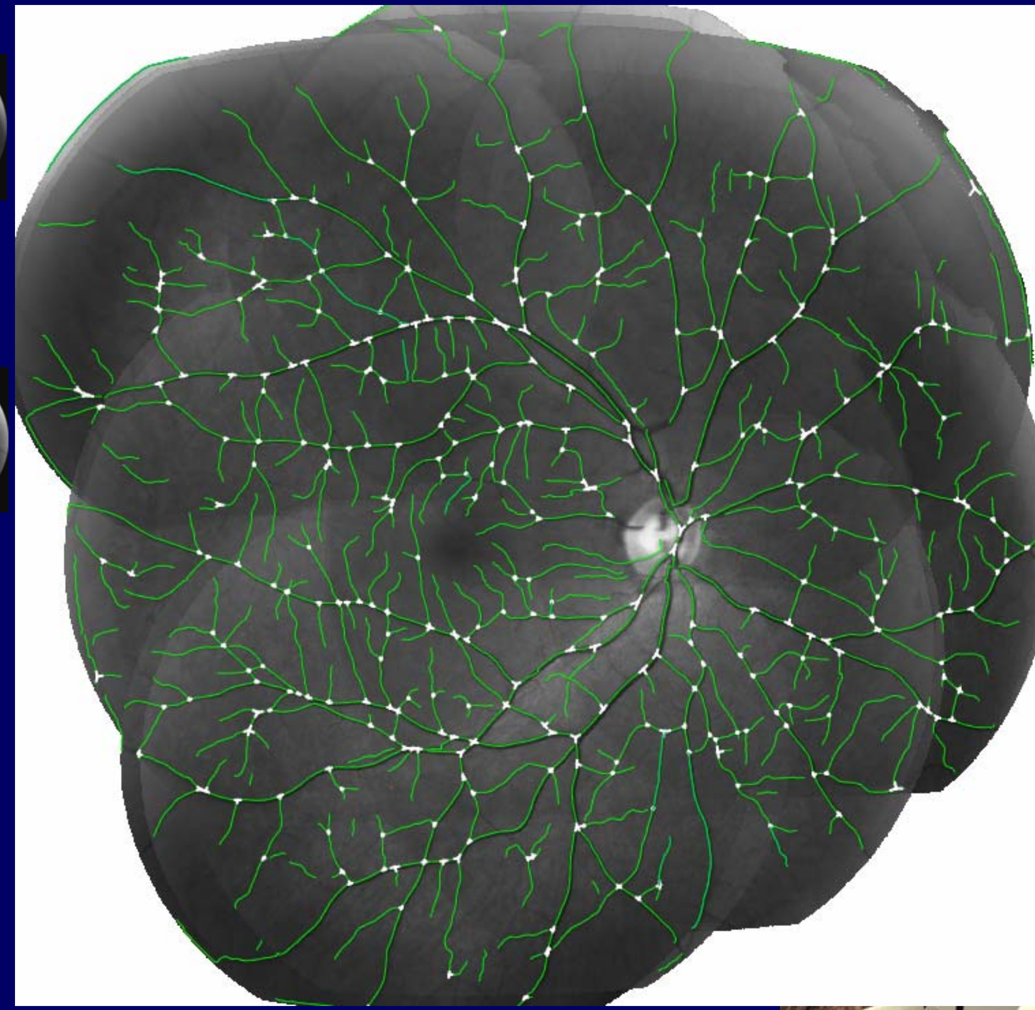


Change Detection



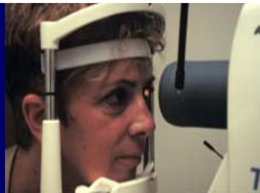
What it takes: Joint Mosaicing & Mapping





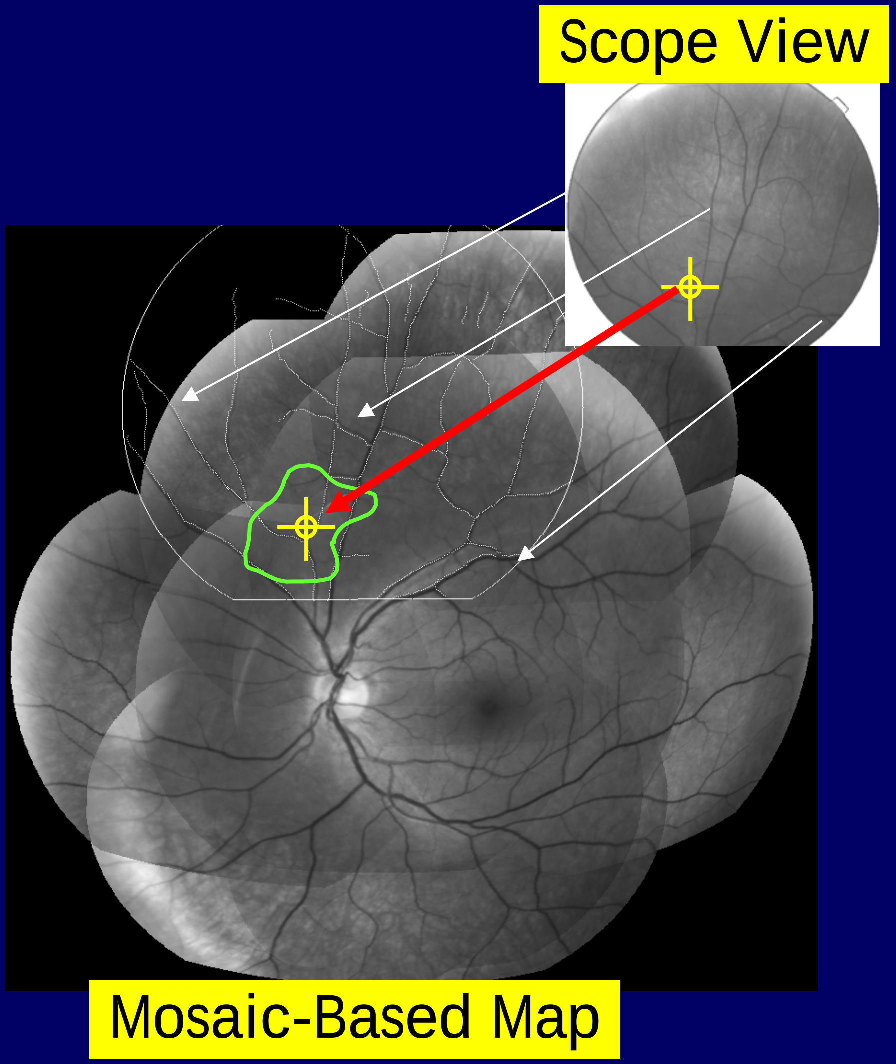
- Direct applications
  - Visualization
  - Corrections
  - Robust Change
- Indirect applications:
  - Basis for spatial mapping

~ 70^{o} Mosaic of Retina

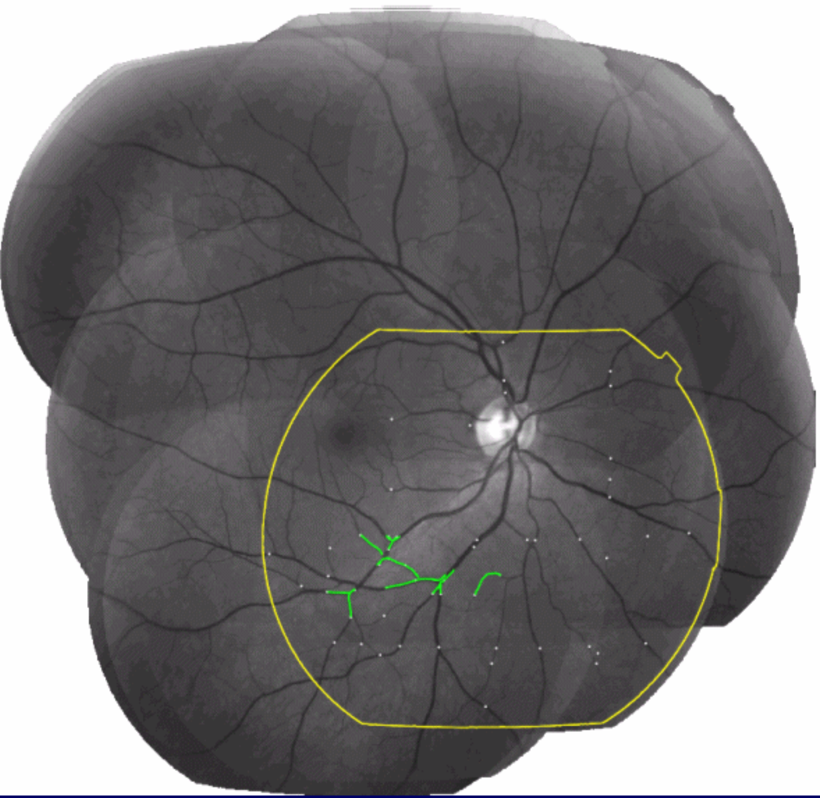


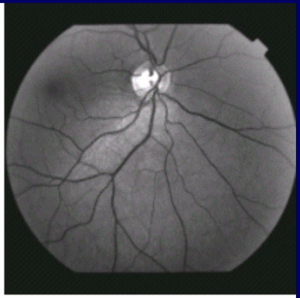
What it takes: On-line Registration

- Determine location of laser with respect to pre-computed spatial map
-
- Issues:
  - High variability
    - Inter-patient
    - Intra-patient
  - Speed (30-200fps)
  - High data rate (1M pixels x frame rate x channels)
  - Minimize light levels and total time
    - Camera sensitivity
    - Discomfort
  - Predictability for real-time control

