Integrating Ontologies with Three-Dimensional Models of Anatomy

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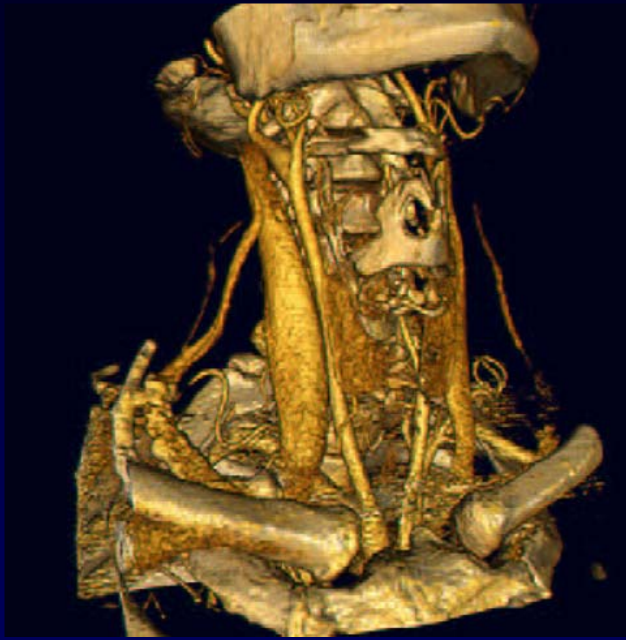
Projectile Injury

- Penetrating trauma responsible for many civilian deaths; major cause of battlefield fatalities
- Survivability after projectile injury depends on rapid acquisition & interpretation of knowledge
  - Need to know anatomic structures injured and extent of organ damage
  - Need to know physiological consequences
  - Need to make triage decision (immediate surgery, medi-vac, observe, etc.)

Objectives

- Build computable model of human anatomy
  - Predict direct anatomic injuries
  - Predict propagation of injuries
- Develop intelligent applications
  - On-scene diagnosis
  - Assist triage decisions
- Provide graphical display of anatomy, bullet trajectory, and tissue damage

3-D Geometric Models

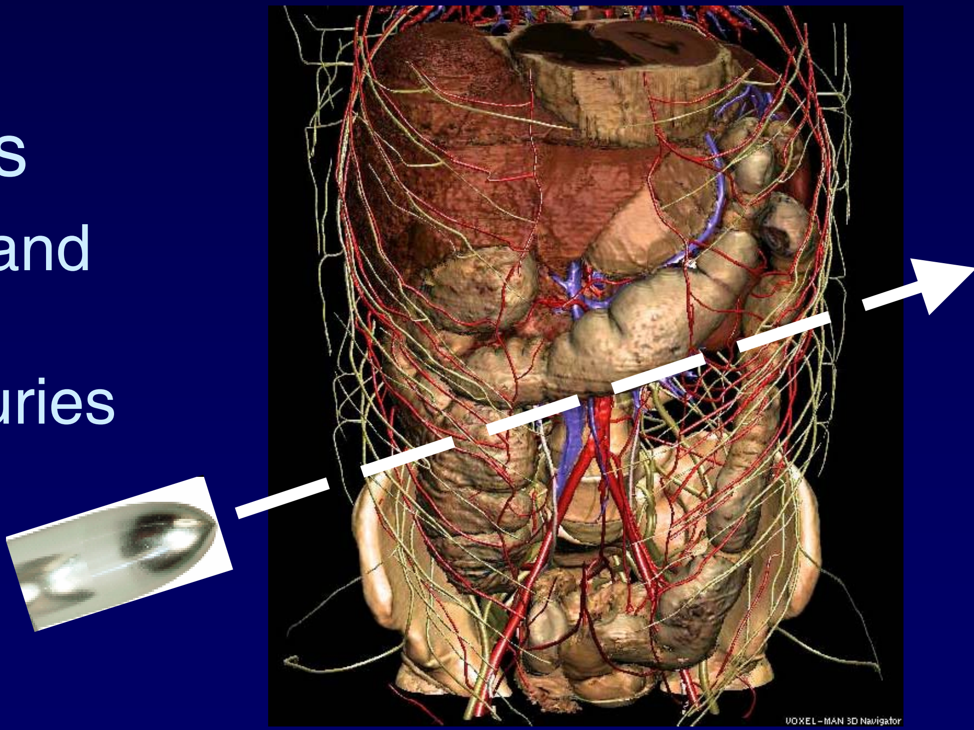


- Many prior applications
  - Surgical simulation, planning
  - Medical visualization
  - Teaching
- Encode spatial geometric information
- Contain no knowledge about contents of these models
  - Identity of anatomic structures
  - Tissue properties
  - Physiological status of organs

Requirements

- Intelligent applications for injury:
  - 3-D geometric data
  - Knowledge pertinent to injuries
  - Reasoning services

    Use geometric data and knowledge to predict consequences of injuries



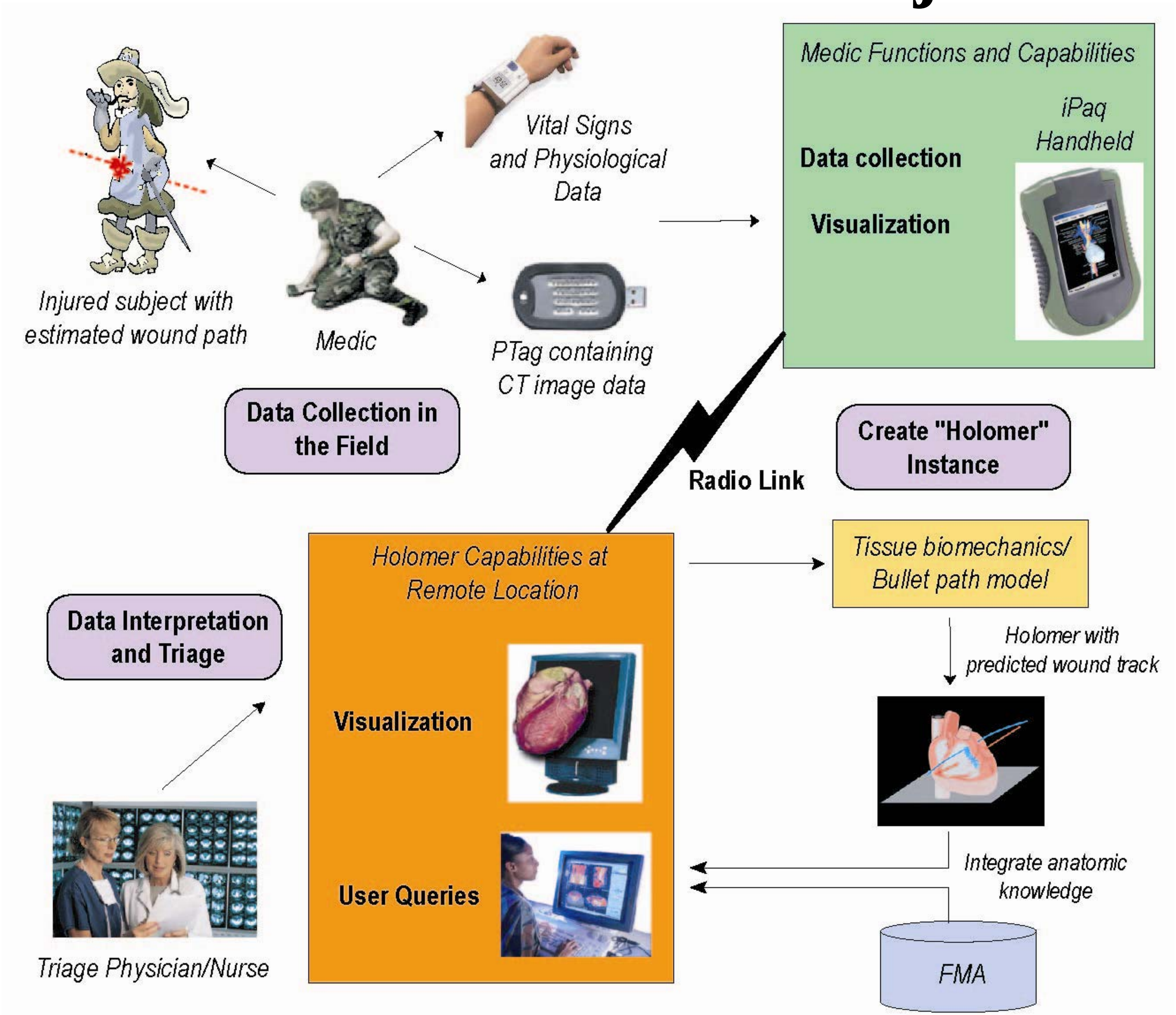
Need Variety of Knowledge

- Anatomic knowledge
  - Where do organs lie in the body?
  - What organs are fed by different arteries?
  - What are the subparts of an organ?
- Biomechanical knowledge
  - What are the tissue material properties of an organ?
- Tissue injury knowledge
  - How do different organs respond to injury?

Need Variety of Reasoning Services

- Which organs were directly injured?
- What additional tissue damage will occur as the primary injury propagates?
- How will physiological parameters be altered by the injury?
- How should the subject be treated?

The Virtual Soldier Project



Approaches

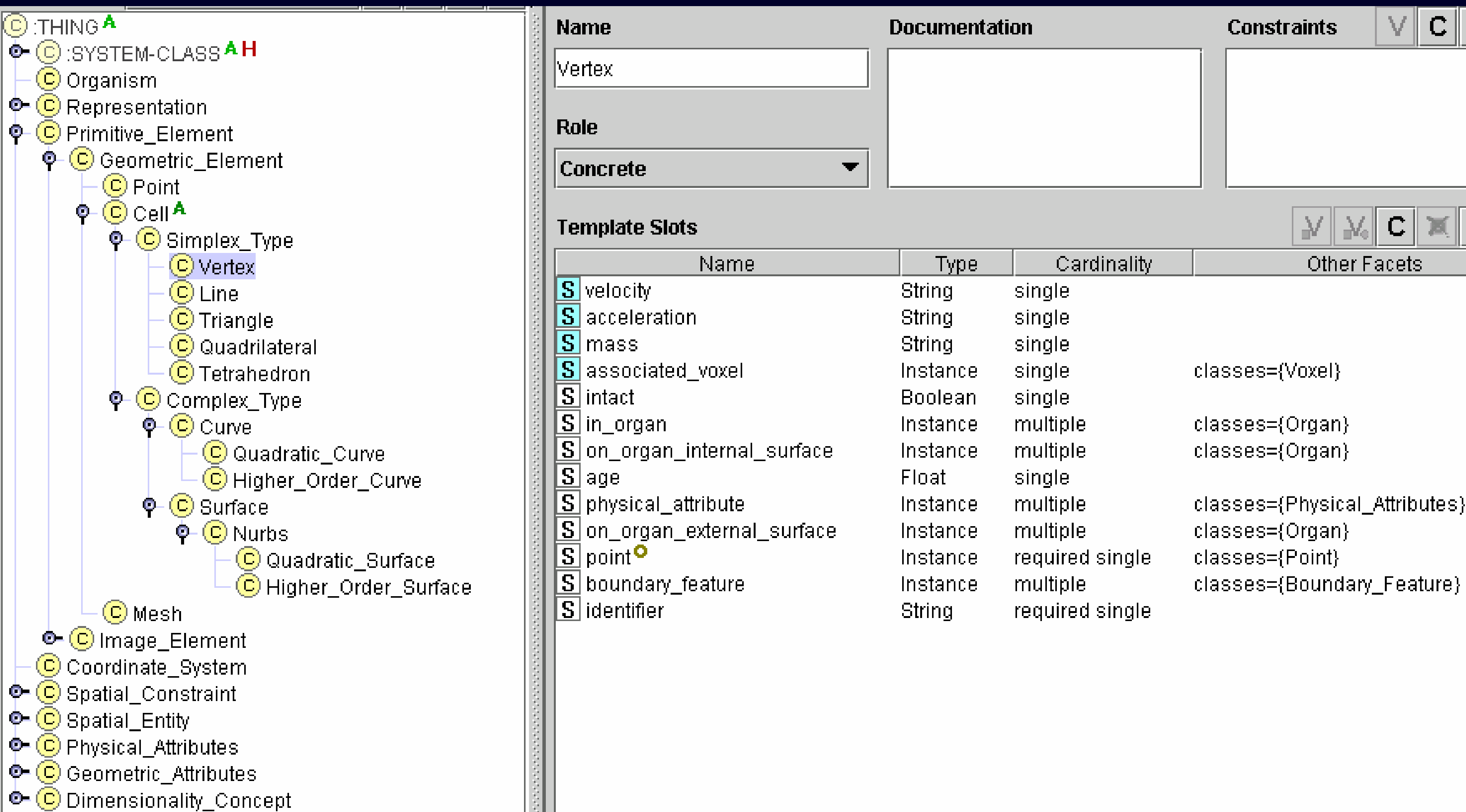
- Make knowledge explicit and computable
  1. Use ***ontologies*** for knowledge representation
     - Useful in rich and complex domains
     - Can reuse existing knowledge sources
- Integrate patient data and canonical knowledge
  2. Create patient-specific models
  3. Develop reasoning services

