Hybrid AI for knowledge representation and model-based medical image understanding

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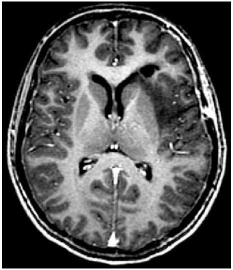
2021

Image Understanding

Multiple definitions

- Recognition of one object or structure, of several objects.
- Global recognition of a scene.
- Semantics.
- Linguistic descriptions
  - in which language?

Example: brain MRI



Data and Knowledge

Is everything in the data?

- Powerful methods, with excellent results (e.g. deep learning).
- But:
  - access to the data sometimes limited,
  - important data sets and number of examples usually required,
  - high annotation and learning cost.

$\Rightarrow$ Importance of knowledge and models.

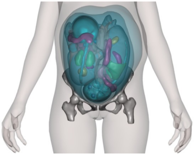
Models for Image Understanding

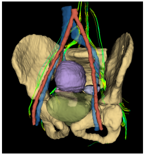
From models to interpretation

- Mathematical models to represent
  - knowledge (domain, structure of the scene...),
  - image information,
  - their combination,
  - their imperfections (imprecision, uncertainty, incompleteness...).
- Algorithms and applications.
- Semantic gap.
- Pathological cases.
- Knowledge representation and reasoning.

From images to models

- Examples: knowledge extraction, learning bases, digital twins, virtual patients...





Hybrid Artificial Intelligence

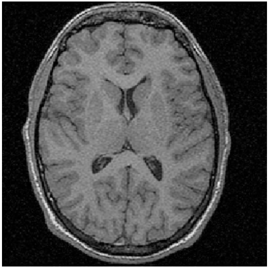
Merging different fields of AI, whether symbolic or statistical

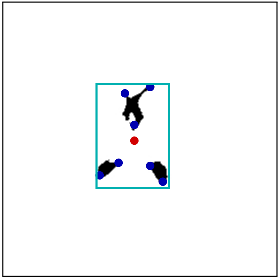
- Abstract knowledge representation and formal reasoning (logics).
- Structural representations (graphs and hypergraphs, ontologies, conceptual graphs, concept lattices...).
- Imprecision (fuzzy sets).
- Semantic gap to link concepts to visual percepts in the images.
- Statistical learning, deep learning (machine learning, neural networks).
- ...

Spatial reasoning: Knowledge representation on spatial entities and spatial relations, and reasoning on them.

Spatial entities

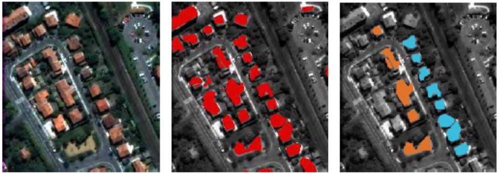
- Regions, fuzzy regions.
- Keypoints, landmarks.
- Simplified regions (center, bounding box...).
- Abstract representations (formulas in some logic, RCC...).





Spatial relations

- Structural information.
- Different types (binary / n-ary, simple / complex, well-defined / vague or imprecise).
- Fuzzy representations are useful (Freeman 1975, Kuipers 1978...).



Structural information: spatial relations

Many relations can be formally modeled using mathematical morphology:

- set theoretical relations,
- topological relations (neighborhood, adjacency...),
- distance (minimal, Hausdorff),
- directional relations,
- more complex relations (between, along, parallel...).

In different frameworks:

- sets, fuzzy sets,
- logic,
- graphs and hypergraphs,
- formal concept analysis, conceptual graphs, ontologies
- ...

Commun mathematical structure: lattice

Mathematical morphology in a nutshell (Serra, 1982)

Dilation: operation in complete lattices that commutes with the supremum.
Erosion: operation in complete lattices that commutes with the infimum.

$\Rightarrow$ applies in any mathematical framework endowed with a lattice structure.

Using a structuring element:

- dilation as a degree of conjunction: $\delta_B(X) = \{x \in \mathcal{S} \mid B_x \cap X \neq \emptyset\}$,
- erosion as a degree of implication: $\varepsilon_B(X) = \{x \in \mathcal{S} \mid B_x \subseteq X\}$.

A lot of other operations...

Fuzzy sets in a nutshell (Zadeh, 1965)

- Space $\mathcal{S}$ (image space, space of characteristics, etc.).
- Fuzzy set: $\mu : \mathcal{S} \rightarrow [0,1]$ – $\mu(x)$ = membership degree of x to μ.
- Set theoretical operations: complementations, conjunctions (t-norms), disjunctions (t-conorms).
- Logics, aggregation and fusion operators...