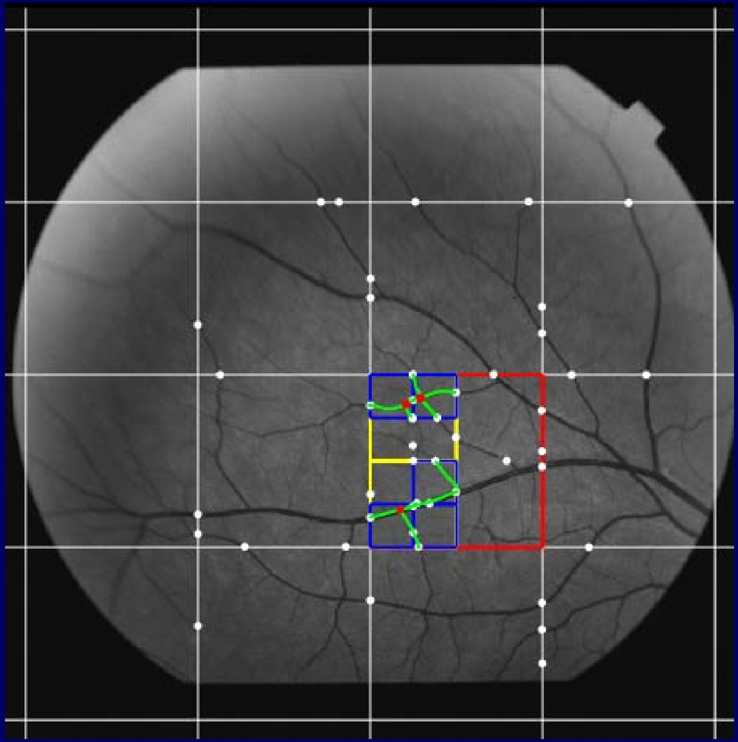


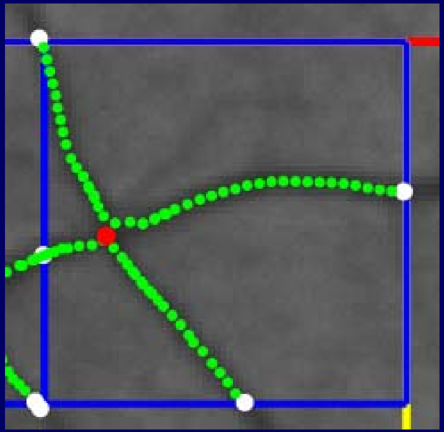
Fast Map-based Positioning





Instrument View

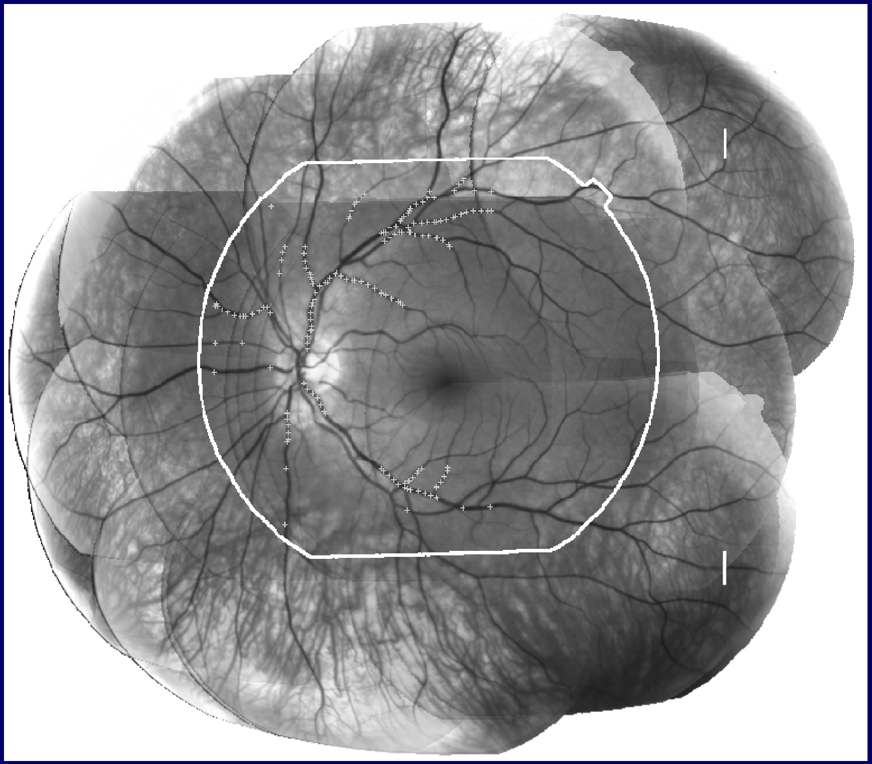


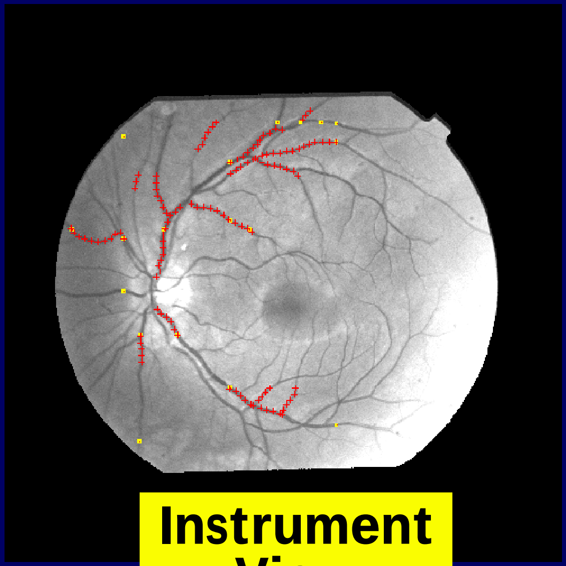


Key ideas:

Just-sufficient, opportunistic,
Progressive, imprecise computation
Atlas = Mosaics + structure indexing
database + treatment map

Hybrid Tracking and Referencing





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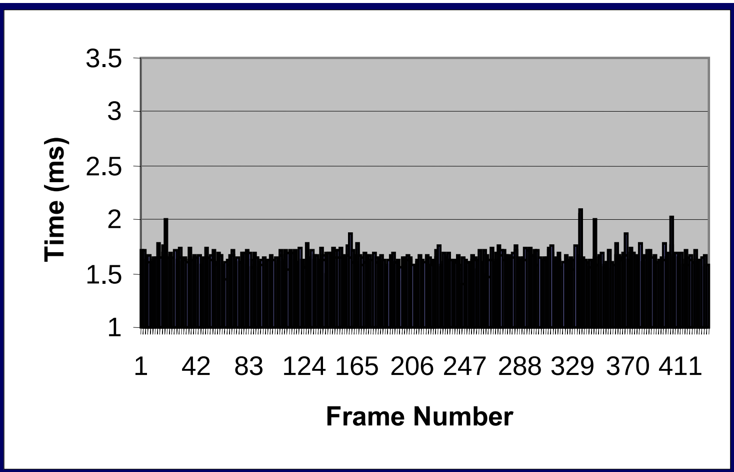
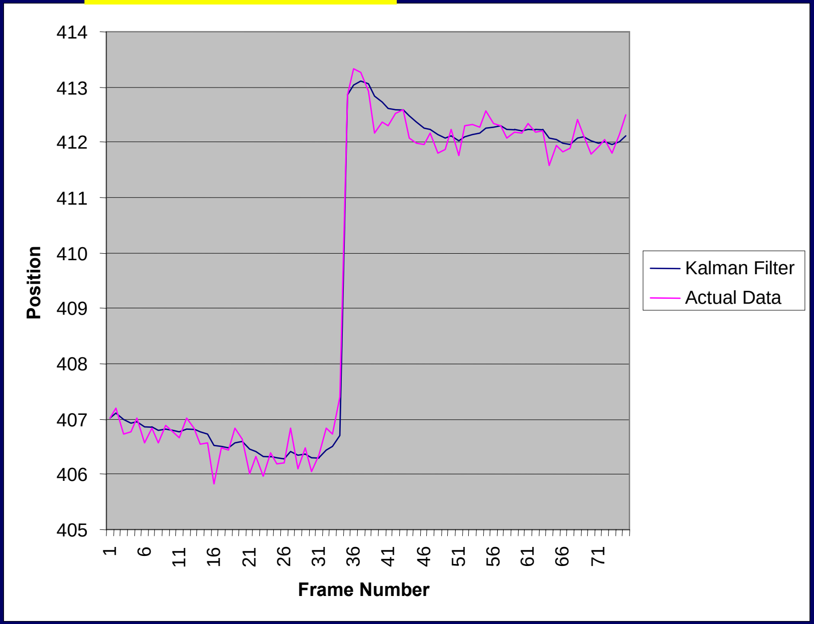
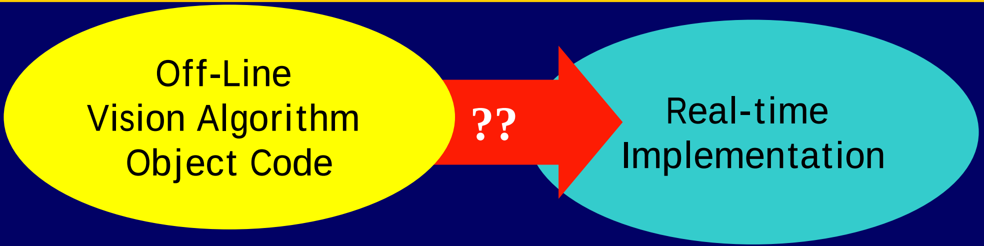
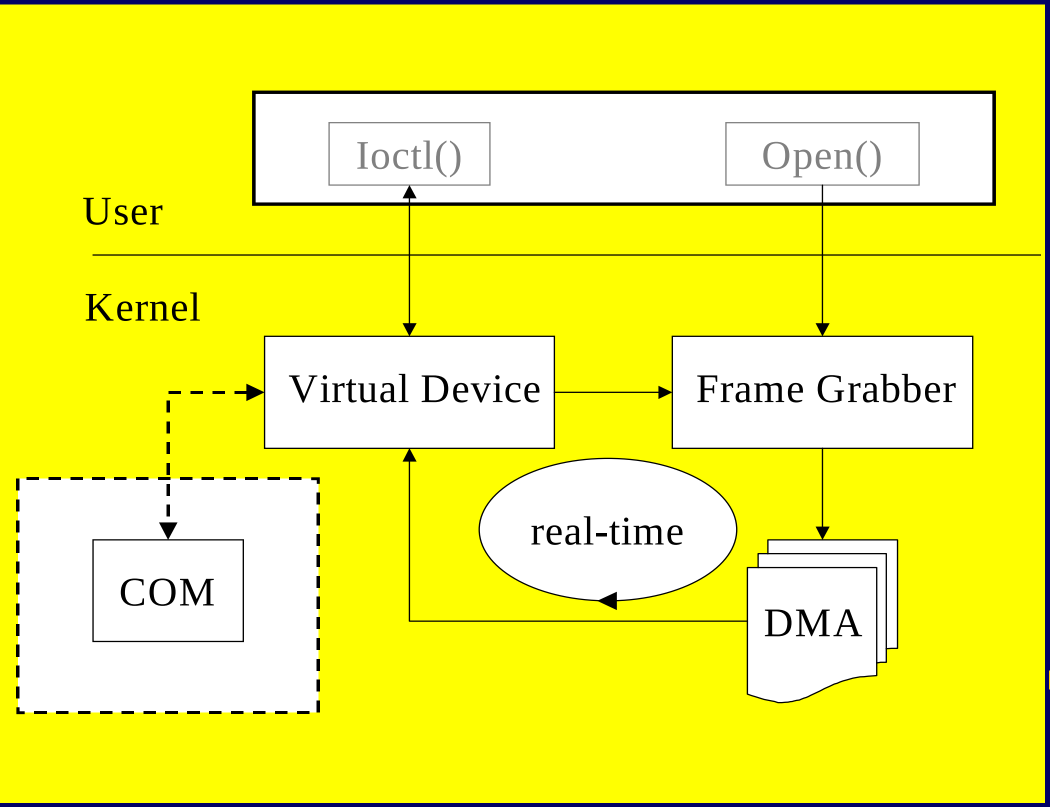




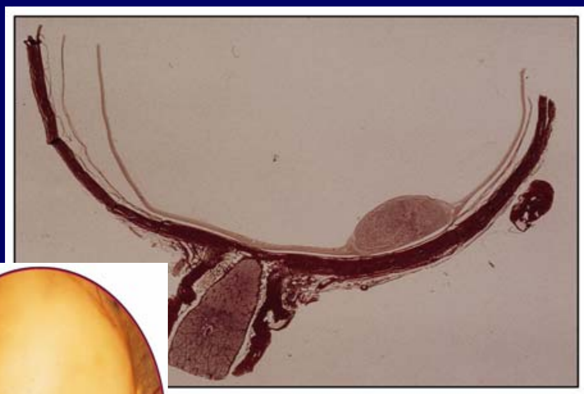
Real-Time Computing Issues

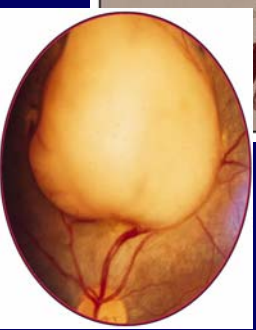


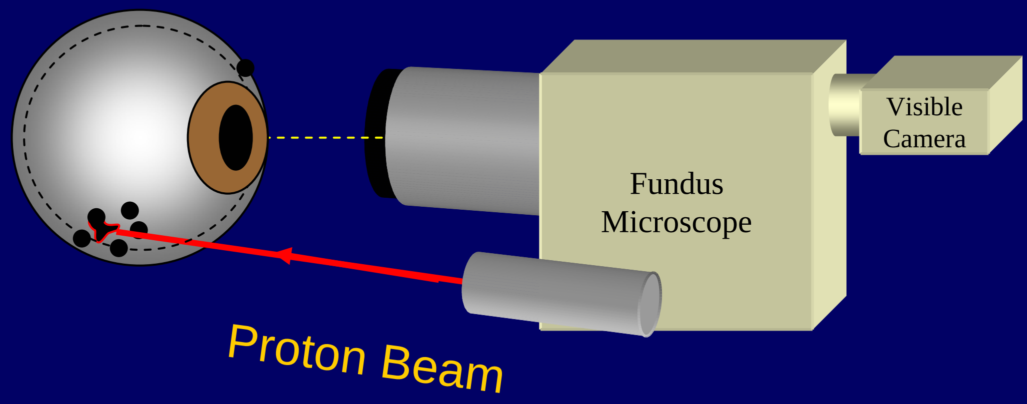


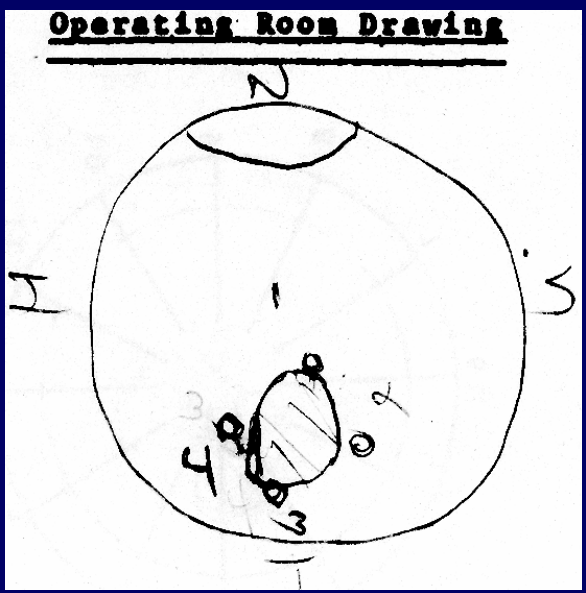
- **Issues:**
  - **Large and complex code libraries (libc, vxl, libm,..etc)**
    - **Too expensive to re-write, and evolve**
    - **Unpredictable operations such as dynamic memory allocation**
  - **Interrupts, Scheduling, Virtual Memory overheads, Computational efficiency.**
  - **COTS a good match to exploratory vision code, hyper-threaded CPUs**
- **Solution:**
  - **Linux kernel-based virtual devices**