1. Ontologies for knowledge representation

Knowledge Sources

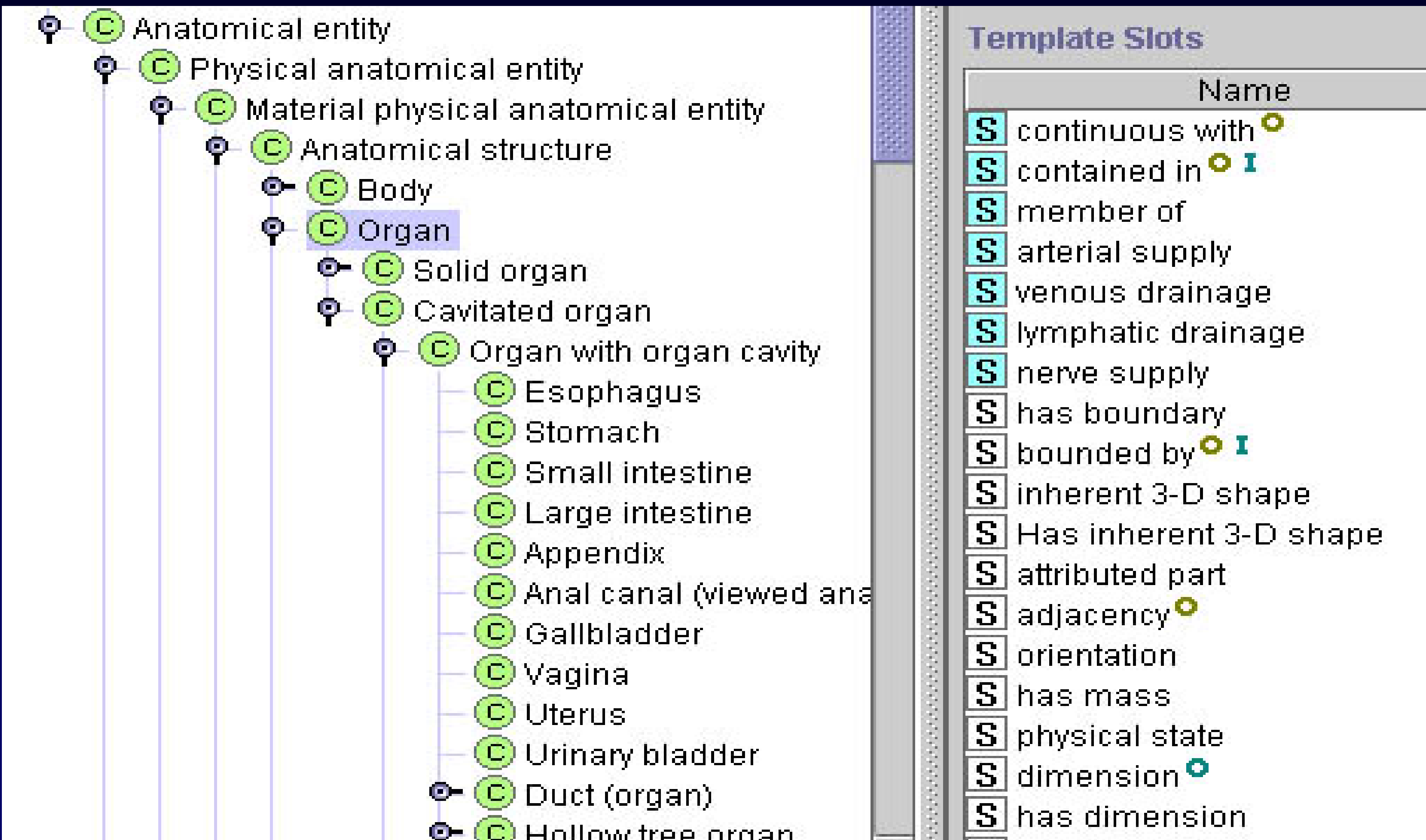
- Geometric Knowledge
  - Geometry ontology constructed to describe computer graphics principles
  - Specifies data structures used to represent geometric models
- Anatomic Knowledge
  - Foundational Model of Anatomy (FMA) ontology
  - Specifies anatomical entities and relationships (e.g., partonomies, continuities, adjacencies)
  - Logical as opposed to spatial model

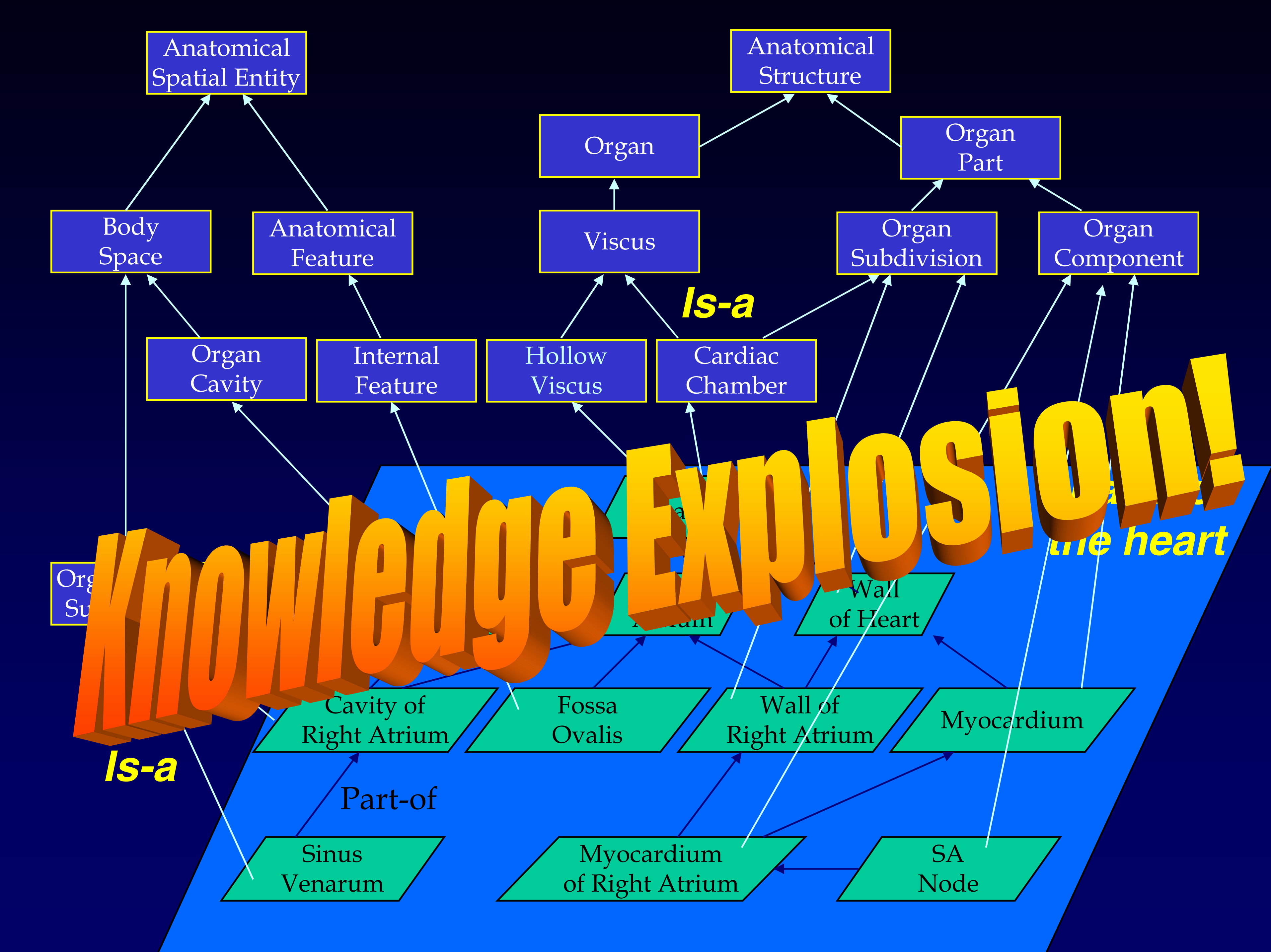
Ontology of Geometric Modeling



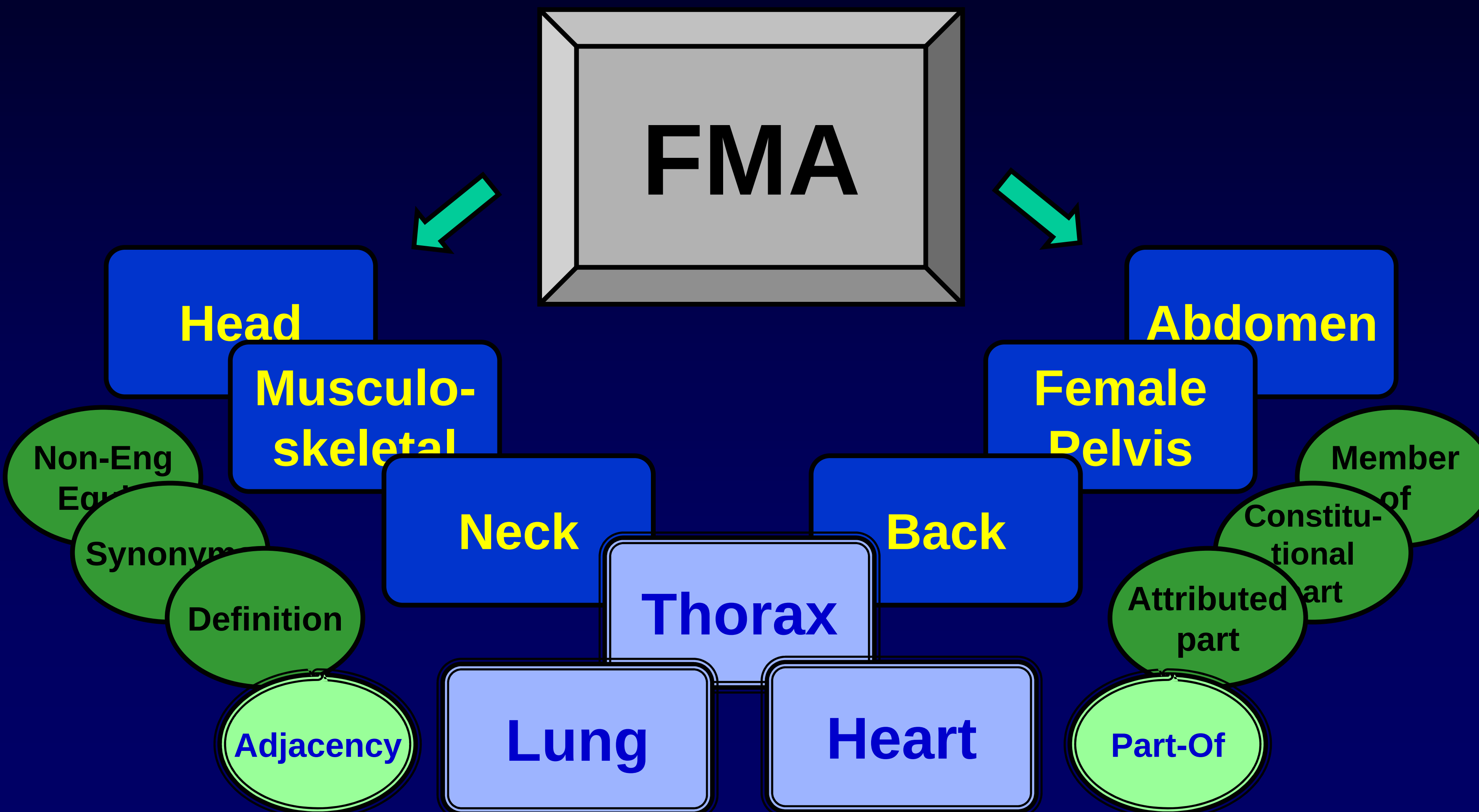
Foundational Model of Anatomy

Ontology **Slots**




Anatomical Spatial Entity
Anatomical Structure
Organ
Organ Part
Body Space
Anatomical Feature
Viscus
Organ Subdivision
Organ Component
Is-a
Organ Cavity
Internal Feature
Hollow Viscus
Cardiac Chamber
Knowledge Explosion!
the heart
Wall of Heart
Cavity of Right Atrium
Fossa Ovalis
Wall of Right Atrium
Myocardium
Is-a
Part-of
Sinus Venarum
Myocardium of Right Atrium
SA Node

