FORMAL GRAMMARS

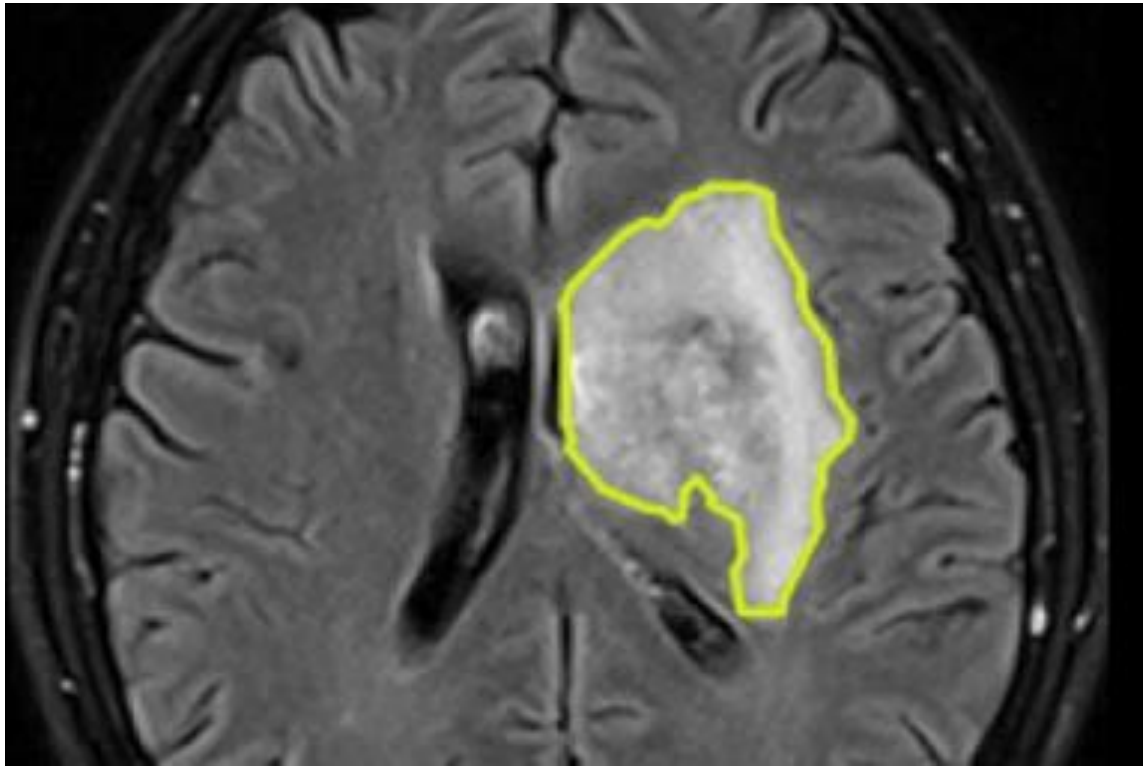
FOR MEDICAL IMAGE ANALYSIS

BRAIN GLIOMAS SEGMENTATION

A segmentation is kind of a contour or a delineation made to enclose a region damaged by the cancerous tissues.

It is used to judge the cancer developement and more importantly to perform a medical treatment.

We cooperate with the medical experts from Lublin Oncology Center who perform a brahytherapy treatment of brain gliomas. The therapy is usually performed after a initial surgical removal of the main glioma volume.



WHY WE NEED SEGMENTATION

Brahytherapy is a method of cancer treatement that involves placing a radiation source inside the patient's body.

The brachytherapy requires an accurate representation of the tumor volume.

This is beceause segmentation will be used as a guideline for machine operation. The radiation should possibly damage only the tumor and cause as low harm to nearby tissues as possible.
The damage to essential brain structures such as a brainstem and an eye nerve can have catastrophous implications.

WHY AUTOMATED SOLUTION WOULD HELP

Source: GettyImages, simonkr

Experts typically spend alot of time and effort on glioma segmentation. The time saved could be spent on other stages of the therapy such as treatment planinng.

It's worth noting that any resonably accurate software is already usefull, but professionals expect to have the possibility to controll automated segmentation results.
The requirements vary between doctors and are influenced by the treatment plan used in the medical facility.