Treating Intra-Ocular Tumors





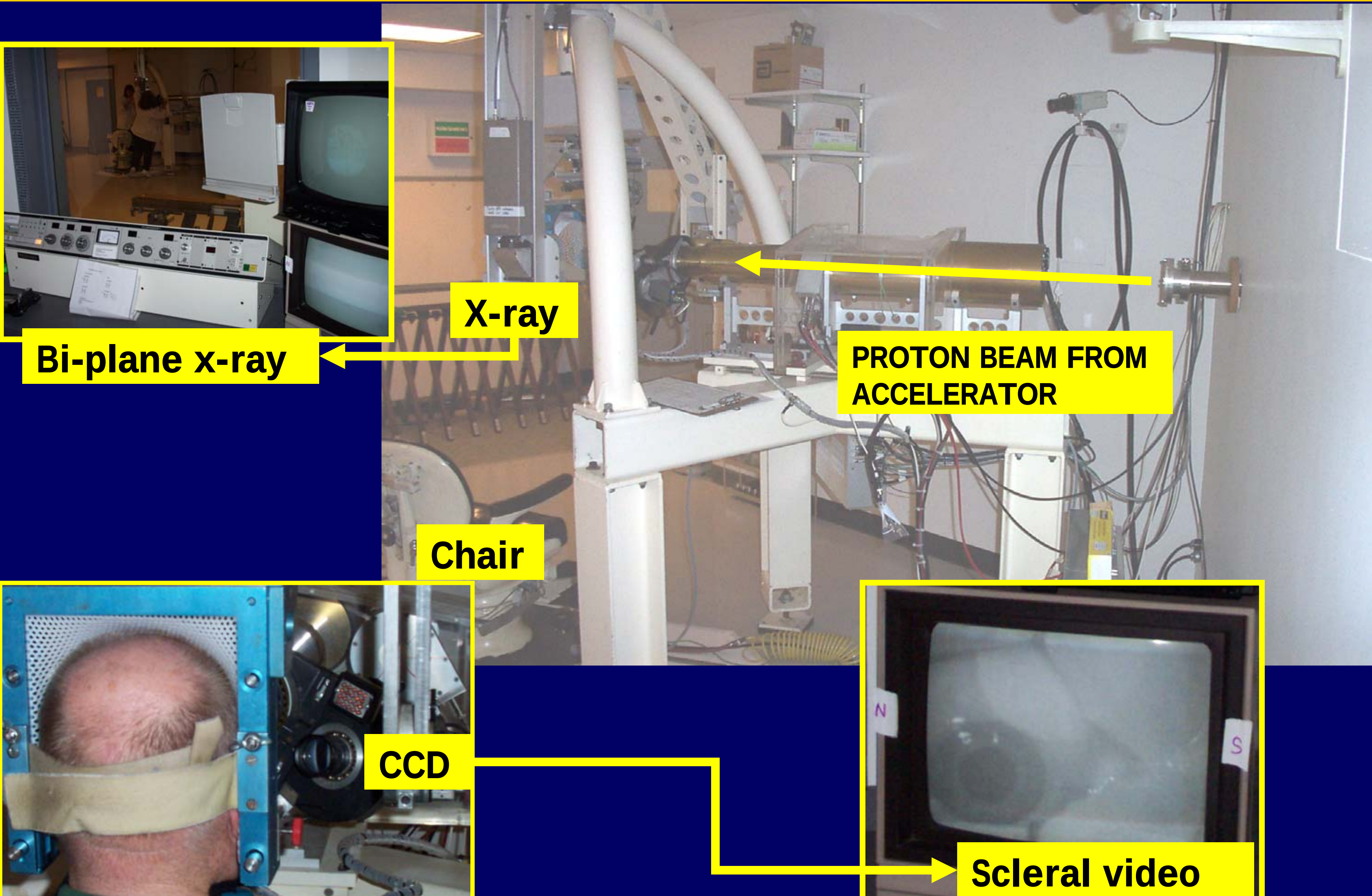




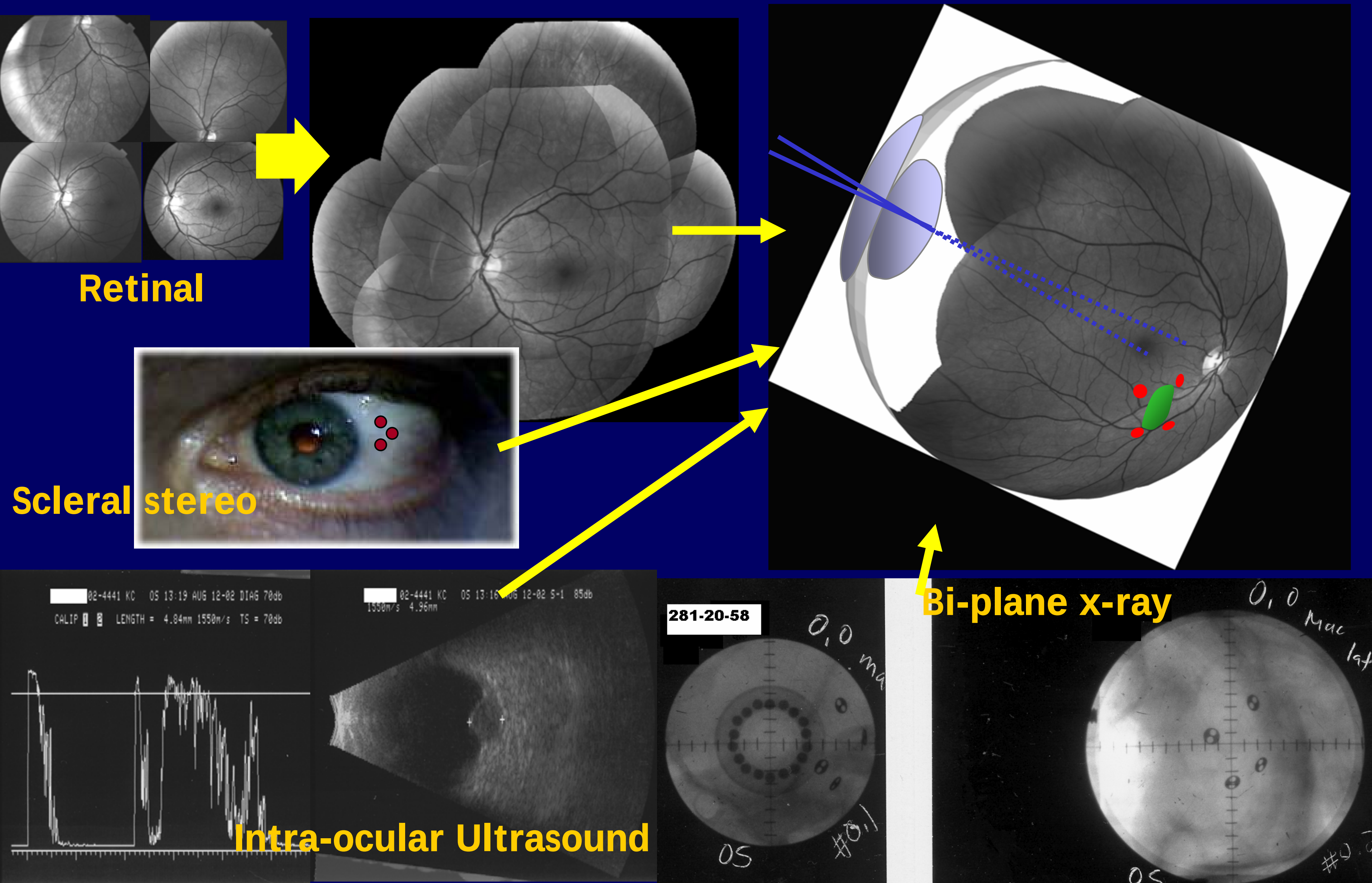
Requires 3-D radiation treatment plan to:

- Maximize tumor dosage
- Minimize non-tumor dosage
- Motion compensation
- Safety Shutoffs
- Spatial Dosimetry