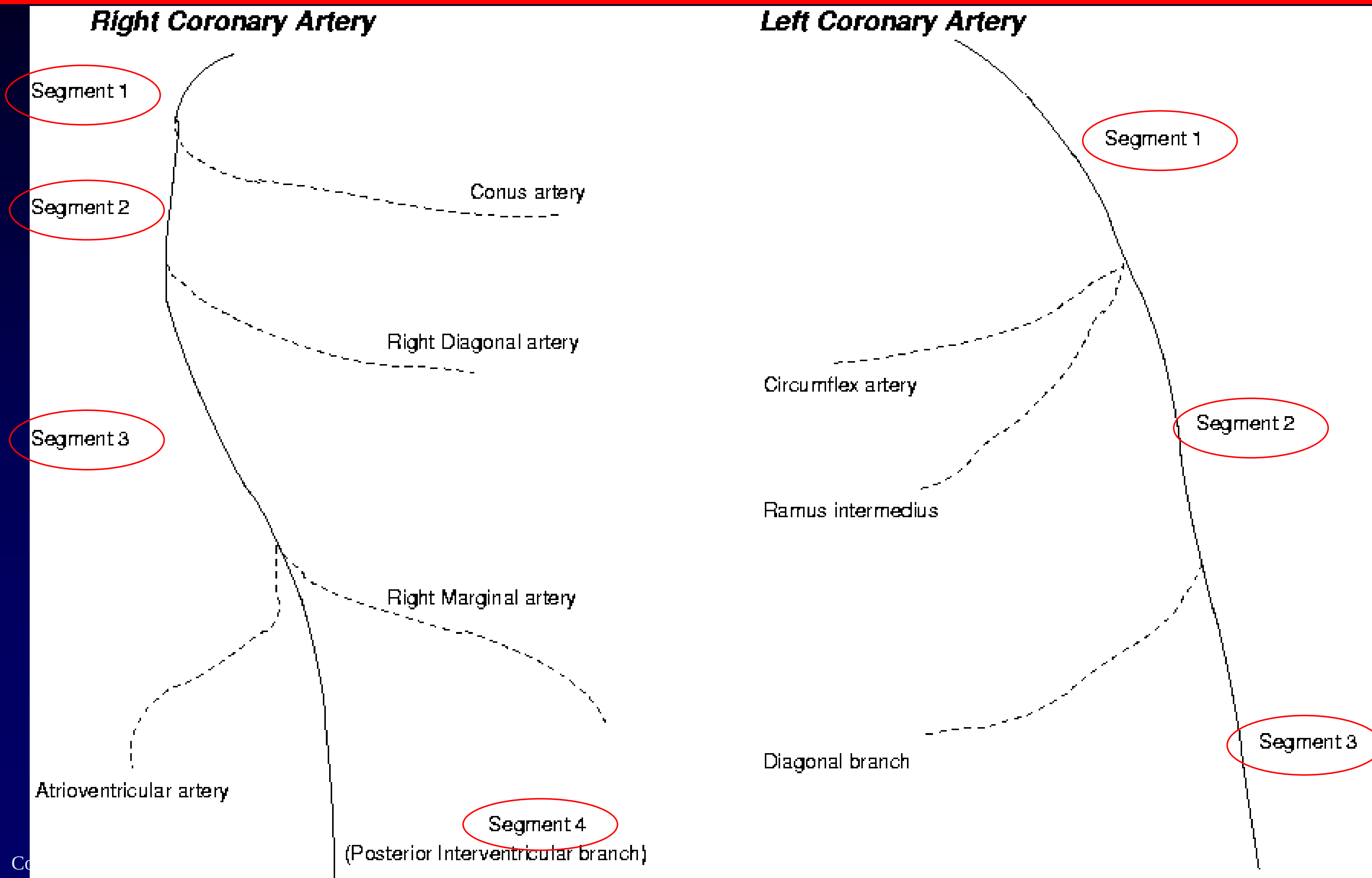
Ontology Views



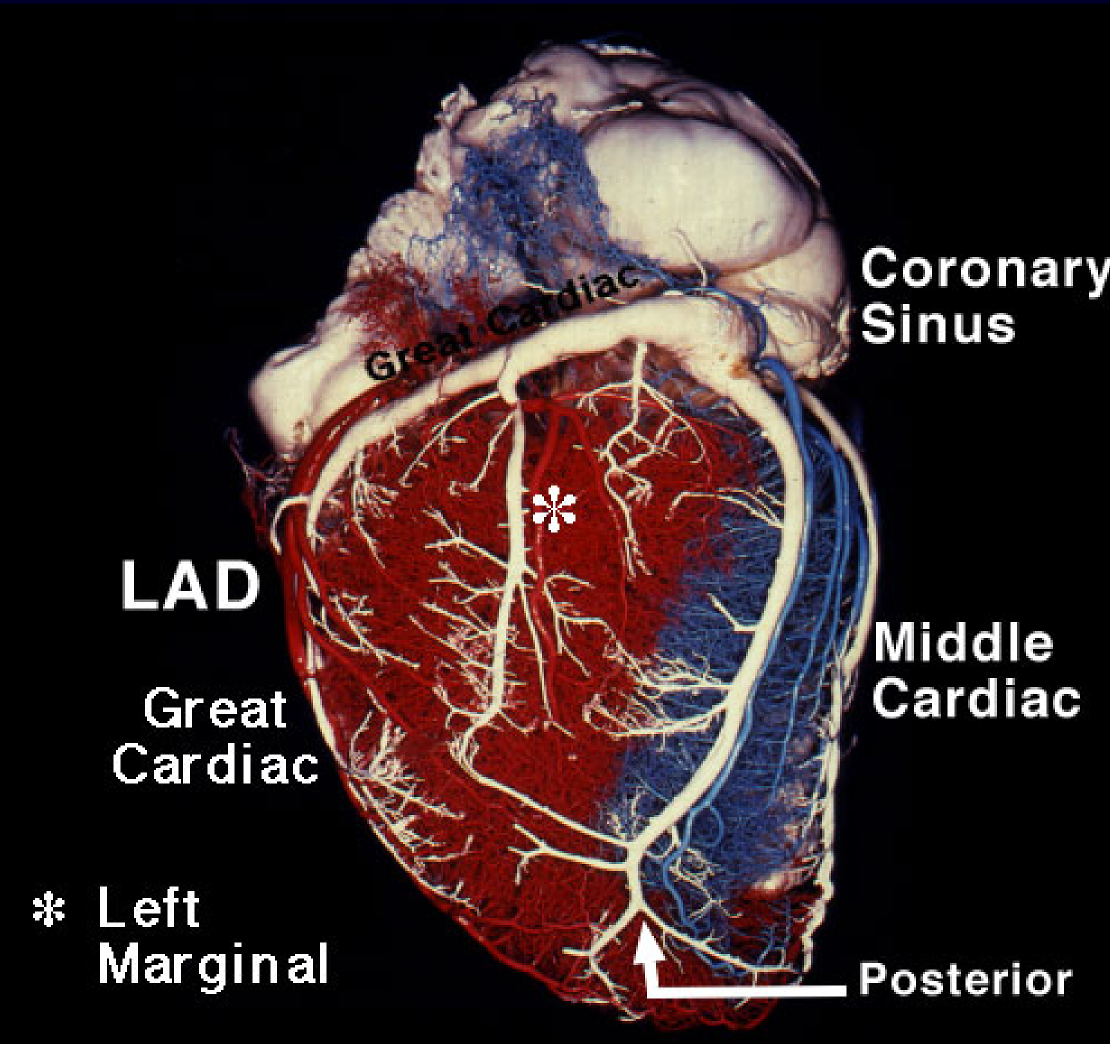
Ontology Views for Reasoning

- Catalog of organs; controlled vocabulary of names
- Organ parts and compositionality
- Adjacencies for organs and organ parts
- Connectivity
- Containment
- Arterial supply & regional organ perfusion

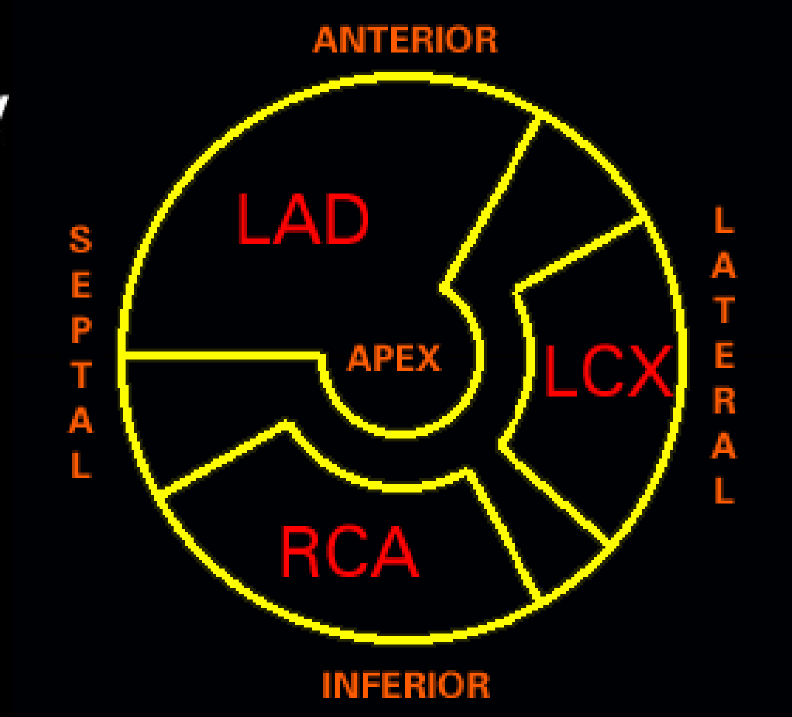
Organ Sub-Parts: Artery Segments



Subdivision of Myocardial Regions Based on FMA Knowledge



Regions of Left Ventricle



Other Knowledge Sources

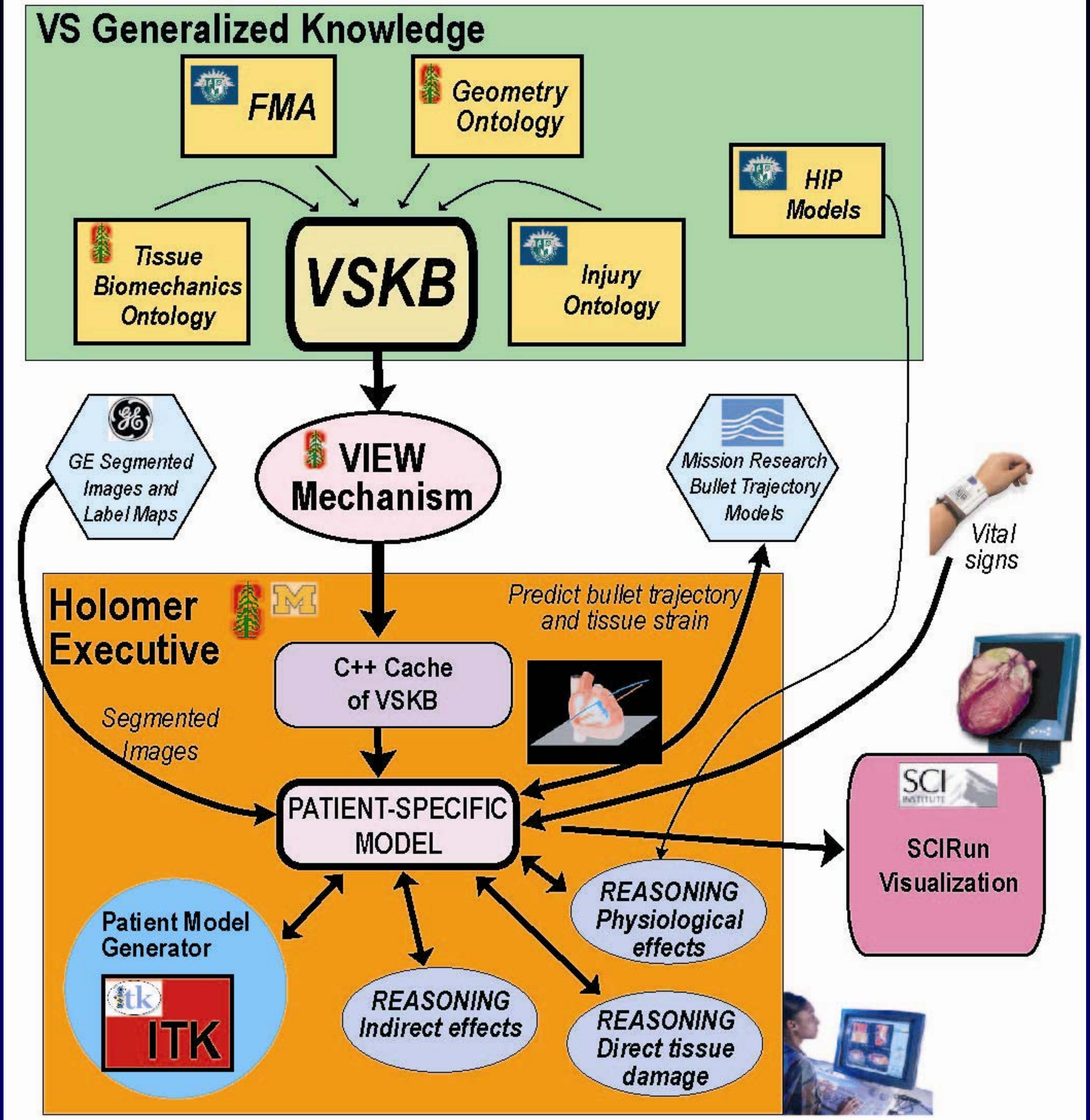
- Biomechanics ontology
  - Tissue material properties
  - Useful for predicting trajectory of projectiles
- Tissue injury ontology
  - Taxonomy of types of injuries
- Physiology ontology
  - Knowledge of how injuries affects circulatory dynamics