Example: spatial fuzzy set

- $\mathcal{S}$: $\mathbb{R}^3$ or $\mathbb{Z}^3$ in the digital case
- $\mu : \mathcal{S} \rightarrow [0,1]$ - $\mu(x)$ = degree to which x belongs to the fuzzy object

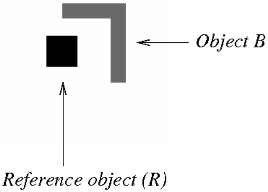
Usefulness of spatial relations

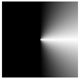
- Often used in scene descriptions, textbooks or ontologies.
- Provide structural information.
- More robust to the presence of pathologies or unexpected event than information on shape or appearance.

But usually vague and imprecise.

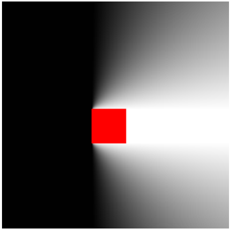
⇒ Formalized using fuzzy sets and mathematical morphology.

Example: Find B knowing that it should be to the right of R?

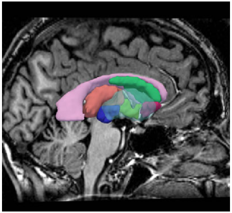




ν_{right}



$\delta_{\nu_{right}}(R)$



$$Right(B, R) = f(\delta_{\nu_{right}}(R)(x), x \in B)$$

⇒ Important component in spatial reasoning, in model-based segmentation and recognition.

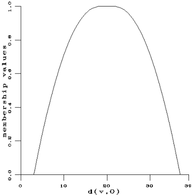
Reasoning

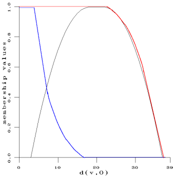
- Representations:
  - ontological: concepts, relations, roles...
  - graphs and hypergraphs,
  - logical knowledge base,
  - semantic gap between abstract / symbolic concepts and information extracted from images,
  - linguistic variable: useful notion to establish links between concepts and concrete domains.
- Reasoning for image understanding:
  - matching,
  - sequential interpretation,
  - constraint satisfaction problems,
  - logical reasoning (abduction...)

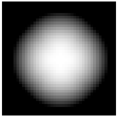
Linguistic variable and concrete domains

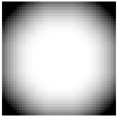
- Abstract level: concept, linguistic values of a variable.
- Concrete domain: representation of the semantics of each value as a fuzzy set.