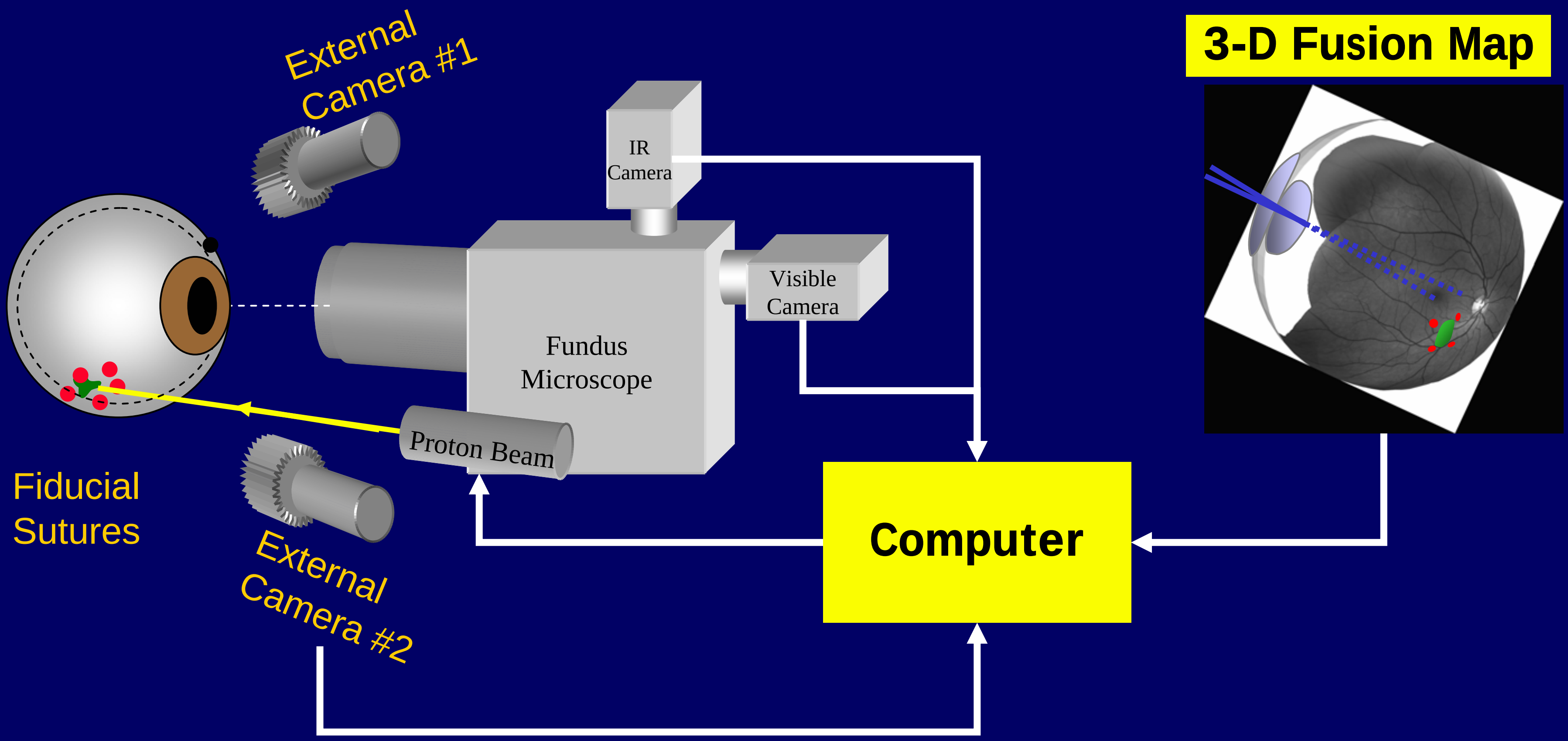
Current Proton Beam Therapy



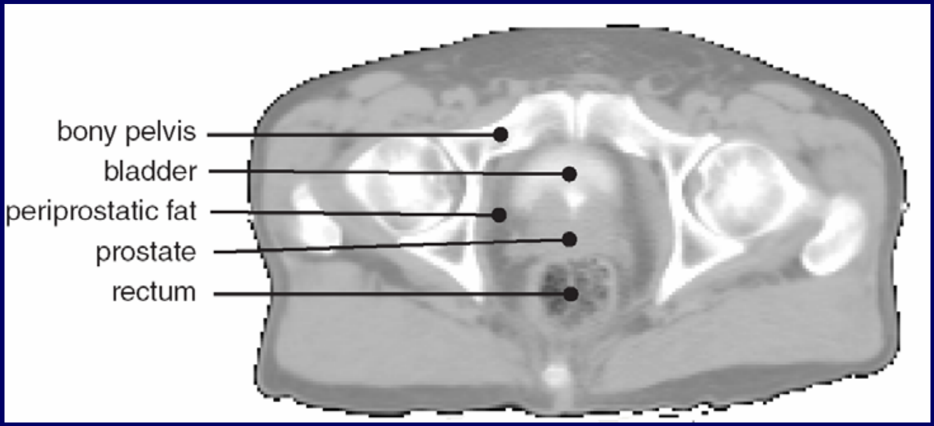
Generalized 3-D Ocular Atlas

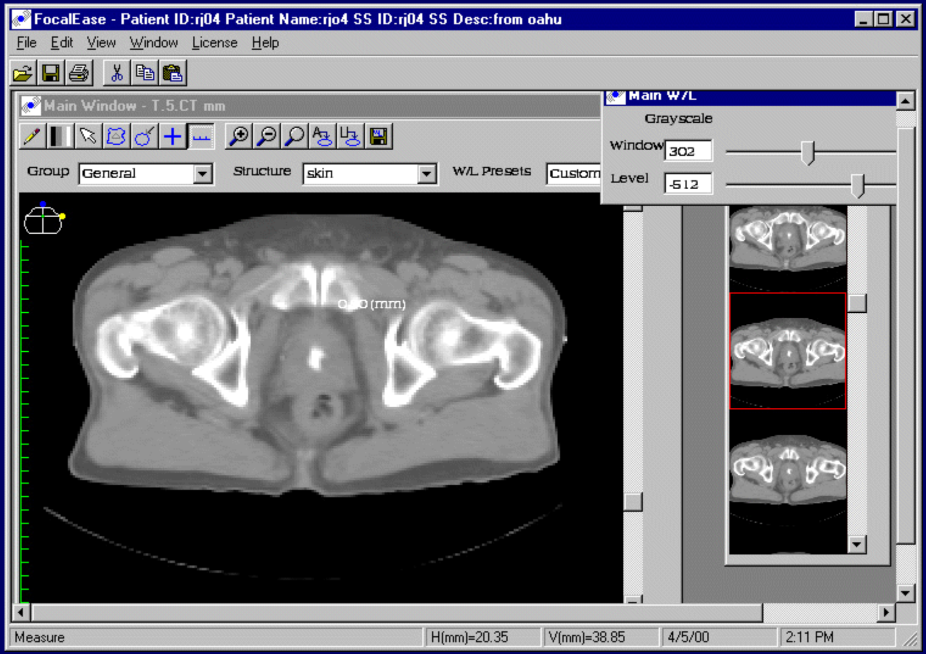


Future IGT System



IGT for Deformable Structures

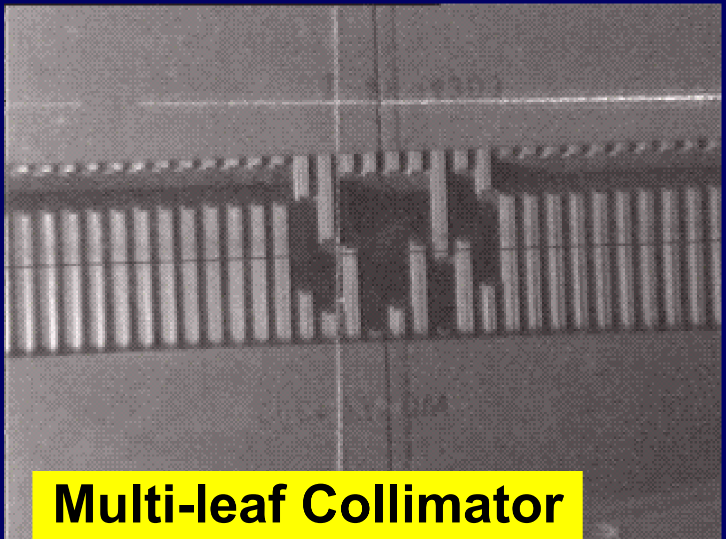




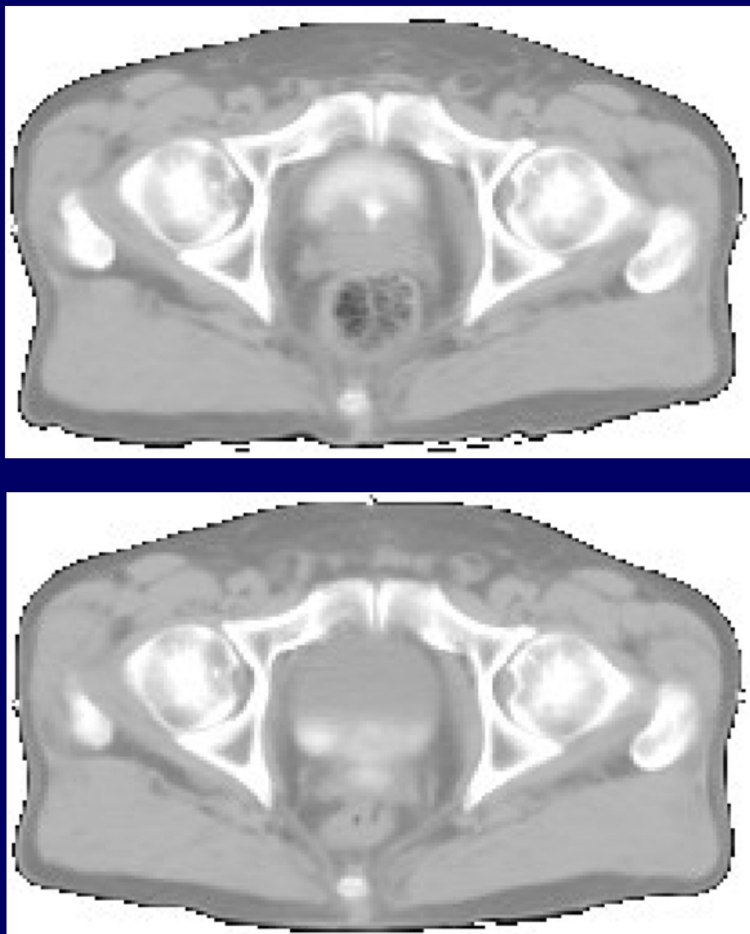
- **Examples:**
  - **Prostate, lung**
- **4D Systems needed**
  - **Visualization**
  - **Segmentation**
  - **Planning Tools**
  - **Delivery Tools**
- **Multiple motions and deformations**
  - **Intra-fractional motion: (lung, abdomen)**
  - **Inter-fractional motion: (organ deformations & change)**
  - **Motion of beam delivery system**

Current Method

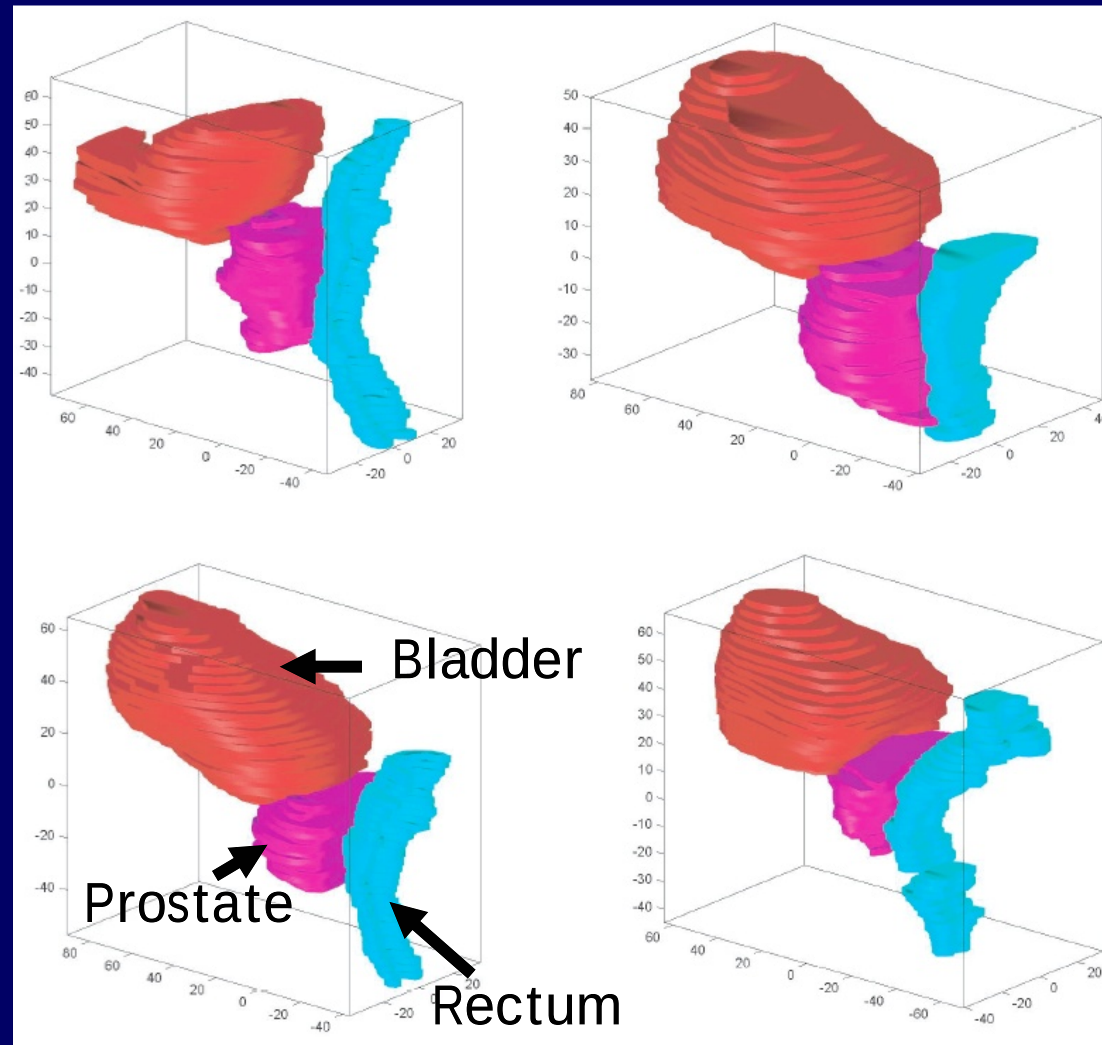
- Patient in restraint
- 3D CT “du jour” taken
- Patient-specific fractional dose calculations & adjustments
- Transfer patient to Linac for dose delivery
  - Conformal radio-therapy
  - Intensity-modulated radio-therapy