“VSKB” = all pertinent ontologies in VS Project

2. Creating patient-specific models

A "Patient-Specific Model (PSM)"

- Contains data specific to the patient at a point in time
  - Patient-specific geometry
  - Description of projectile path of damage
  - Vital signs
- Links to canonical ontologies
- Provides API for queries, reasoning services, and visualization routines



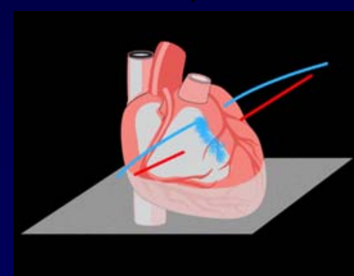
VS Generalized Knowledge
FMA
Geometry Ontology
HIP Models
Tissue Biomechanics Ontology
VSKB
Injury Ontology
GE Segmented Images and Label Maps
VIEW Mechanism
Mission Research Bullet Trajectory Models
Vital signs
Holomer Executive
Predict bullet trajectory and tissue strain
C++ Cache of VSKB
Segmented Images
PATIENT-SPECIFIC MODEL
SCI INSTITUTE
SCIRun Visualization
REASONING Physiological effects
Patient Model Generator
itk
ITK
REASONING Indirect effects
REASONING Direct tissue damage

Building Geometric/Knowledge Models

Biomechanical Knowledge

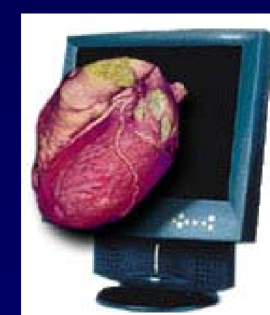
FMA

Segmented
CT Volume Data
of the Chest
(or Visible Human
Image set)



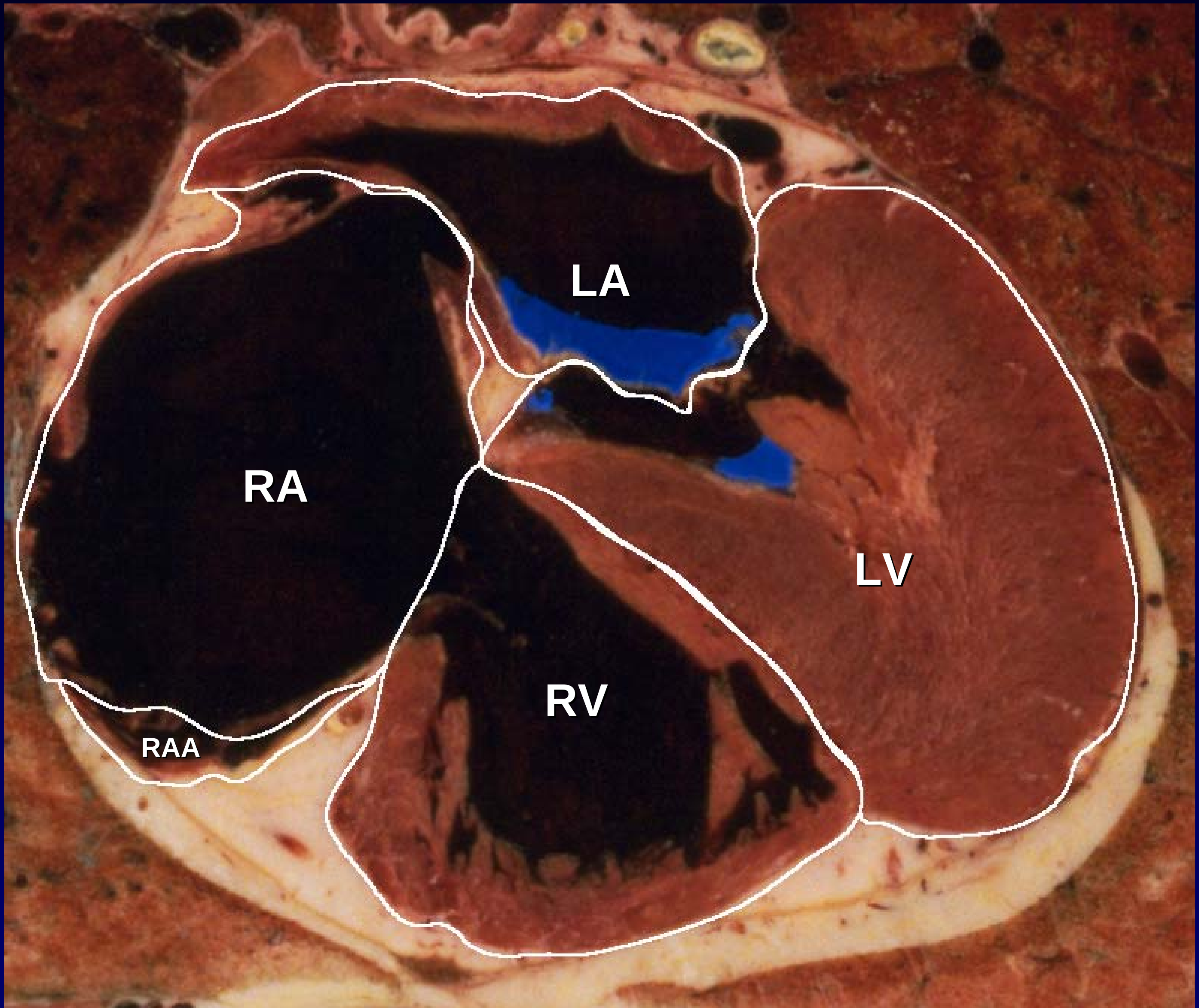
3-D Geometric
Model

Reasoning

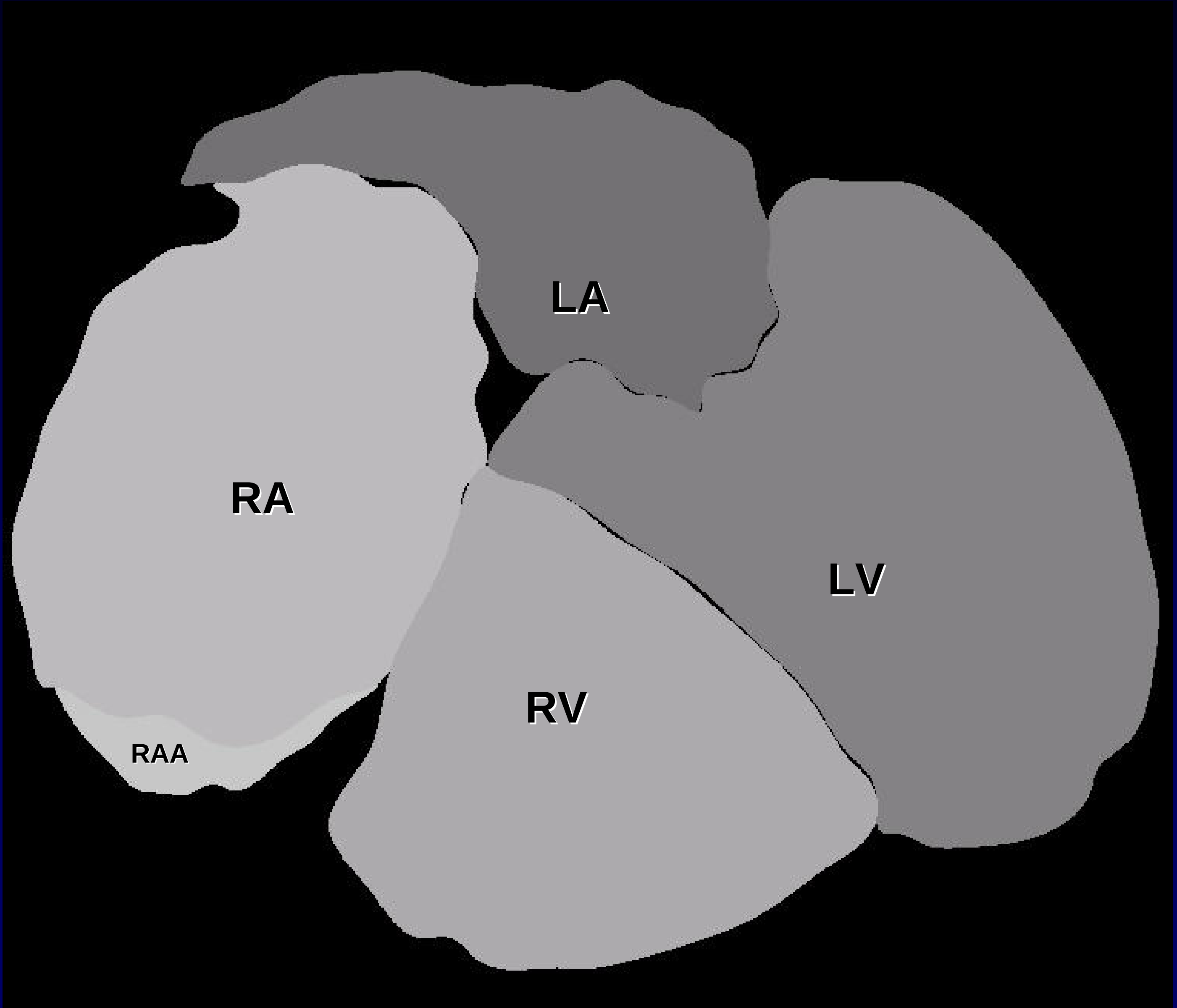


Display and
User Queries

Visible Human Raw Data



Visible Human Segmented Data



3. Developing reasoning services

Reasoning Tasks

- Predict organ injury
- Predict physiological consequences of organ injury
- Classify injuries (trauma score; ICD-10)
- Predict survival
- Decision support
  - Diagnosis and triage
  - Recommend additional tests