Example: medium distance

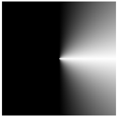


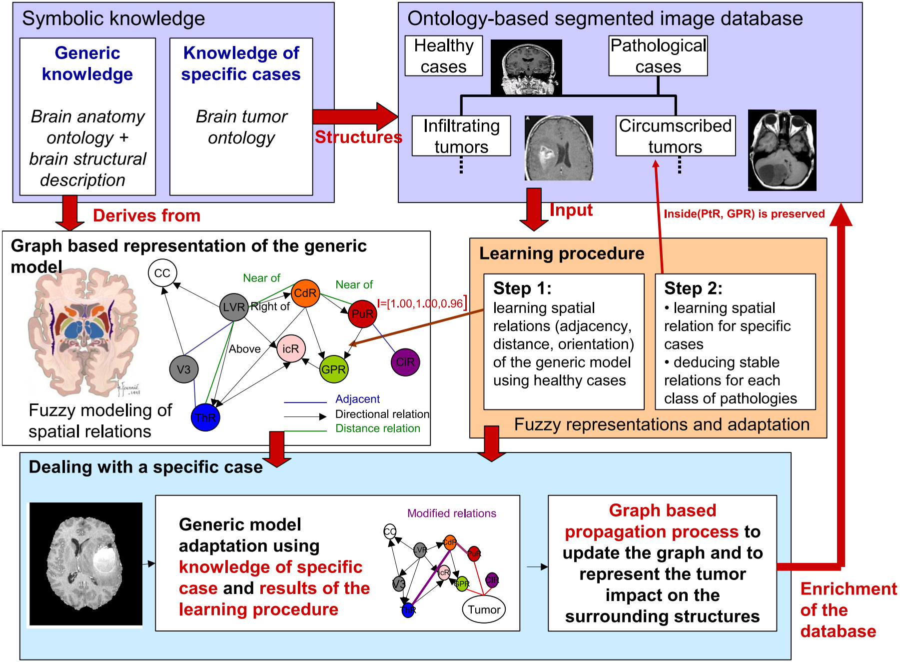




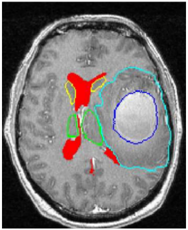
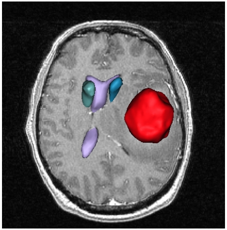
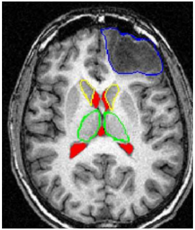
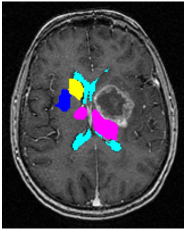


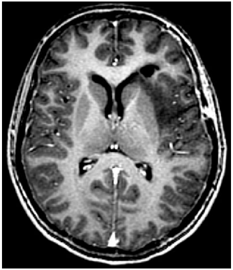
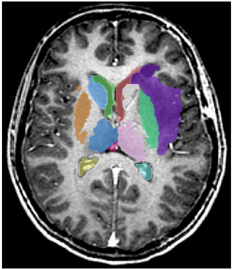
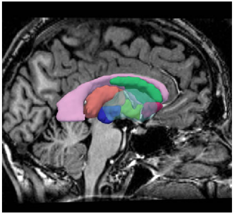
Example: to the right of




Symbolic knowledge
Generic knowledge
Brain anatomy ontology + brain structural description
Knowledge of specific cases
Brain tumor ontology
Structures
Ontology-based segmented image database
Healthy cases
Pathological cases
Infiltrating tumors
Circumscribed tumors
Derives from
Input
Inside(PtR, GPR) is preserved
Graph based representation of the generic model
CC
LVR
CdR
PuR
icR
GPR
ClR
V3
ThR
Near of
Right of
Above
I=[1.00,1.00,0.96]
Fuzzy modeling of spatial relations
Adjacent
Directional relation
Distance relation
Learning procedure
Step 1:
learning spatial relations (adjacency, distance, orientation) of the generic model using healthy cases
Step 2:
• learning spatial relation for specific cases
• deducing stable relations for each class of pathologies
Fuzzy representations and adaptation
Dealing with a specific case
Generic model adaptation using knowledge of specific case and results of the learning procedure
Modified relations
Tumor
Graph based propagation process to update the graph and to represent the tumor impact on the surrounding structures
Enrichment of the database

Examples in MRI Brain Imaging

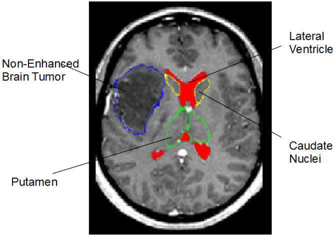





with J. Atif, G. Fouquier, H. Khotanlou, O. Nempont

Applications

- Finding explanations and descriptions.
- Guiding surgery planning.
- Treatment follow-up.
- ...



Abductive reasoning: *Find the best explanation to the observations and segmentation results, taking into account expert knowledge.*

- Which level of description?
- Which language?
- To whom is the description/explanation dedicated?

Example in description logic

Tbox:

$$
\begin{aligned}
\mathit{Brain} &\sqsubseteq \mathit{HumanOrgan}\\
\mathit{CerebralHemisphere} &\sqsubseteq \mathit{BrainAnatomicalStructure}\\
\mathit{PeripheralCerebralHemisphere} &\sqsubseteq \mathit{CerebralHemisphereArea}\\
\mathit{SubCorticalCerebralHemisphere} &\sqsubseteq \mathit{CerebralHemisphereArea}\\
\mathit{GreyNuclei} &\sqsubseteq \mathit{BrainAnatomicalStructure}\\
\mathit{LateralVentricle} &\sqsubseteq \mathit{BrainAnatomicalStructure}\\
\mathit{BrainTumor} &\sqsubseteq \mathit{Disease} \sqcap \exists \mathit{hasLocation}.\mathit{Brain}\\
\mathit{SmallDeformingTumor} &\equiv \mathit{BrainTumor} \sqcap \exists \mathit{hasBehavior}.\mathit{Infiltrating}\\
&\quad \sqcap \exists \mathit{hasEnhancement}.\mathit{NonEnhanced}\\
\mathit{SubCorticalSmallDeformingTumor} &\equiv \mathit{SmallDeformingTumor} \sqcap\\
&\quad \exists \mathit{hasLocation}.\mathit{SubCorticalCerebralHemisphere}\\
&\quad \sqcap \exists \mathit{closeTo}.\mathit{GreyNuclei}\\
\mathit{PeripheralSmallDeformingTumor} &\equiv \mathit{BrainTumor} \sqcap\\
&\quad \exists \mathit{hasLocation}.\mathit{PeripheralCerebralHemisphere}\\
&\quad \sqcap \exists \mathit{farFrom}.\mathit{LateralVentricle}\\
\mathit{LargeDeformingTumor} &\equiv \mathit{BrainTumor} \sqcap\\
&\quad \exists \mathit{hasLocation}.\mathit{CerebralHemisphere}\\
&\quad \sqcap \exists \mathit{hasComponent}.\mathit{Edema}\\
&\quad \sqcap \exists \mathit{hasComponent}.\mathit{Necrosis}\\
&\quad \sqcap \exists \mathit{hasEnhancement}.\mathit{Enhanced}
\end{aligned}
$$

$$
\begin{aligned}
\mathit{DiseasedBrain} &\equiv \mathit{Brain} \sqcap \exists \mathit{isAlteredBy}.\mathit{Disease} \\
\mathit{TumoralBrain} &\equiv \mathit{Brain} \sqcap \exists \mathit{isAlteredBy}.\mathit{BrainTumor} \\
\mathit{SmallDeformingTumoralBrain} &\equiv \mathit{Brain} \sqcap \exists \mathit{isAlteredBy}.\mathit{SmallDeformingTumor} \\
\mathit{LargeDeformingTumoralBrain} &\equiv \mathit{Brain} \sqcap \exists \mathit{isAlteredBy}.\mathit{LargeDeformingTumor} \\
\mathit{PeripheralSmallDeformingTumoralBrain} &\equiv \mathit{Brain} \sqcap \\
& \exists \mathit{isAlteredBy}.\mathit{PeripheralSmallDeformingTumor} \\
\mathit{SubCorticalSmallDeformingTumoralBrain} &\equiv \mathit{Brain} \sqcap \\
& \exists \mathit{isAlteredBy}.\mathit{SubCorticalSmallDeformingTumor} \\
& \ldots
\end{aligned}
$$

Abox:

$$
\begin{aligned}
t_1 &: \mathit{BrainTumor} \\
e_1 &: \mathit{NonEnhanced} \\
l_1 &: \mathit{LateralVentricle} \\
p_1 &: \mathit{PeripheralCerebralHemisphere} \\
(t_1, e_1) &: \mathit{hasEnhancement} \\
(t_1, l_1) &: \mathit{farFrom} \\
(t_1, p_1) &: \mathit{hasLocation}
\end{aligned}
$$

Most specific concept:

$$
\begin{aligned}
C \equiv \mathit{BrainTumor} \sqcap \exists \mathit{hasEnhancement}.\mathit{NonEnhanced} \sqcap \\
\exists \mathit{farFrom}.\mathit{LateralVentricle} \sqcap \\
\exists \mathit{hasLocation}.\mathit{PeripheralCerebralHemisphere}
\end{aligned}
$$

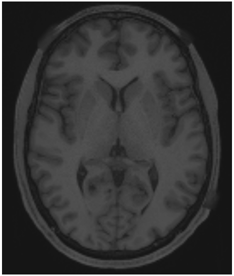
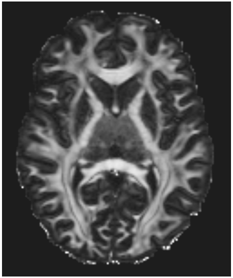
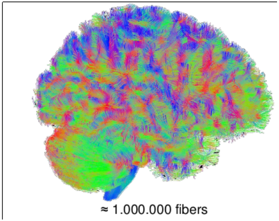
Concept abduction problem $\langle \mathcal{K}, C \rangle$: $\gamma \sqsubseteq_{\mathcal{K}} C$

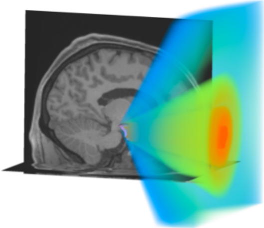
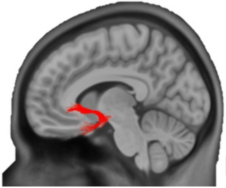
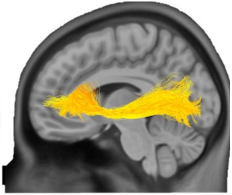
Possible explanation set:
$\{$*DiseasedBrain*$, \exists$*isAlteredBy*$.\top,$ *SmallDeformingTumoralBrain*,
PeripheralSmallDeformingTumoralBrain...$\}$.