Challenges: Appearance & Shape Variability



Intra-patient variability,
10 days apart

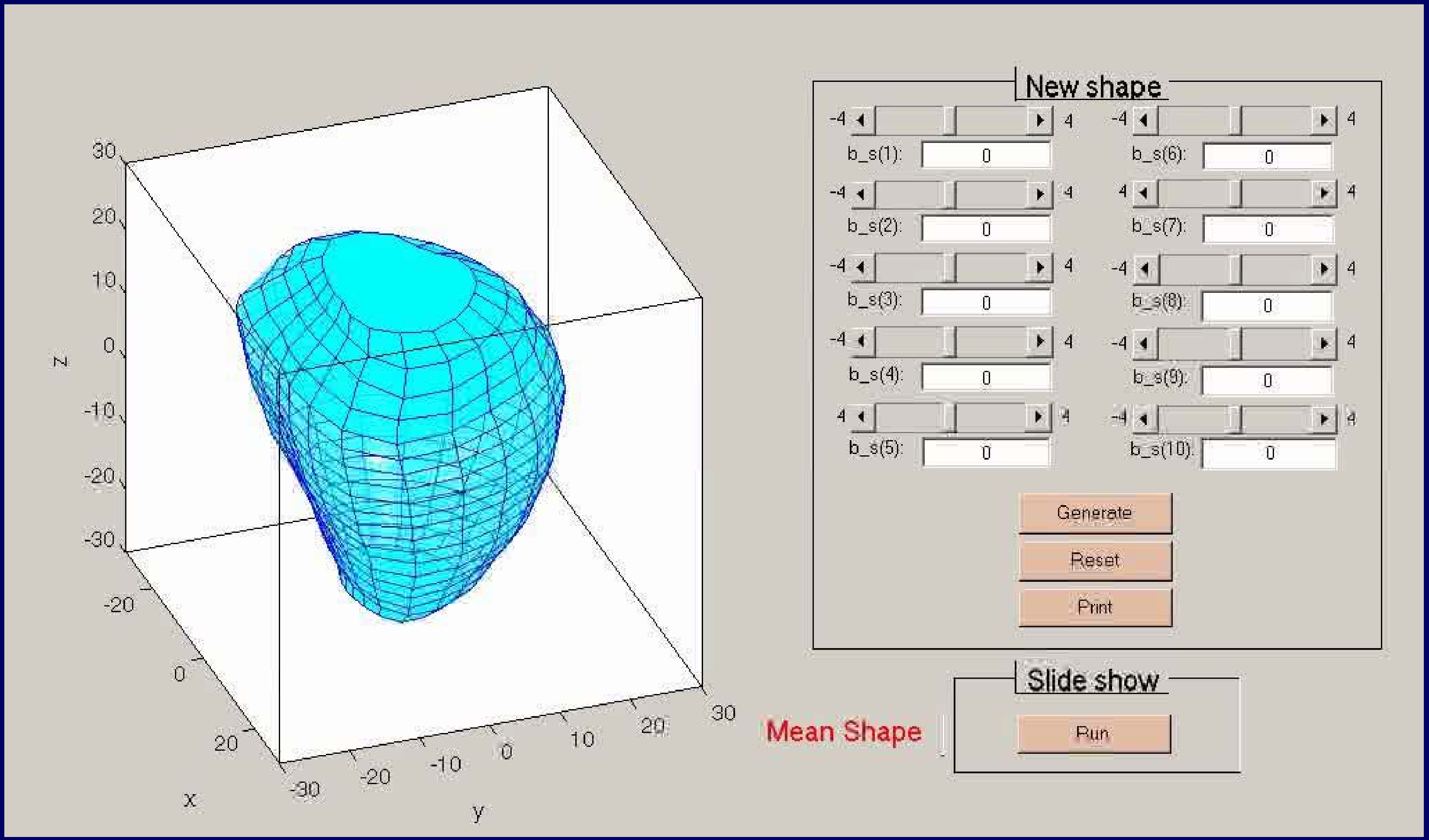


Inter-patient variability

Engineering Implications

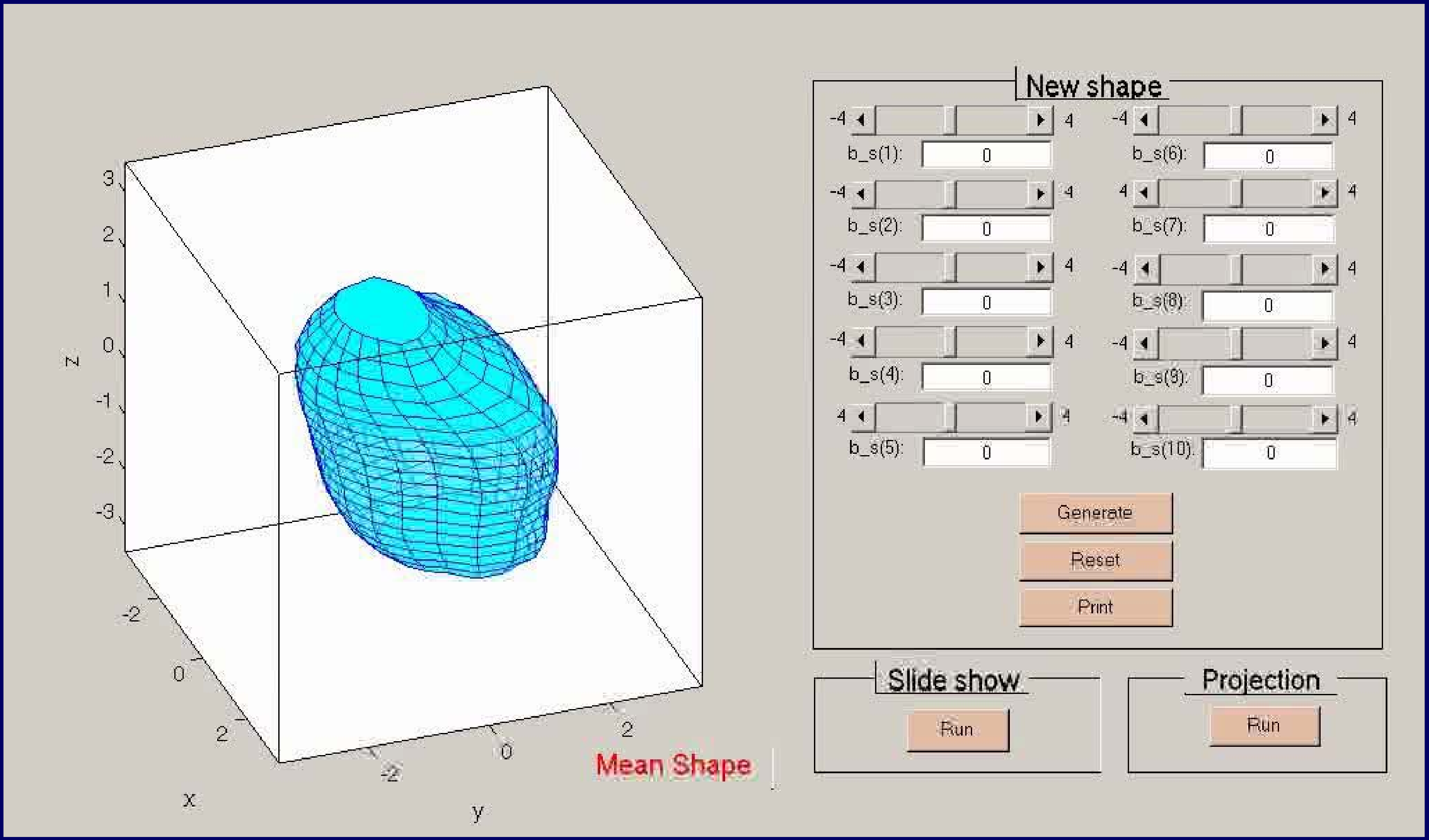
- Problem:
  - Given a new daily CT scan, just prior to a radiation fraction, segment the prostate, bladder, rectum, etc. for IGT and conformal avoidance
- Approach:
  - Construct effective low-dimensional models for intra- and inter-patient variability
  - Robust fitting of models to image data
  - Update the treatment plan
- Current Limitations:
  - Timeliness and verifiable accuracy of the model fitting
  - Expert manual segmentation takes 15-45 mins

Inter-Patient Modes of Variation



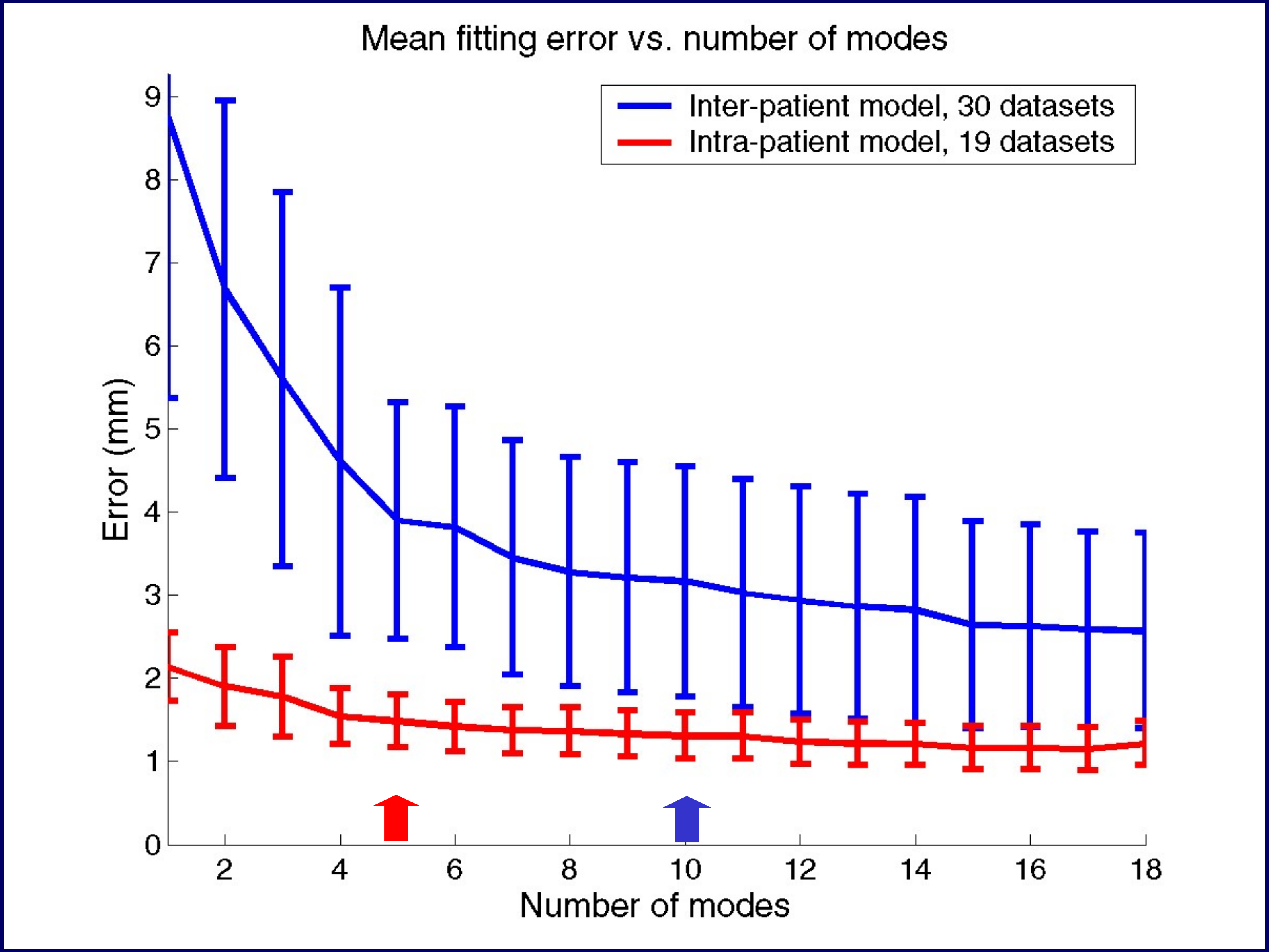
Modes learned from MGH data (25 scans)

Intra-Patient Modes of Variation

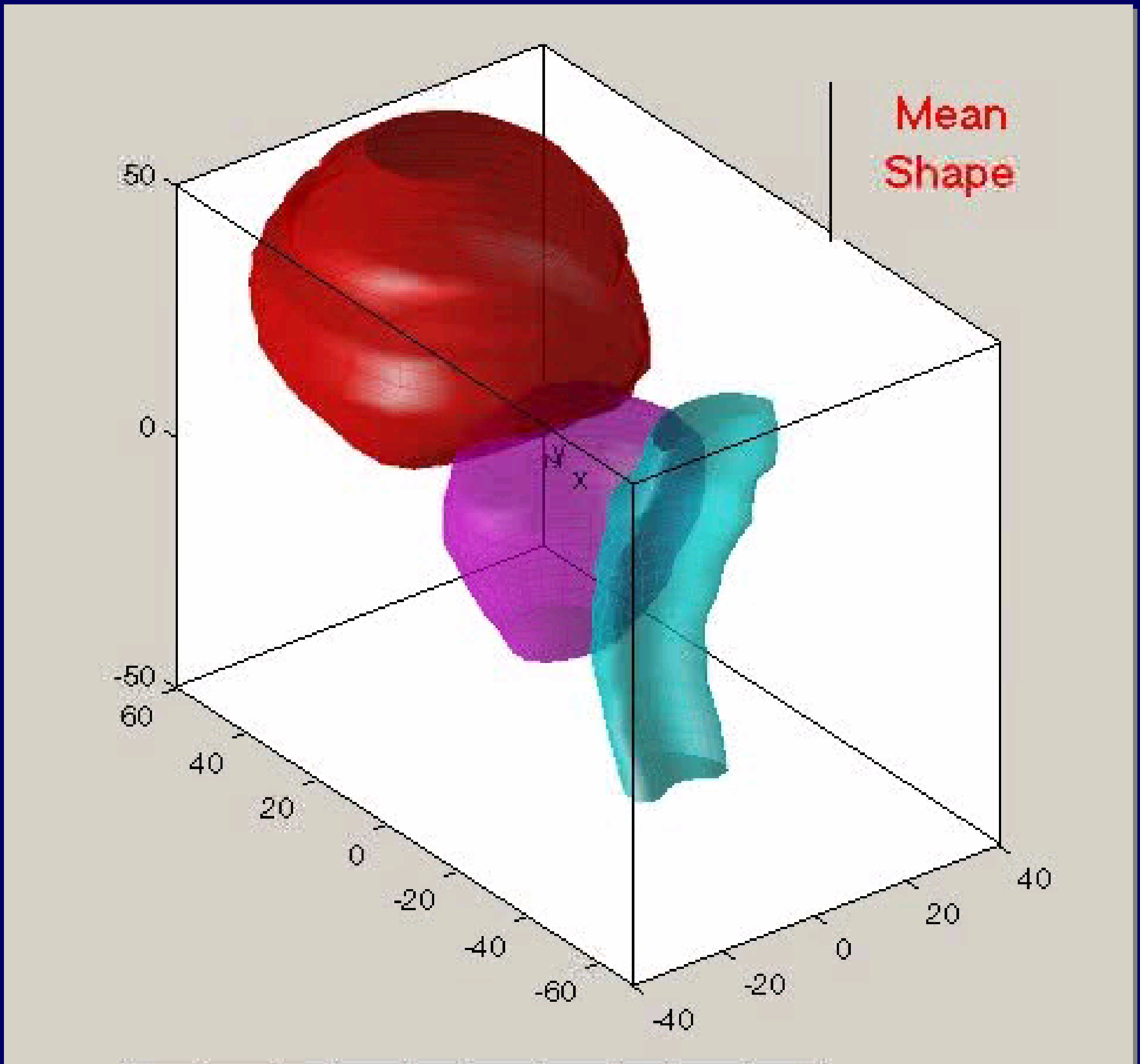


Modes learned from MSKCC data (19 scans)

How Many Modes to Consider?