DIFFICULTIES CHARACTERISTIC TO THE MRI SEGMENTATION

- The data is scarce.
- The data may be incomplete.
- Variablity of brain structures is quite high.
- The tumor can overlap with or push away some brain structures.
- The DICOM format should be both the input and output standard for the application.
- Data needs to be anonymized and needs to be stored on-site.

Experts often disagree on correctness of the segmentation results.

SOTA OF THE BRAIN TUMOR SEGEMENTATION

The brain tumor segmentation challenges are popularly solved with the nnU-net architectures.

The BRATS challange is organized yearly to motivate developement in the field.

Those solutions are often left unused due to incompabilities in image formats and low technical proficiency of the medical personnel.

Formal barriers and data quality make domain adaptation complicated. Due to differences in the requirements adaptation would probably need to be done for each medical facility.

THE RESULTS OF MY RESEARCH

THE PUBLICATION AND THE APPLICATION

- The Cooperation with Medical University of Lublin, Lublin Cancer Center, Copernicus Memorial Hospital in Łódź,
- An Ethics Commitee approval of the research and use of the patient data,
- Acceptance of the results by the medical experts,
- Publication in the The European Physical Journal Special Topics,
- Preliminary results of formal grammar based solution accepted by experts

Eur. Phys. J. Spec. Top.
https://doi.org/10.1140/epjs/s11734-025-01688-8

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

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Regular Article

Computer-aided target volume delineation for postoperative radiation therapy in brain glioma patients with the use of the hybrid artificial intelligence model

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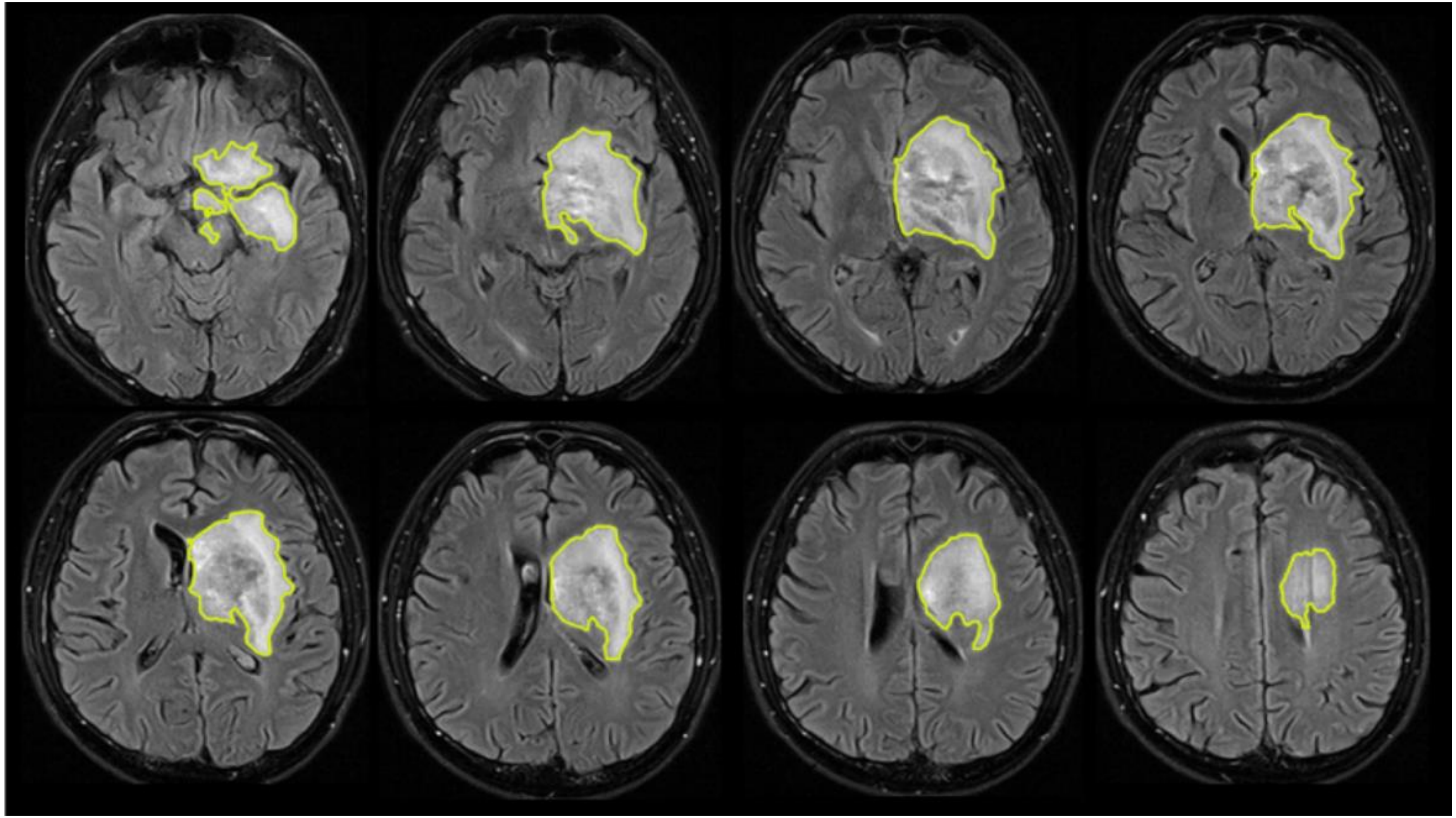
WORKS PRESENTS NOVEL APPROACH TO BRAIN GLIOMA SEGMENTATION