A preferred solution with respect to some minimality criteria:

$$\boxed{\gamma \equiv \mathit{PeripheralSmallDeformingTumoralBrain}}$$

with J. Atif, C. Hudelot, Y. Yang

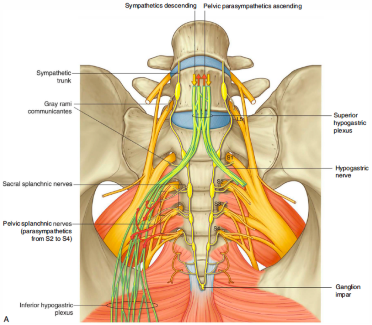




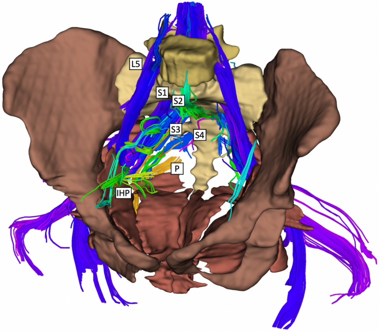




with P. Gori and A. Delmonte

Nerves in pediatric imaging

- Descriptions:
  - Sacral Plexus = (crossing(VertebralCanalL5) and not anterior of(ObturatorMuscle)) or (crossing(SacralHoleS1) and not (anterior of(LevatorAniMuscle) ...
  - S4 = crossing SacralHoleS4 and crossing SacrumCanal
  - L5 = anterior of Sacrum and ...
  - ...
- Spatial relations modeled using mathematical morphology and fuzzy sets.
- Combination and final decision



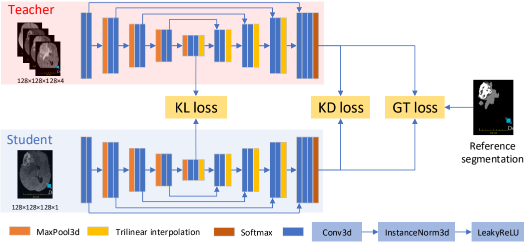


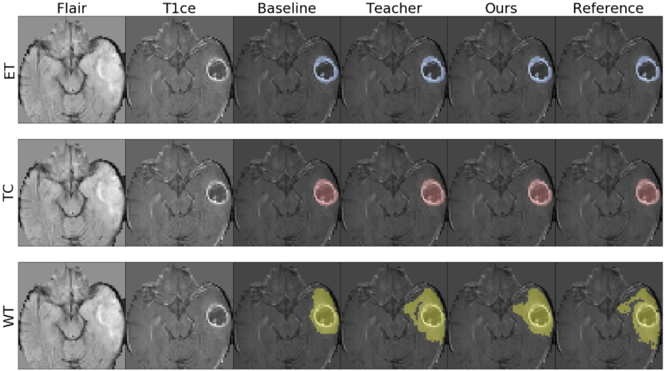
with A. Delmonte, C. Muller, S. Sarnacki

Combining knowledge representation models and deep learning

- Learning representations or their parameters.
- Introducing knowledge in neural networks.
- Explainable AI.

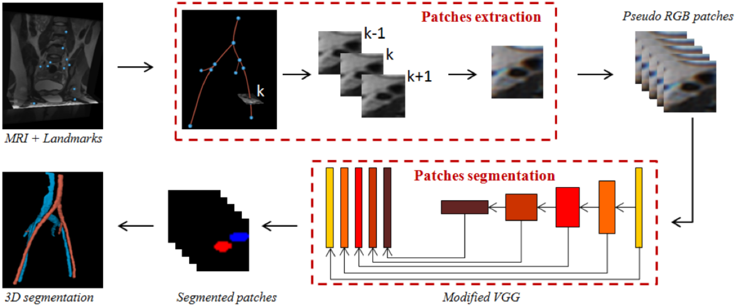
Architectures guided by expert reasoning: different modalities