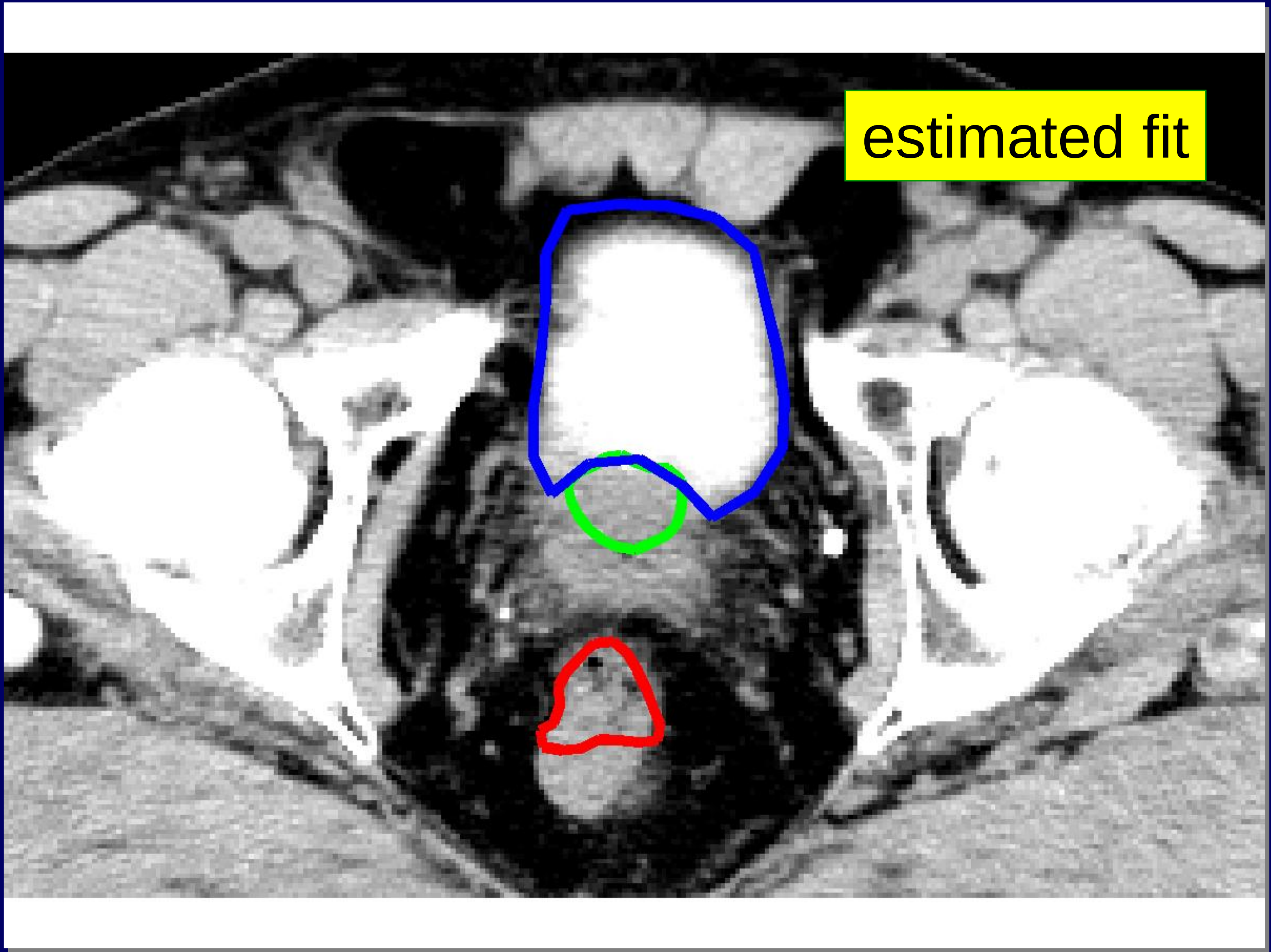


Joint Modeling of Variations



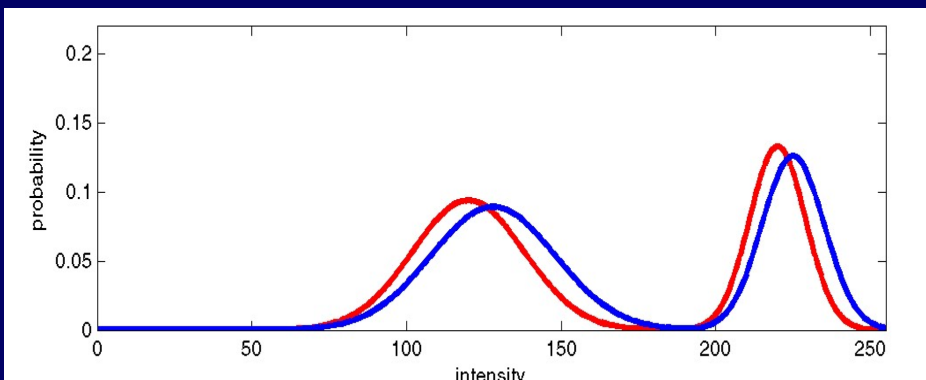
Joint shape model of prostate, bladder, and anterior rectal wall

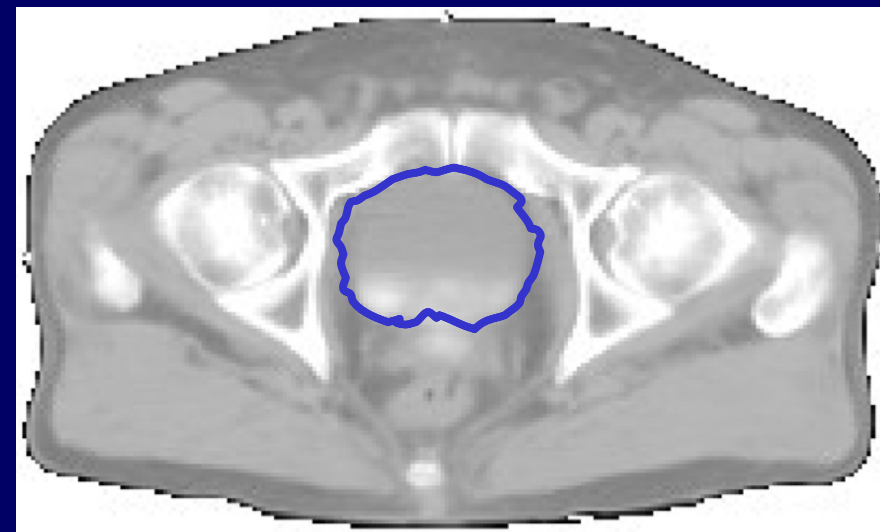
Fitting the Model to a New Image



Density Matching Algorithm

Find the enclosing surface $\omega(b)$ whose sample density *p* is closest to the model density *q, subject to position and shape constraints imposed by the coupling.*





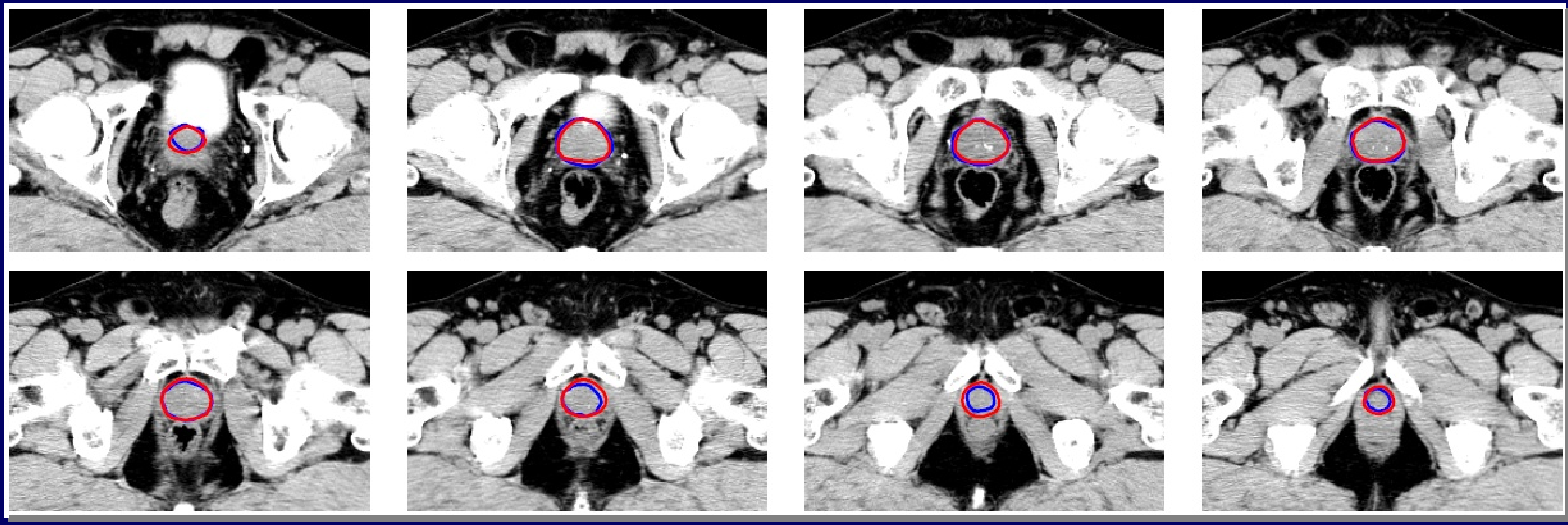
$$K(\omega(b)) = \int q(z) \log\left(\frac{q(z)}{p(z;\omega(b))} \right) dz$$