RESULTS OF THE ALGORTIHM – THESE CAN BE COMBINED WITH THE RESULTS OF nnU-NET SOLUTION ACCORDING TO THE USER'S REQUIREMENTS

CURRENT FORMAL RESEARCH

FORMALISMS TO IMPROVE EXISTING SEGMENTATIONS

The tumor is not but a collection of 2d slices existing in an abstract space.

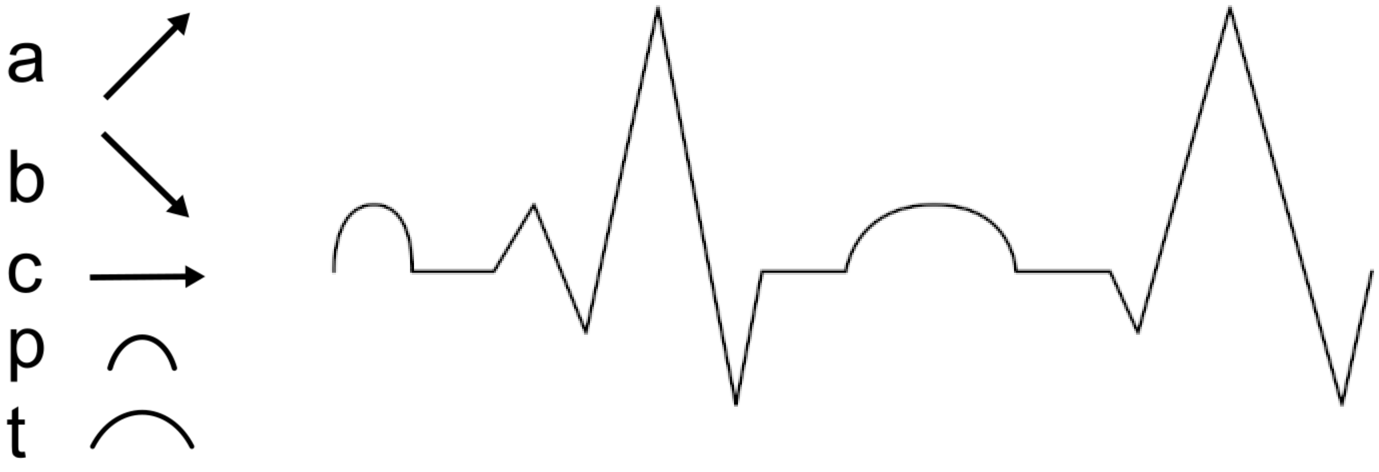
It is spacially coherent 3d shape and should be treated as such. The formal grammars are often used for medical image analysis. I therefore started to work on formalism that will generate coherent shape using such 2d slices provided in the DICOM format.

SYNTACTIC PATTERN RECOGNITION

It’s all about finding the pattern

To analyse and operate on the real-life objects we need to discover most simple and basic building blocks.

Those blocks are called primitives. The same object can often be described by diverse primitive sets. We have to find ones that are optimal for the task at hand.