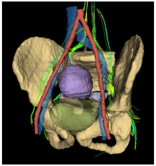




with M. Maillard, M. Hu, P. Gori

Geometrical constraints



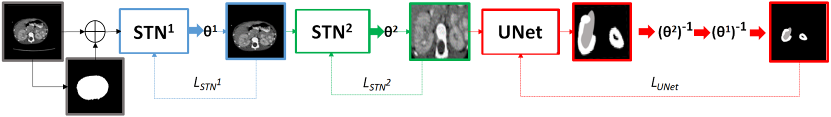


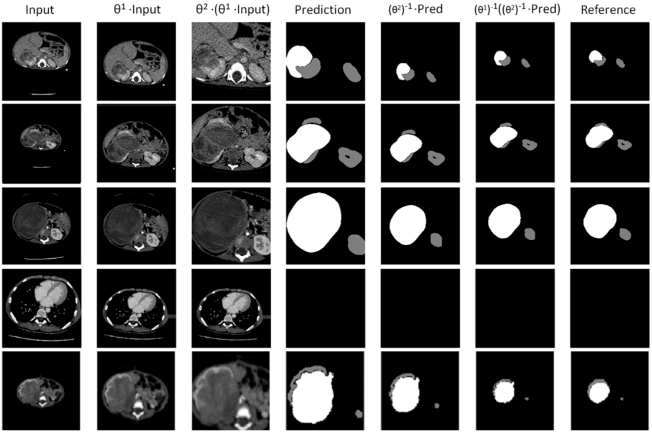
+ Nerve descriptions

⇒ 3D individual patient models for pediatric surgery

with A. Virzi, A. Delmonte, C. Muller, S. Sarnacki

Geometrical transformations

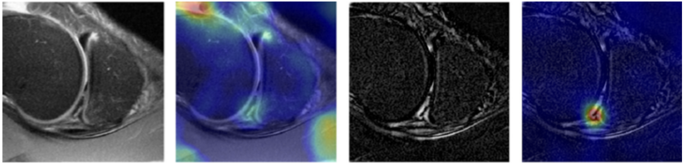




with G. La Barbera, P. Gori, L. Rouet, H. Boussaid...

Improving accuracy and explainability by enhancing the input

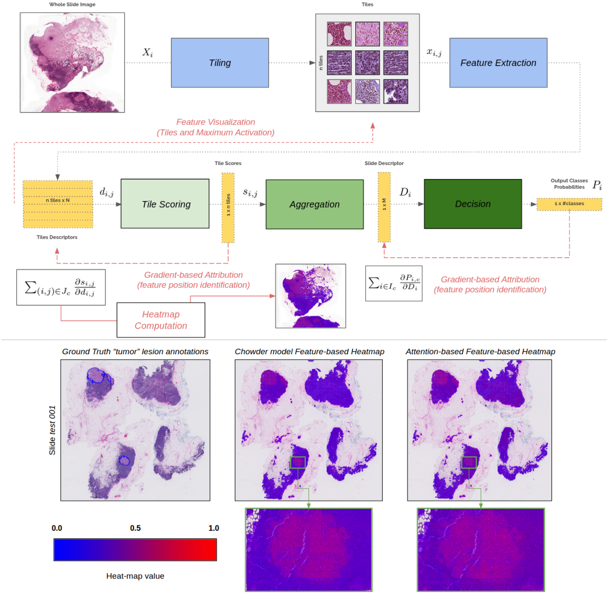
Knee meniscus tear detection from MRI



with V. Couteaux, O. Nempont, G. Pizaine, et al.

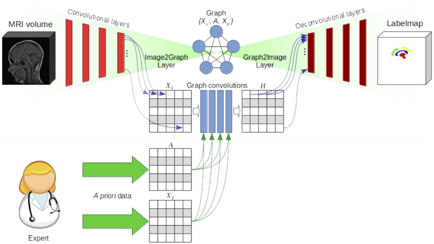
Architectures guided by expert reasoning: different scales and interpretability

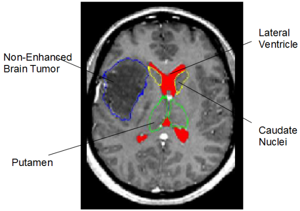
Whole Slide Imaging to detect metastases in lymph nodes



with A. Pirovano, H. Heuberger, S. Berlemont, S. Ladjal

Perspectives





- Which methods to be combined?
- Respective roles of data and knowledge.
- Knowledge acquisition and representation.
- Introducing structural knowledge in deep learning.
- Explain results, potential errors, methods.
- ...

Thanks to...

- PhD candidates, post-doctoral researchers, colleagues, invited professors...
- Academic, medical and industrial collaborations.
- Public and industrial fundings.