Kullback-Leibler divergence

sample density

model density

Prostate Model Fitting

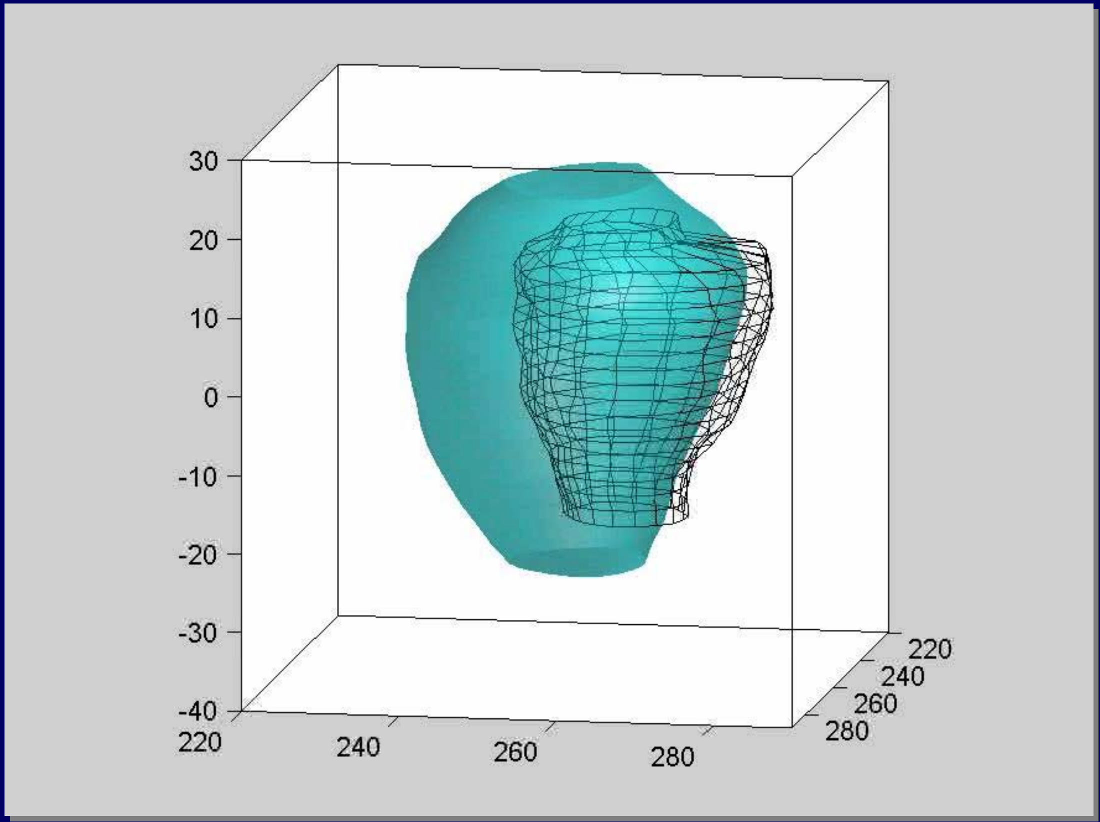


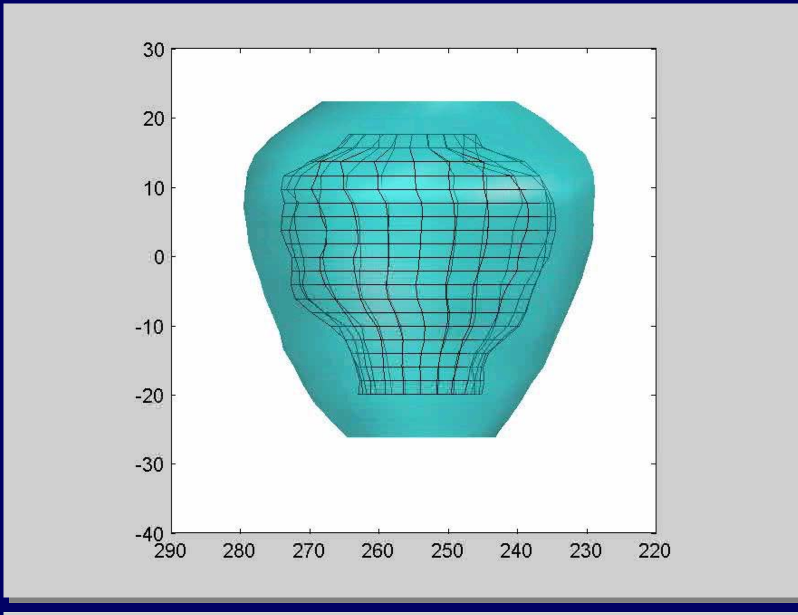
8 of 17 axial slices

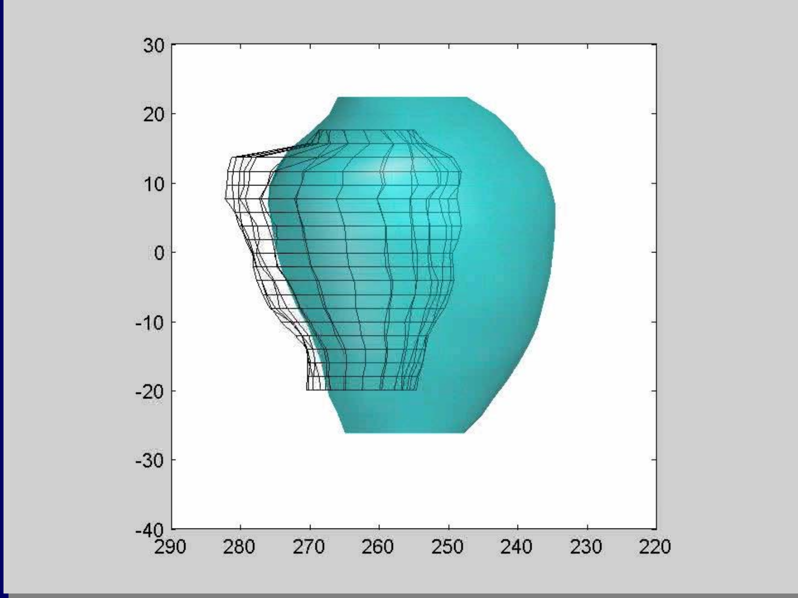
Blue = Ground Truth

Red = Algorithm Result (55 sec)

Prostate Model Fitting



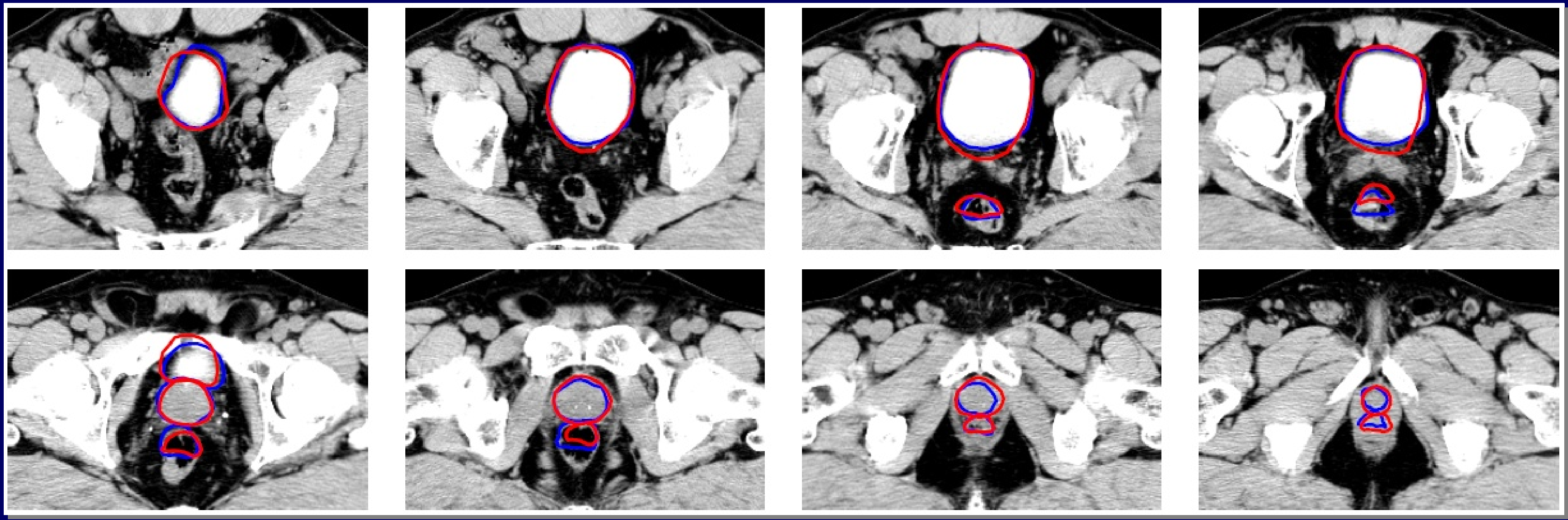




Volume error: 1.4e3 mm^3

Centroid error: 2.7 mm

Joint Model Fitting

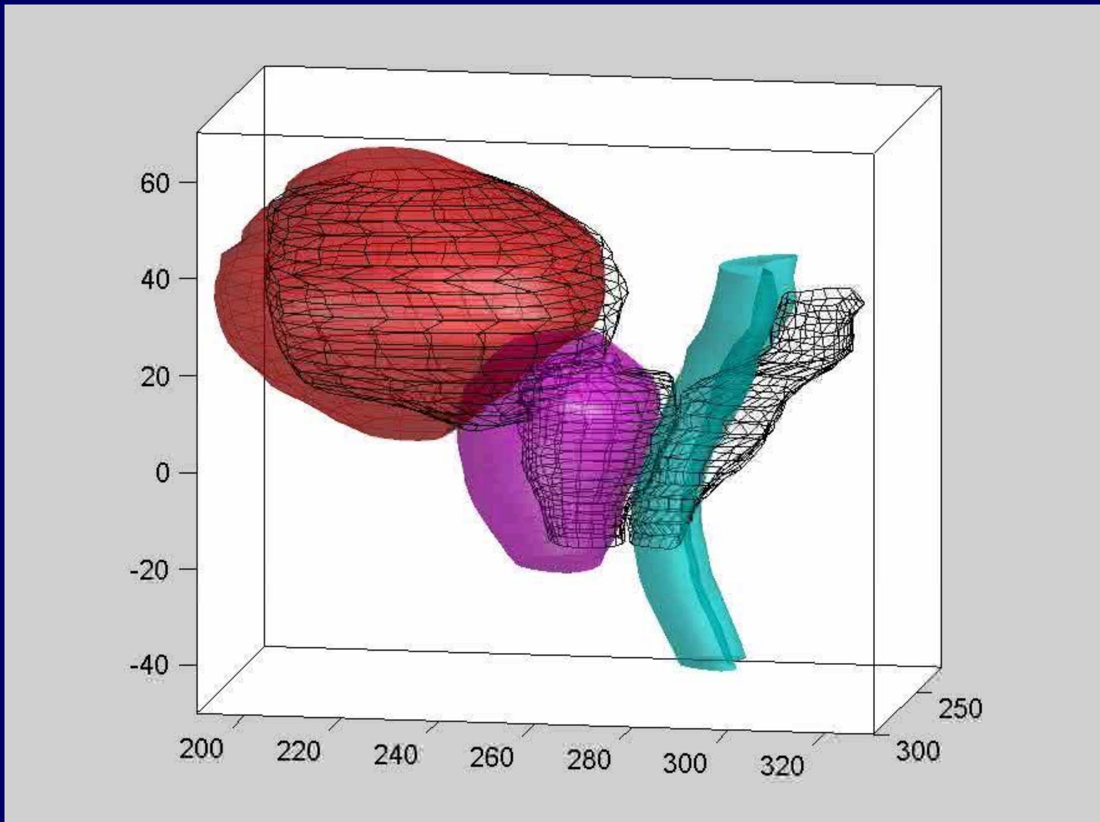


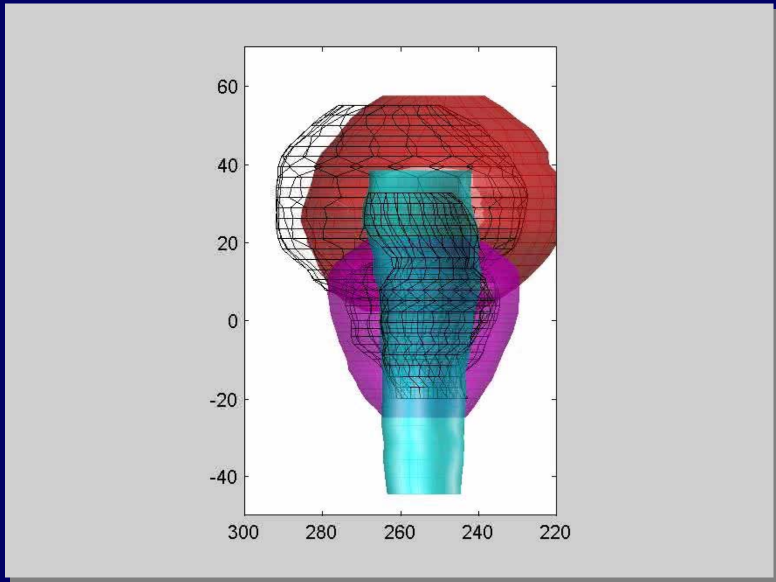
8 of 35 axial slices

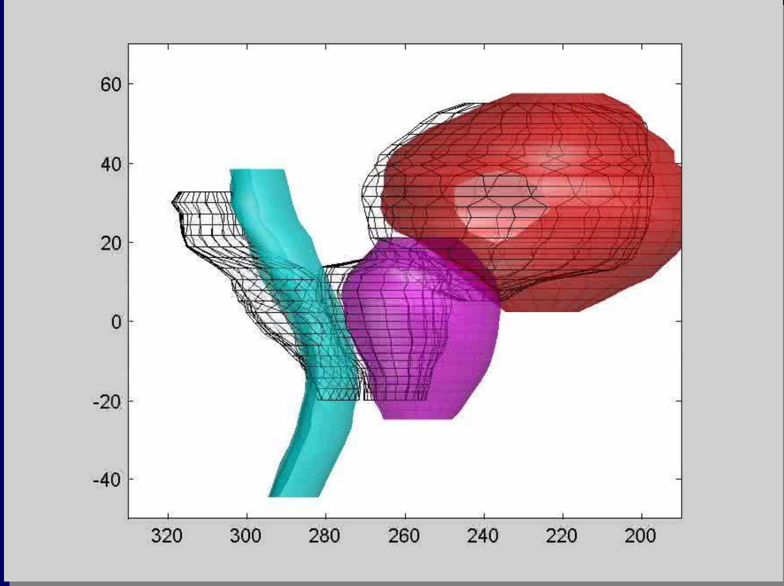
Blue = Ground Truth

Red = Algorithm Result (307 sec)