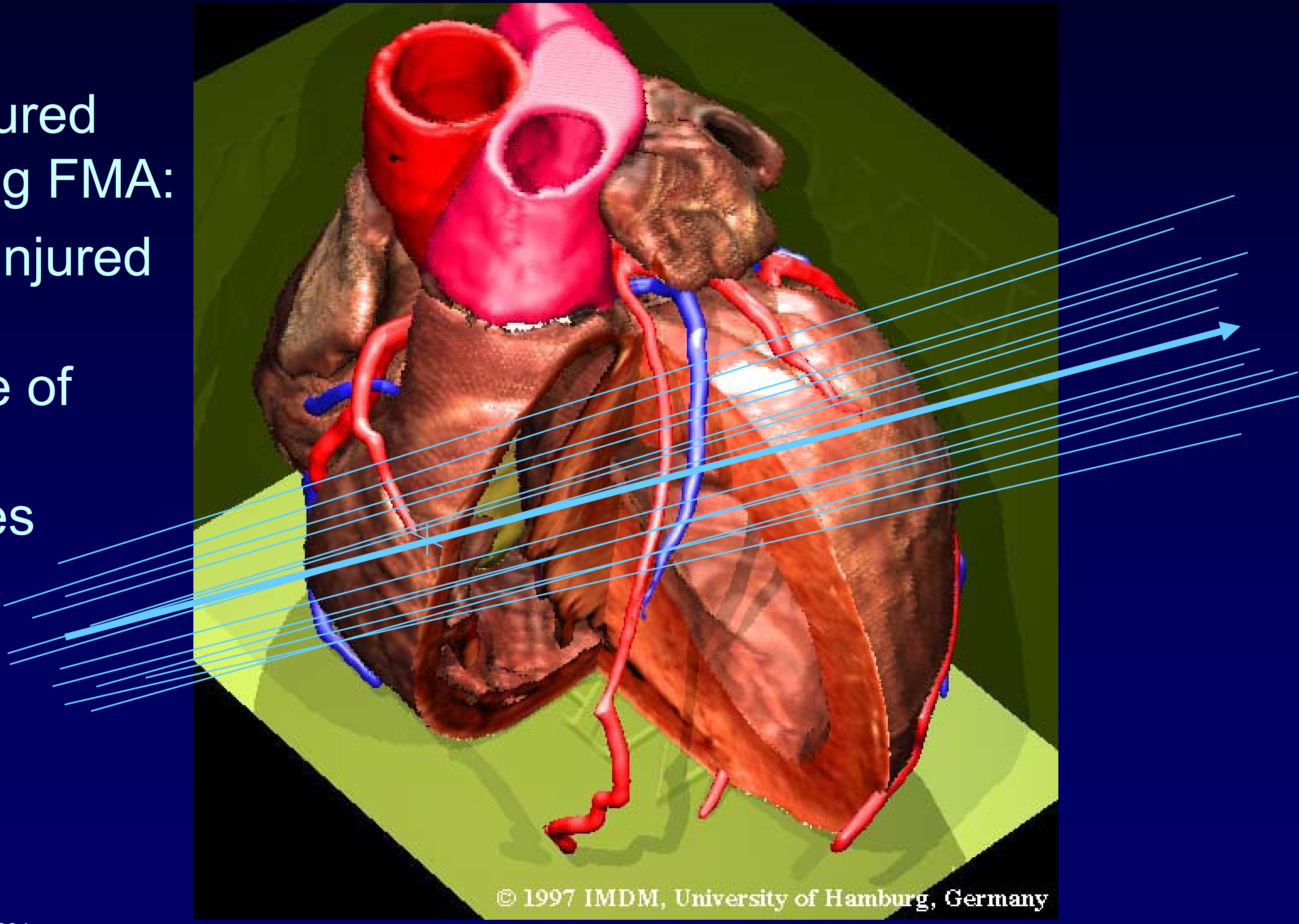
Predicting Organ Injury

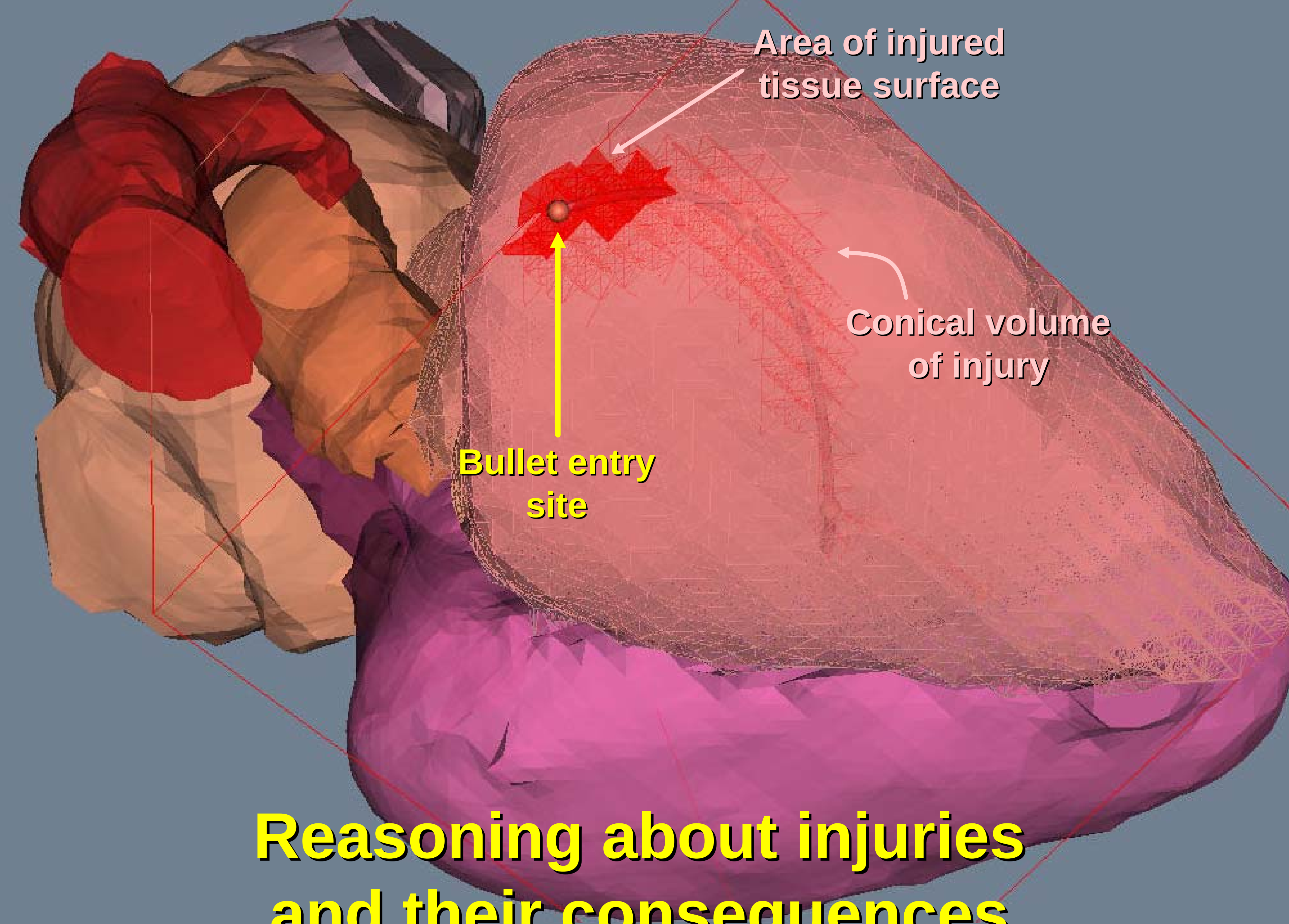
- Direct organ injury
  1. Organs visible on CT: injury predicted by intersection with “cone of damage”
  2. Organs not visible on CT: inferred from adjacency knowledge in FMA
- Propagation of organ injury
  3. Use knowledge of arterial anatomy to infer downstream consequences of arterial damage

Injury Caused by “Cone of Damage”

We infer injured tissues using FMA:

- names of injured tissues
- knowledge of organ adjacencies



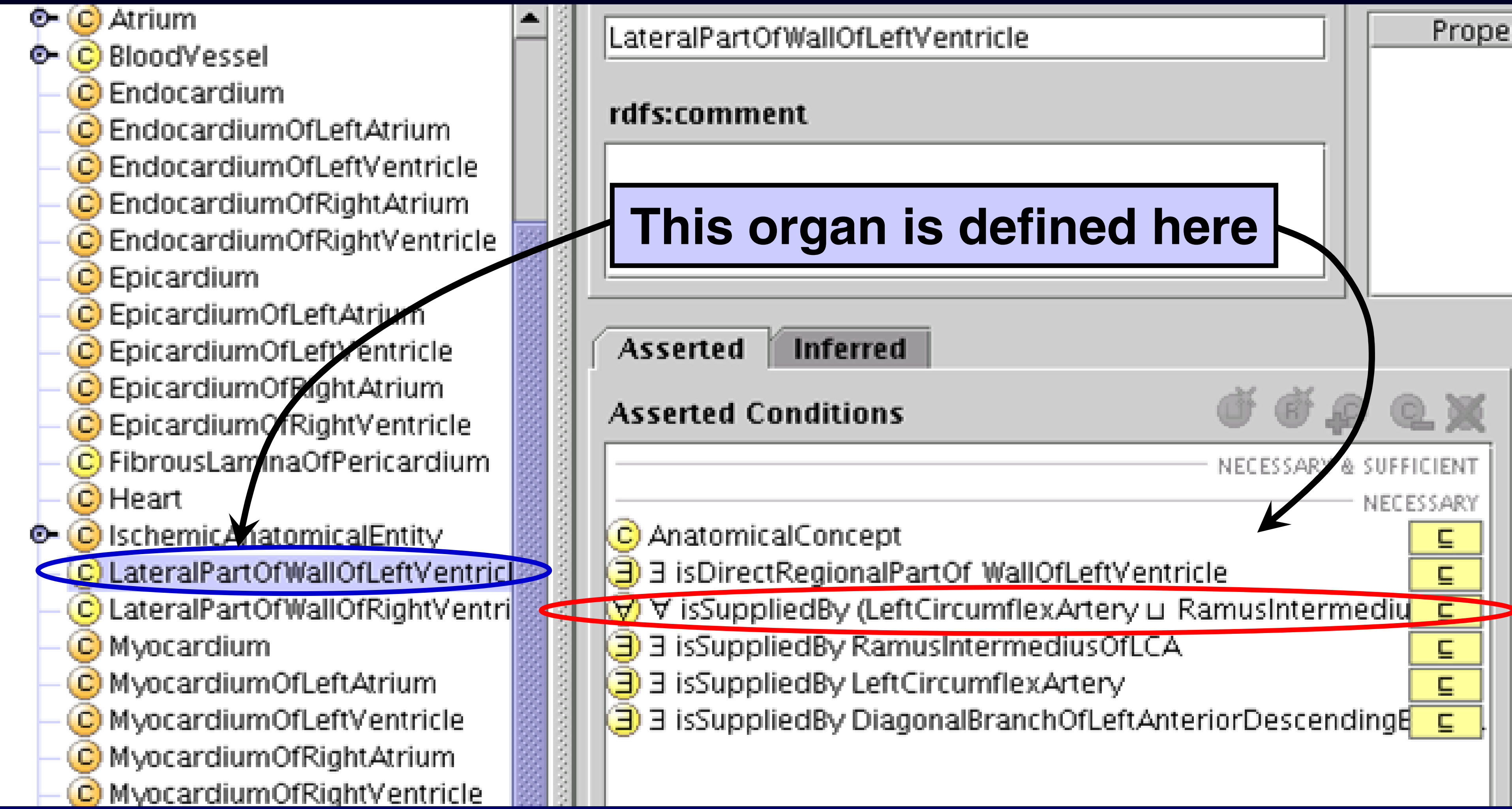


Reasoning about injuries and their consequences

Reasoning using Classification

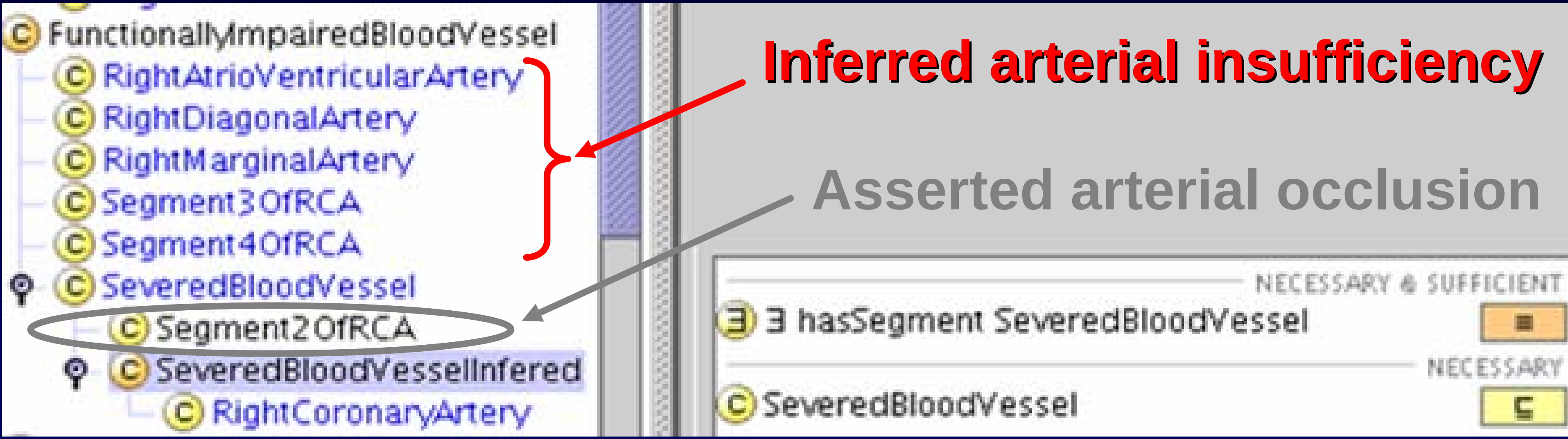
- Some reasoning tasks are classification tasks
  - Diagnosis
  - Extent of injury
  - Consequences of injury (e.g., vascular damage)
  - Triage and associated actions
- Representation of VSKB in Description Logic enables efficient classification
  - Represent knowledge conducive to classification
  - Infer non-obvious relationships among concepts (e.g., ischemia)
- This approach builds on current standards for knowledge interoperability (OWL)