The EEG signal above can be described as:

$$pcab^2a^3b^4a^2ctcba^4b^5a^2$$

Context-free grammar:

$$S \to aSb,$$
$$S \to \epsilon,$$

It's easy to see those rules generate $\{a^n b^n : n \geq 0\}$ language.

Example strings are: ab, $aabb$, $aaaabbbb$.

FORMAL GRAMMAR MACHINES

- Formal grammar machines are used in EEG analysis, electric load forecast, medical image analysis, scene description, manufacturing defects detection and hundreds of other applications (see „Syntactic Pattern Recognition", 2019, Flasiński M.)
- These formalisms are excellent for cases when expert knowledge has to be explicitely included in the working system. A formal grammar machine performs intelligent operations that are readily explainable and can provide user with detailed decision path the system have chosen.
- While a lengthy and complicated process, the formal grammar construction according to expert knowledge provides a tool that yields itself to generalization in the scope of application domain. The quality of results and the generalizability depends on primitive selection.
- Methods of automatic grammar inference exist.

FORMAL GRAMMAR MACHINES – WHAT ARE THEY?

Have the grammar? Let the analysis start

Most known machines are varius automata. These detect if supplied patterns belong to the grammar.

The automaton will transition from one state to another while reading symbols from the input string.

It will accept the string if reached state belongs to "final" states F like so:

$$T(A) = \{\gamma \in \Sigma_T^* \mid \delta(q_0, \gamma) \in F\}.$$

A deterministic finite-state finite automaton is defined as a quintuple

$$\mathfrak{A} = (\Sigma_T, Q, \delta, q_0, F),$$

Σ_T: finite set of input symbols,

Q: finite set of states,

$\delta : Q \times \Sigma_T \longrightarrow Q$ is the transition function,

q_0: the initial state

$F \subseteq Q$: the set of final states.

SYNTAX DRIVEN TRANSLATION

$T = (N, \Sigma, \Delta, R, S)$ where,

N: a finite set of nonterminals, $S \in N$: the starting nonterminal;
Σ and Δ: finite input and output alphabets;
R: a finite set of translation rules like:
$A \times \alpha, \beta$ for $A \in N$, $\alpha \in (N \cup \Sigma)^*$, and $\beta \in (N \cup \Delta)^*$,
nonterminals in α being a permutation of those in β.

SYNTAX DRIVEN TRANSLATION

A schema is used like two synchronized context-free grammars:

(i) (S, S) is a translation form with associated S's.

(ii) If $(\rho A\theta, \omega A\delta)$ is a translation form with associated A's and $A \times \alpha, \beta$ is in R, then $(\rho\alpha\theta, \omega\beta\delta)$ is also a translation form, in which case we write $(\rho A\theta, \omega A\delta) \Rightarrow (\rho\alpha\theta, \omega\beta\delta)$.

With the reflexive-transitive closure of the $\Rightarrow$ relation denoted by $\overset{*}{\Rightarrow}$, the translation produced by schema T is

$$\tau(T) = \left\{(x, y) \mid (S, S) \overset{*}{\Rightarrow} (x, y), x \in \Sigma^*, y \in \Delta^*\right\}.$$

Simply stated a transducer is obtained by permitting an automaton to emit a string of output symbols on each transition.

$$P = (Q, \Sigma, \Gamma, \Delta, \delta, q_0, Z_0, F)$$

Q: a set of states, Σ: the input alphabet,
Γ: the alphabet of pushdown memory,
Δ: the output alphabet,

δ is a mapping from $Q \times (\Sigma \cup \{\lambda\}) \times \Gamma \to Q \times \Gamma^* \times \Delta^*$,
q_0 the initial state, $Z_0 \in \Gamma$: the start symbol from the pushdown memory,
$F \subseteq Q$, the set of final states.