Joint Model Fitting

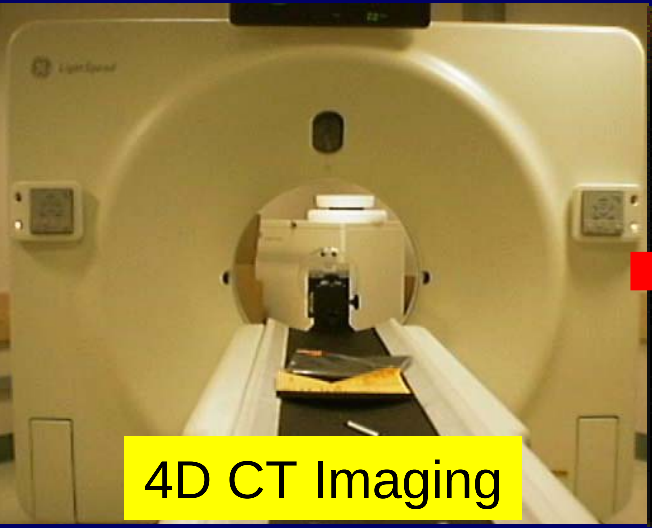


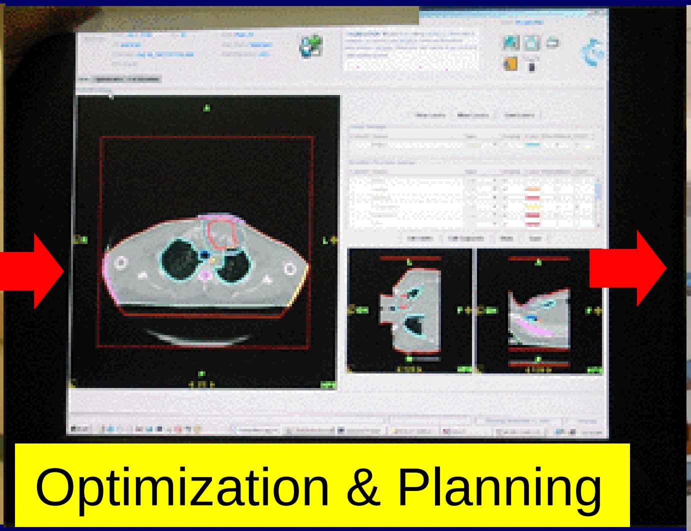




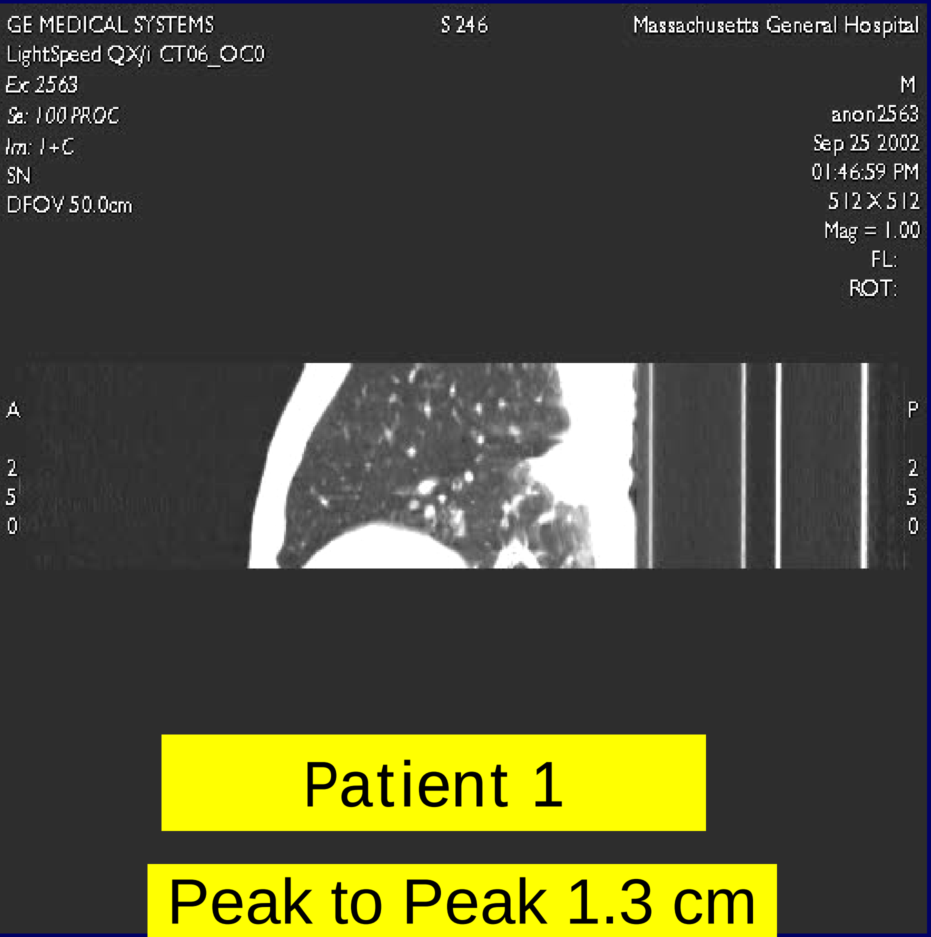
- Automatic fitting algorithm is 5 to 10X faster than manual contouring
- Accuracy comparable to manual segmentation
  - Can be edited as needed
  - Will enable accurate radiation delivery on day of treatment

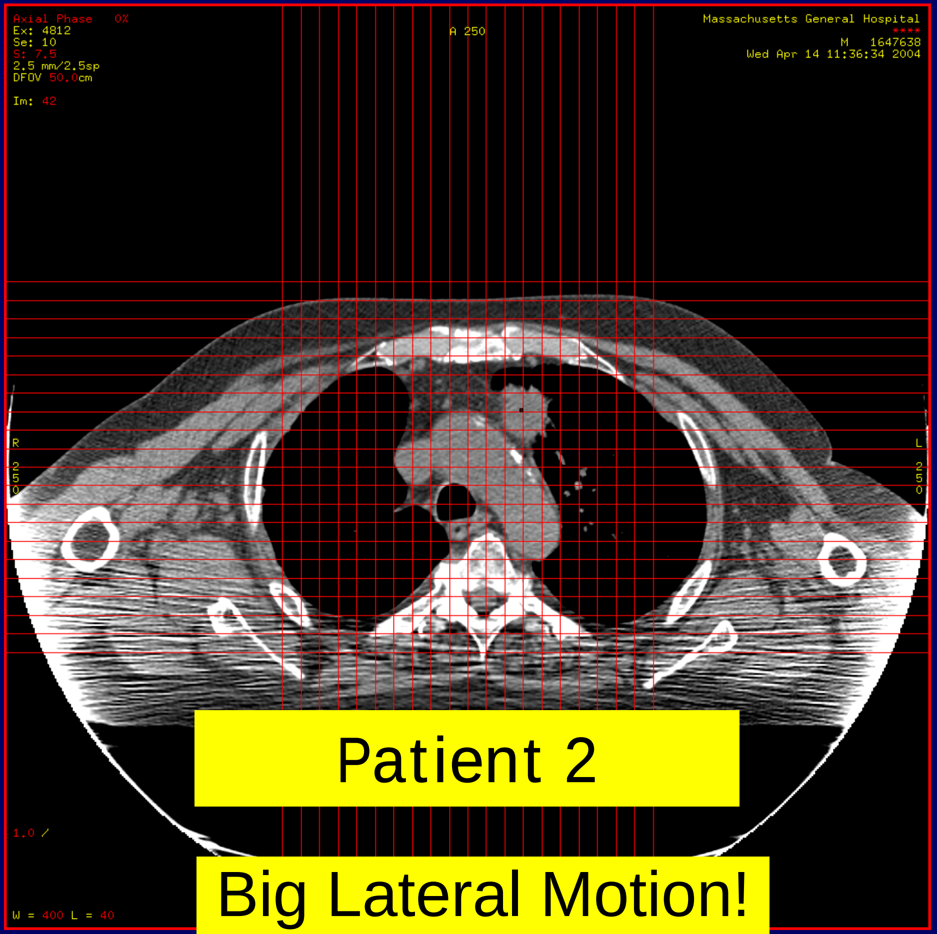
Towards 4D Systems





Lung Tumor Motion





Patient 1

Peak to Peak 1.3 cm

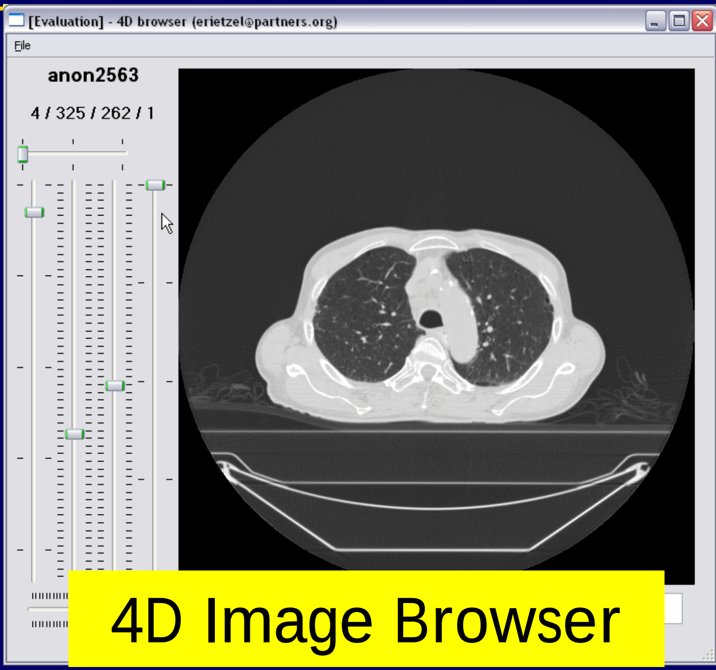
Patient 2

Big Lateral Motion!

Caveat: Single cycle looped!

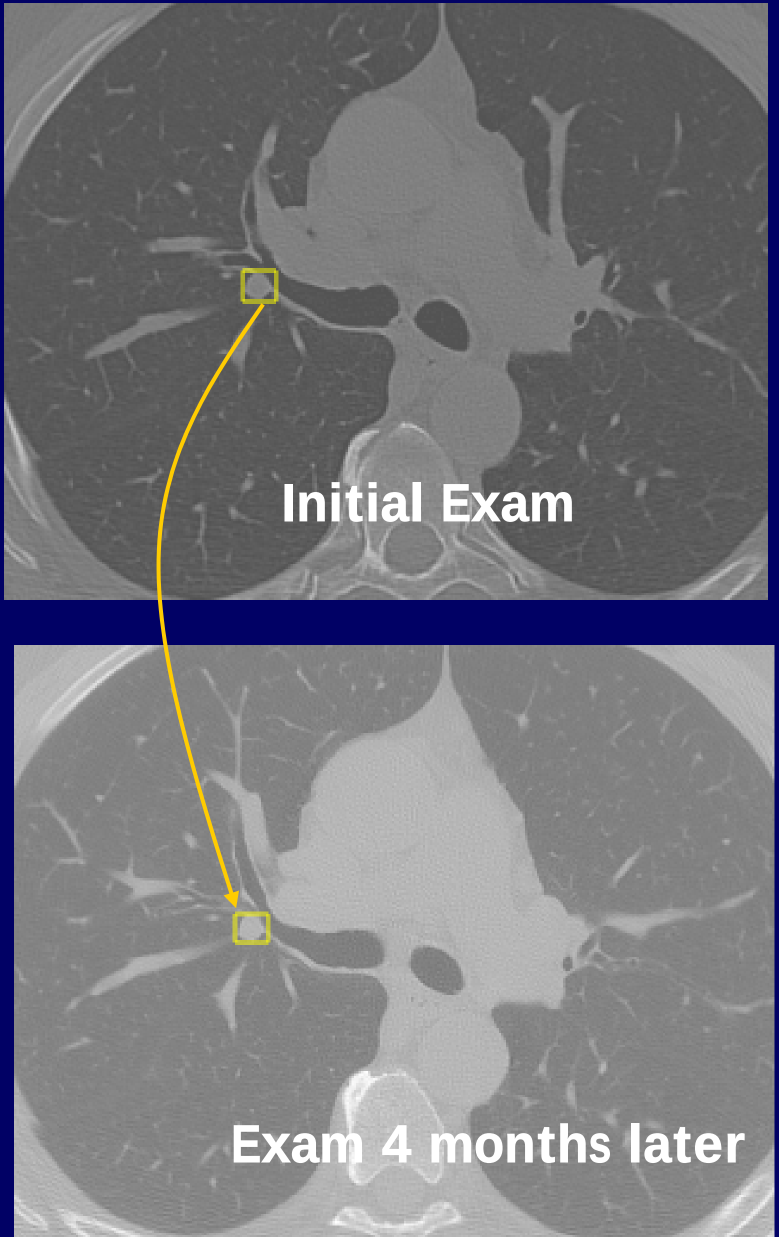
Challenges and Opportunities from 4D

- Artifact-free 4D Imaging
  - Need for motion-compensated reconstruction
- Effective visualization tools needed
- Effective and timely segmentation
  - Variability
  - Low contrast, poor edges
  - Massive data volume!
  - Verification/visualization tools
- 4D Dose calculation tools
- 4D Dose delivery systems
- Deformable registration with change intelligence



Improving Deformable Registration

- Temporal Registration of CT Lung Volumes
  for Improved Radiation Treatment
- Sub-millimeter accuracy desired notwithstanding lung deformations
- New B-spline registration algorithm: uncertainty driven hybrid of intensity-based and feature-based techniques
- Preliminary tests:
  - B-spline deformation model: 1.5mm accuracy
  - Current State of the Art 11.7mm accuracy



Summary

- Image-guided intervention is a powerful multi-disciplinary technology driver
  - Several disciplines
    - Computer vision
    - Imaging
    - Systems
    - Imaging Systems
    - Chemistry and Physics
    - High-speed Computing
  - Common, pervasive themes across applications
    - Need to enhance cross-disciplinary collaboration
    - Need to achieve greater efficiency in building new systems
      - Toolboxes, Frameworks, Taxonomy,…
    - Could be applied to several other areas:
      - Cell and tissue level work
      - Biotechnology automation
      - Environmental remediation

Thank you & keep in touch!

Badri Roysam

Professor of Electrical, Computer, & Systems Engineering

Associate Director, CenSSIS ERC

Rensselaer Polytechnic Institute

Troy, New York 12180

Phone: (518) 276 8067

Email: roysam@ecse.rpi.edu

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