OWL model relates anatomic structures to vascular supply



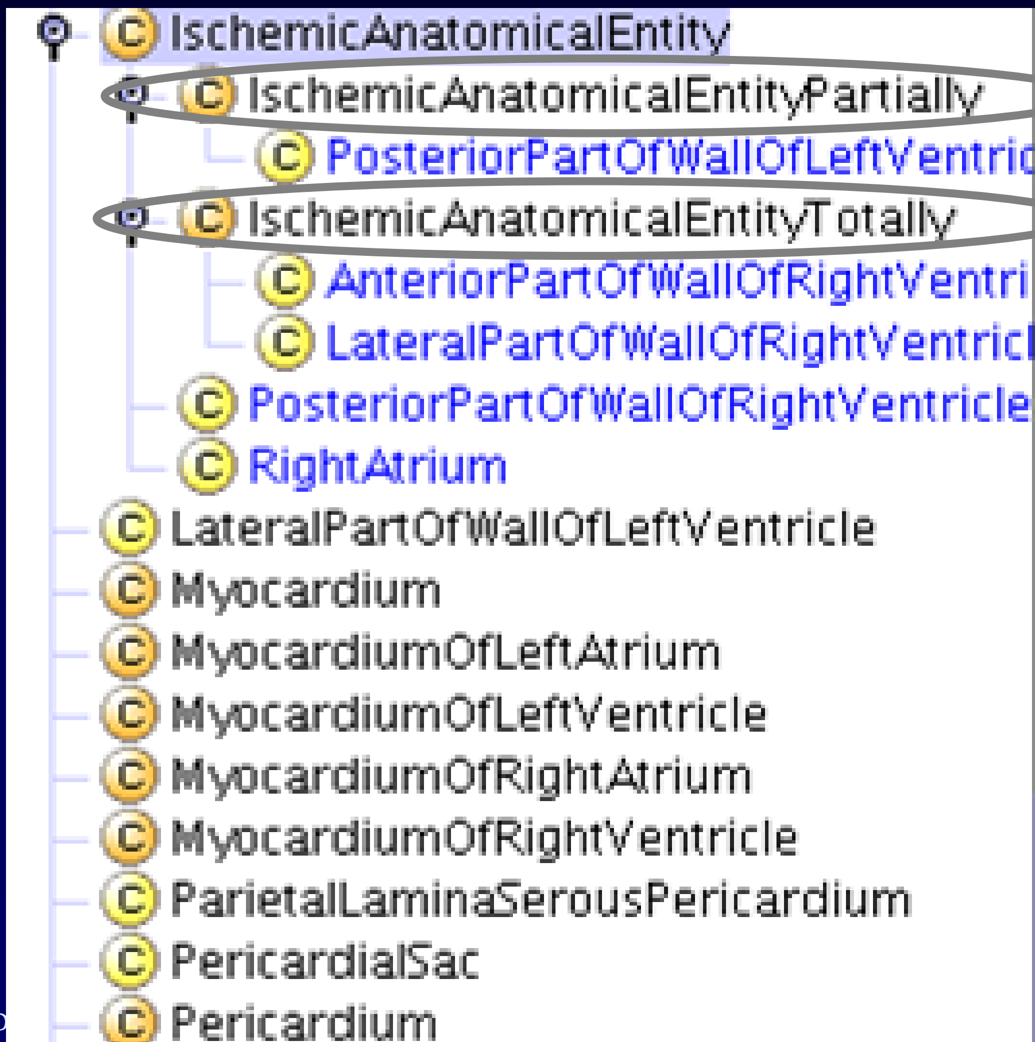
Anatomy Ontology **Concept Definitions**

OWL automatically infers where distal blood flow is lost



If we assert that the RCA is occluded *between conus a. and and diagonal a.*, we can infer the ischemic consequences

OWL automatically infers what structures are damaged



Types of ischemic organs

Predicted regions of heart that will be ischemic

Implementation

- VSKB ontolgies in Protégé
- PSM
  - Geometric data objects in ITK (C++)
  - API to read patient data; visualize output
  - C++/Java interface to link PSM to ontologies
- OWL-based reasoning deployed as a Web service
- Outputs of reasoning updates PSM

C++/Protégé Interface

- Geometric modeling code in C++; Protégé API in Java
- C++/Protégé interface developed using JACE
- Proxy C++ classes created for core Java classes (KnowledgeBase, etc.)
- JVM invoked in C++; direct Protégé API calls via JACE interface

DEMO

Conclusions

- Benefits of integrating *geometric models* with *ontologies*
  - Makes anatomic knowledge and relationships explicit and computer-accessible
  - Useful for reasoning (e.g., propagation of vascular injury)
- Benefits of integrating *additional information* in Patient Specific Model
  - Biomechanical and other data for simulation
  - Extensibility to accommodate future data

Acknowledgements

- Defense Advanced Research Projects Agency (DARPA)
- Protégé Resource (LM007885)

Thank you.

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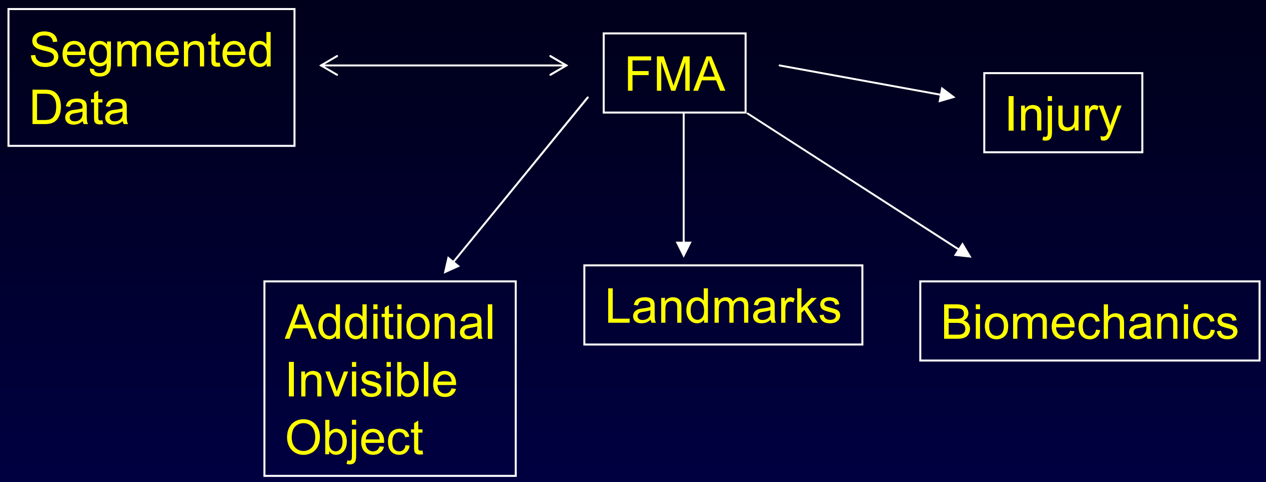
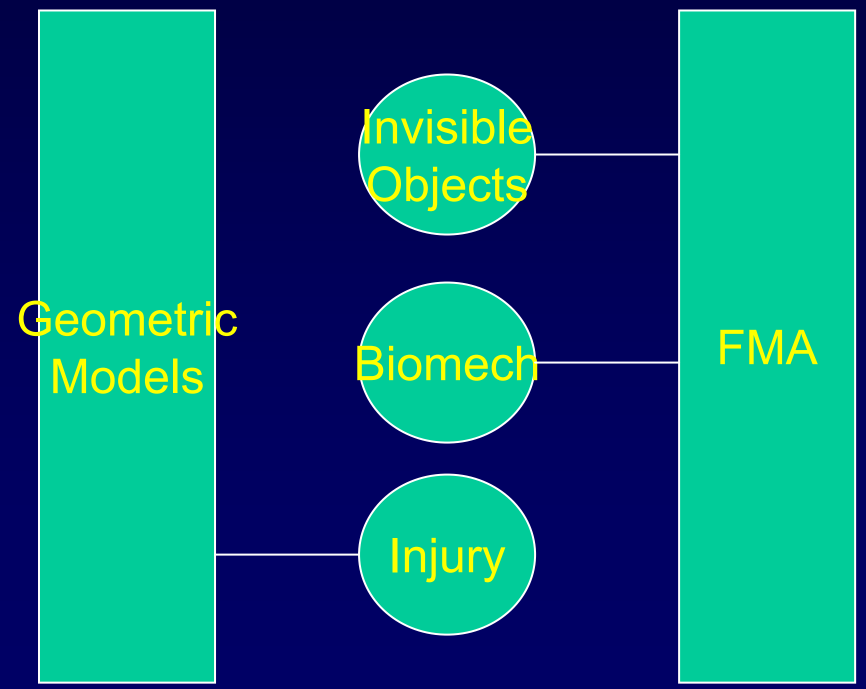


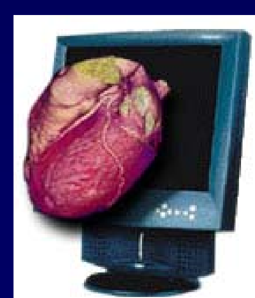
Pre-processing of link
Between {geometry (image+mesh), biomechanics, etc}
and FMA.
How? Spatial objects (abstract geometry objects)



Working with the PSM: Reasoning and Visualization

Patient-Specific Model (PSM)