THE TRANSDUCER

If $\delta(q, a, Z)$ contains (p, α, z), then we write:

$$(q, ax, Z\gamma, y) \vdash (p, x, \alpha\gamma, yz), \quad \text{for all } x \in \Sigma^*, y \in \Delta^*, \text{ and } \gamma \in \Gamma^*.$$

THE TRANSDUCER

CONTINUED

By previous relation, v is an output for $u \in L$, by final states, if:

$$(q_0, u, Z_0, \lambda) \vdash^* (q, \lambda, \alpha, v), \quad \text{where } q \in F.$$

v is an output for $u \in L$, by empty pushdown memory, if:

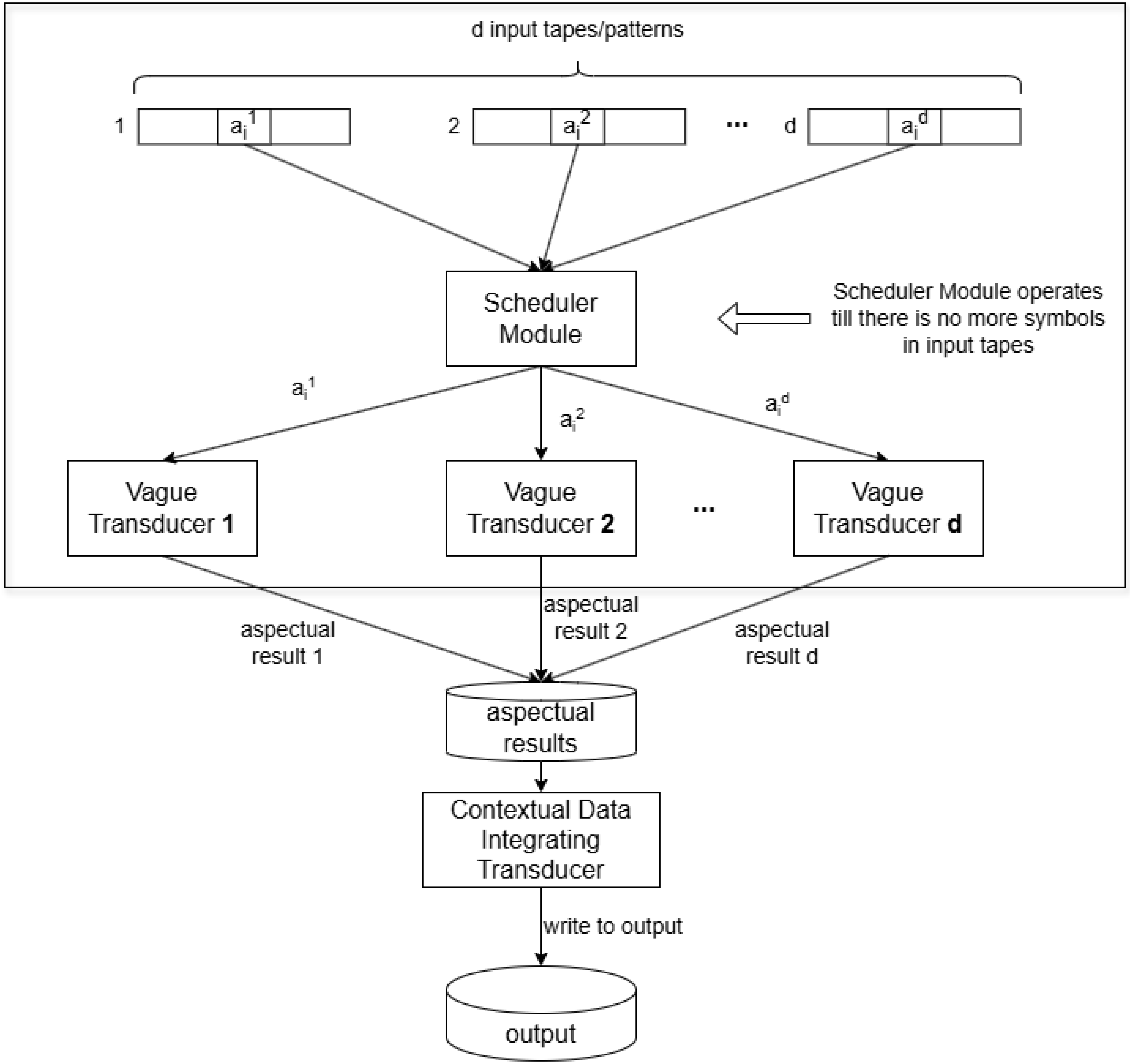
$$(q_0, u, Z_0, \lambda) \vdash^* (q, \lambda, \lambda, v), \quad \text{where } q \in Q.$$