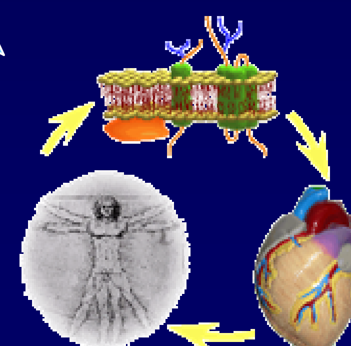
Reasoning



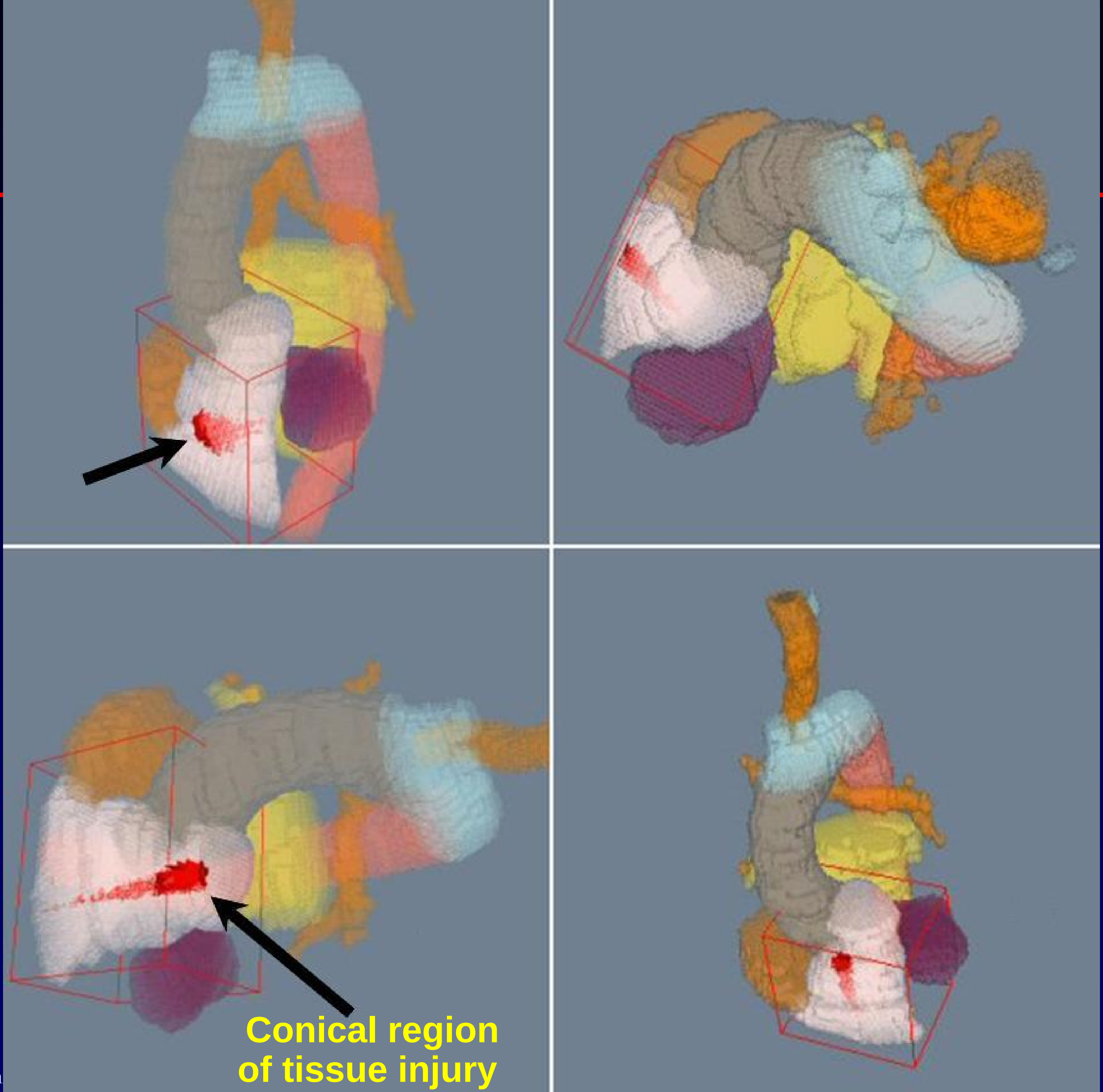
Visualization

Physiological effects

Tissue damage



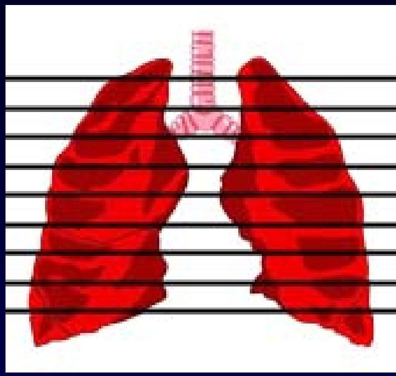
Indirect effects


Conical region
of tissue injury

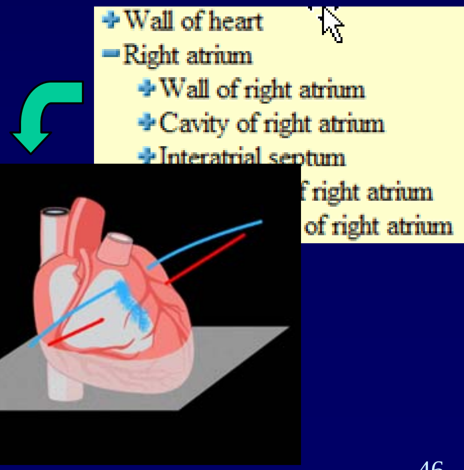
Architecture for Integrating Image Data and Knowledge

- Provide reasoning services for current and anticipated requirements
- Use blackboard architecture where all reasoners relate to data available in a Patient-Specific Model (PSM)
- Enable all modules in VSP to read and write to PSM at runtime

Ontologic approach to geometric models of anatomy



- Input: segmented CT data (pre-injury)
- Build an integrated 3-d model of anatomy:
  - *__Represent__* 3-d geometry of anatomic structures
  - *__Integrate__* tissue physical properties, biomechanics, physiology, and clinical parameters (vital signs)
  - *__Simulate__* geometric effects of penetrating injury
- Geometric model *links* to knowledge sources (e.g., anatomy in FMA ontology)
- *(Use physiologic models to predict consequence of the injury)*
- Display predicted organ injury



Geometric Model Building

- Organ parts derived from segmented CT data
- Construct mesh models from segmented organ parts using VTK and ITK (added to PSM)
- Biomechanical and other information added to PSM
  - Tissue physical properties; density
- Knowledge in VSKB is cached in PSM for efficient computation
  - E.g., Heart → pericardium; LA; LV; RA; RV
- This model is *extensible*; can include other info

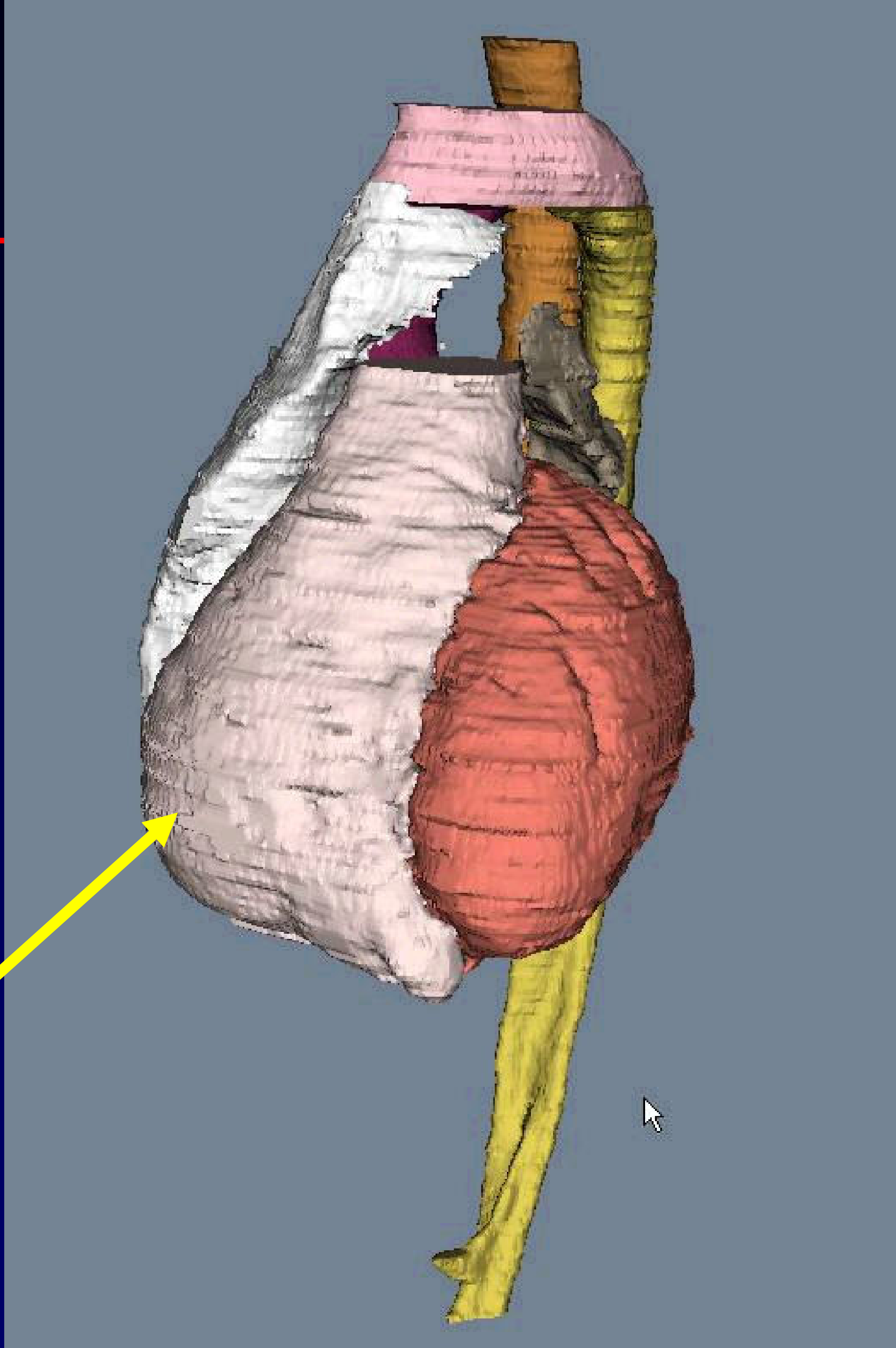
VSKB Knowledge Cached in PSM

VSKB

Geometry
Tissue Density
Elasticity
Surface area
...

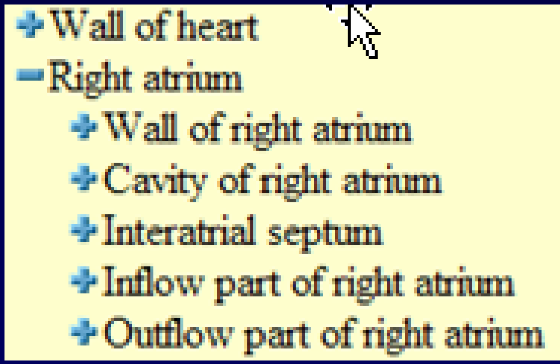
Cached knowledge

Rendering of geometric data associated with cached geometric knowledge



What Is An Ontology?

- Enumerates concepts, attributes of concepts, and relationships among concepts
  - Defines a structure ("model") for the application area
  - Encodes knowledge
  - A "knowledge source"



- Can be comprehended by people and processed by machines
- Provides a "domain of discourse" for characterizing some application area; a common vocabulary (shared understanding)

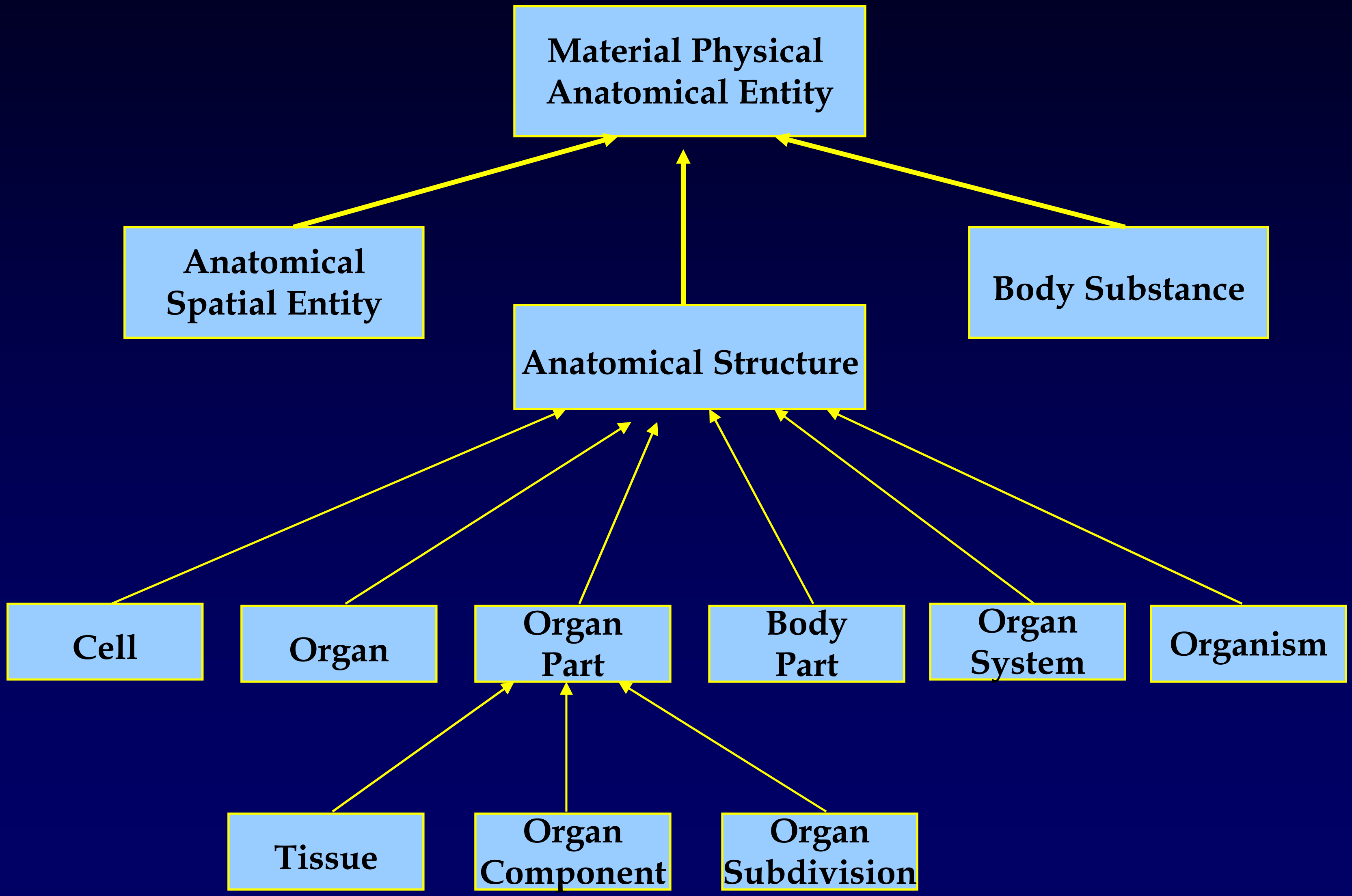
Protégé-2000

- Ontology editor
  - Model concepts, attributes, and relationships
- Tools
  - Visualize ontologies and knowledge bases
- Storage
  - Archive ontologies and knowledge bases in a variety of formats
- Java API
  - Link knowledge bases to other applications
- A world-wide community of active users