APPLICATION OF AN EXTENDED TRANSDUCER

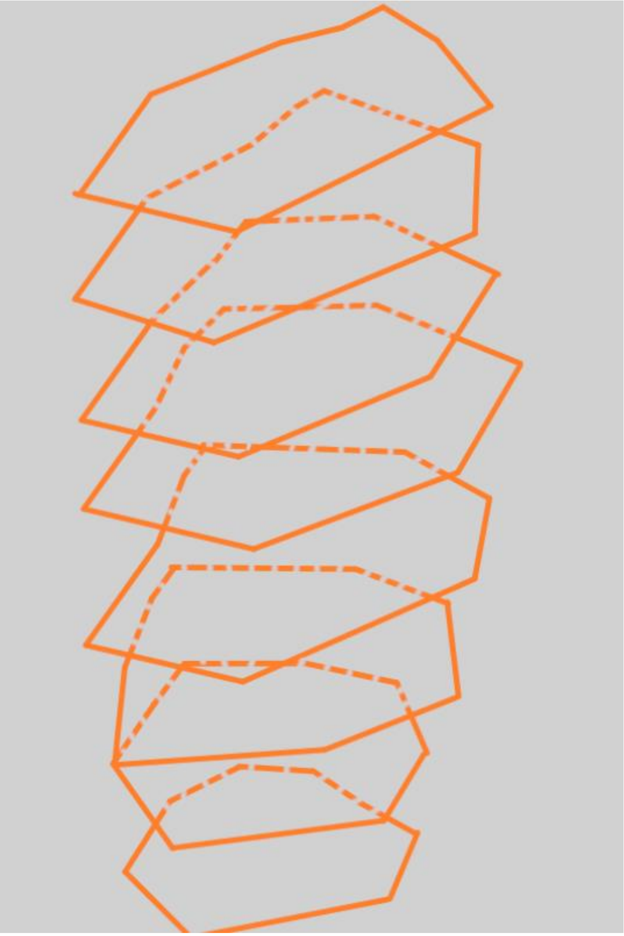
INTER-OBJECT RELATIONSHIPS INCLUDED DURING ANALYSIS

MODEL OF THE MULTI-STRING TRANSDUCER

The specific slices are modified and then the transduction results are combined by additional Integrator which can be any machine, but in case of my application is also a transducer.



THE VERTICAL SLICE VIEW



We model glioma as a 3d shape:

- It is now possible to modify all slices at once to acquire spacial coherence.
- The result will encompass all glioma structures and will take into account inter-slice distances
- Specific subset of rules is applied for outlying slices and the other subset regards middle slices. Both groups are governed by diverse requirements.

COMBINIG MULTI-STRING APPROACH WITH TRANSDUCER OPERATION

- The multi-string methodology includes relationships between parallel slices.
- The enhanced capabilities of such multi-string transducer provide basis for further developement of formal transducers.
- Additional descriptive power is to be acquired with the usage of vague primitives. This approach includes attributes for primitives that express fuzzy nature of the acquired data. Thanks to the primitives it's possible to operate on incomplete or inaccurate data and still acquire satisfactory results.

THE WRAP-UP

- The glioma segmentation is a challenging field due to nature of acquired data and variable medical and inter-expert requirements. Majority of medical centers in Poland do not have any automatic glioma segmentation software.
- We have presented a method of segmentation that generates satisfactionary results and due to hybrid nature of the system is a novelty.
- The inclusion of 3d-awareness thanks to formal grammar transducers can be employed on segmentations generated by any means (nn-Unet, hand-segmented or author's algorithm as in publication).
- The future publication will explain functioning of the above system and present formal details on generalizability of such solution.

CITATIONS

- **Multi-string automata**:
  Flasiński, Mariusz, and Janusz Jurek. "A Novel Approach of Multi-string Parsing for Syntactic Pattern Recognition." *International Conference on Computer Recognition Systems*. Cham: Springer Nature Switzerland, 2023.
- **About transducers in general**:
  Thomason, Michael G. "Syntactic methods In pattern recognition." *Pattern Recognition Theory and Applications: Proceedings of the NATO Advanced Study Institute held at St. Anne's College, Oxford, March 29–April 10, 1981*. Dordrecht: Springer Netherlands, 1982.
- **About novel transducers**:
  Flasiński, Mariusz, and Janusz Jurek. "Formal foundations of vague language transduction for syntactic pattern recognition." *International Conference on Computer Recognition Systems*. Cham: Springer Nature Switzerland, 2025.

THANK YOU

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