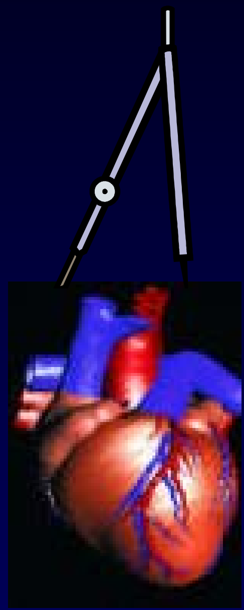
Challenges

- Making knowledge explicit and computable
  - Geometric knowledge: implicitly represented in 3-d models
  - Anatomic/physiologic knowledge: usually in head of observer
  - This separation makes automated reasoning difficult
- Integrating and computing with patient data and canonical knowledge
  - ***Data***: geometry, biomechanics, vital signs
  - ***Knowledge***: anatomy, tissue strain ↔ injury
  - Combining and using these in reasoning tasks

The Foundational Model of Anatomy (FMA) Ontology



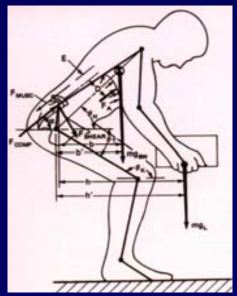
Integrating Knowledge and Data



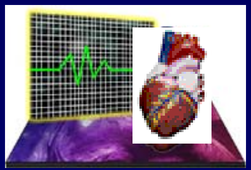
Geometry

Patient-Specific Model (PSM)

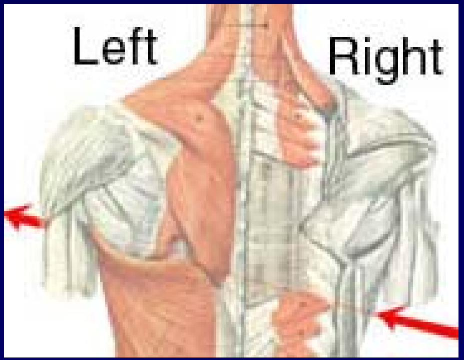
Knowledge



Biomechanics



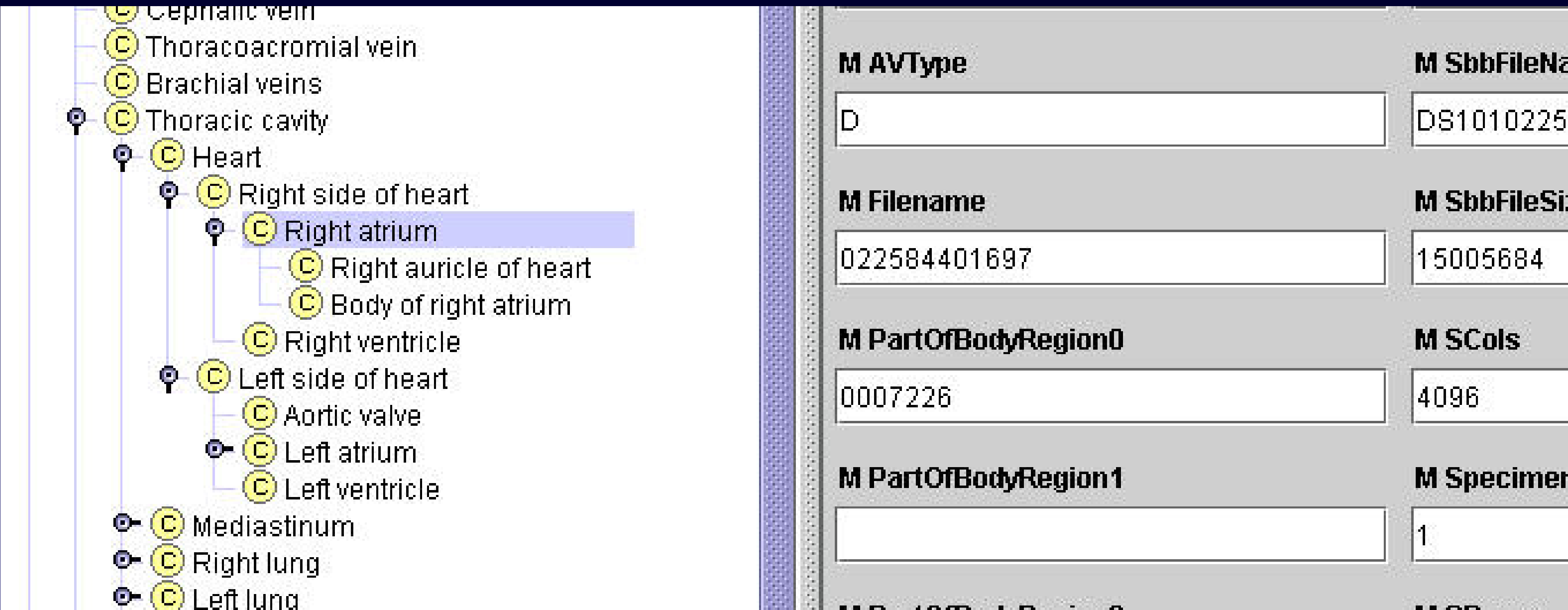
Vital Signs



Injury data

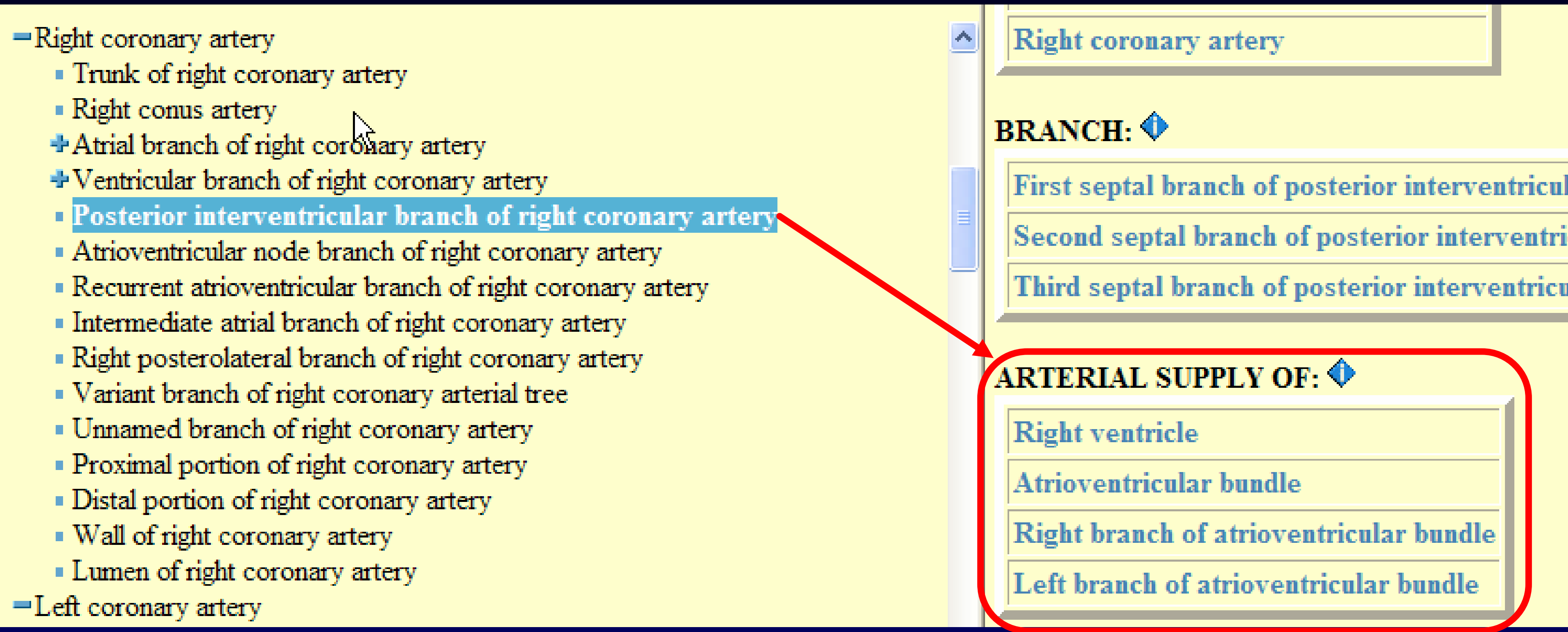
PSM Links VSKB to Runtime Data

Cached knowledge in PSM derived from anatomy ontology



Each node above is an object containing *patient-specific knowledge*: anatomy, geometry, biomechanics, tissue damage, physiology

Knowledge about Vascular Supply



Knowledge for Injury Reasoning

- Heart
  - Wall of heart
  - Right atrium
    - Wall of right atrium
    - Cavity of right atrium
    - Interatrial septum
    - Inflow part of right atrium
    - Outflow part of right atrium
    - Right auricle
    - Right side of interatrial septum
  - Left atrium
  - Right ventricle
  - Left ventricle
  - Right side of heart
  - Left side of heart
  - Fibrous skeleton of heart
  - Papillary muscle
  - Cardiac valve
  - Tricuspid valve
  - Mitral valve
  - Aortic valve
  - Pulmonary valve
  - Interatrial septum
  - Interventricular septum
  - Cavity of right atrium
  - Cavity of left atrium
  - Cavity of left ventricle
  - Right coronary artery
  - Left coronary artery
  - Coronary sinus
  - Great cardiac vein
  - Right marginal vein
  - Left marginal vein

Part-of knowledge

Other useful knowledge

ADJACENCY:

related object	coordinate	laterality
Right lung		Right
Left lung		Left
Esophagus	Posterior	
Right main bronchus	Superior	Right
Left main bronchus	Superior	Left
Diaphragm	Inferior	

ORIENTATION:

related object	coordinate	laterality
Apex of heart	Inferior	Left
Base of heart (anatomical)	Posterior	Right

CONTAINED IN:

Middle mediastinum

ARTERIAL SUPPLY:

Right coronary artery

Left coronary artery

VENOUS DRAINAGE:

Coronary sinus

Great cardiac vein

- Heart
  - Wall of heart
  - Right atrium
    - Wall of right atrium
    - Cavity of right atrium
      - Cavity of inflow part of right atrium
      - Cavity of outflow part of right atrium
      - Cavity of right auricle
    - Interatrial septum
    - Inflow part of right atrium
    - Outflow part of right atrium
    - Right auricle
    - Right side of interatrial septum
  - Left atrium
  - Right ventricle
  - Left ventricle
  - Right side of heart
  - Left side of heart
  - Fibrous skeleton of heart
  - Papillary muscle
  - Cardiac valve
  - Tricuspid valve
  - Mitral valve
  - Aortic valve
  - Pulmonary valve
  - Interatrial septum
  - Interventricular septum
  - Cavity of right atrium
  - Cavity of left atrium
  - Cavity of left ventricle
  - Right coronary artery
  - Left coronary artery
  - Coronary sinus

Key knowledge used in reasoning

ADJACENCY:

related object	coordinate	laterality
Right lung		Right
Left lung		Left
Esophagus	Posterior	
Right main bronchus	Superior	Right
Left main bronchus	Superior	Left
Diaphragm	Inferior	

ORIENTATION:

related object	coordinate	laterality
Apex of heart	Inferior	Left
Base of heart (anatomical)	Posterior	Right

CONTAINED IN:

Middle mediastinum

ARTERIAL SUPPLY:

Right coronary artery
Left coronary artery

VENOUS DRAINAGE:

Coronary sinus
Great cardiac vein
Right marginal vein