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Prof. Dr.-Ing. C. Stiller
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Karlsruhe Institute of Technology

Description Logic for Vision-Based Intersection Understanding

Britta Hummel, Werner Thiemann, Irina Lulcheva

- **Motivation:** Road recognition for toy worlds only?
- **DL Road Network Knowledge Base Development**
  - DL Tutorial
  - Hypothesis Space
  - Sensor Input
- **DL Inference for Semantic Road Recognition**
  - Deduction
  - Model Construction

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Road Recognition
Status Quo

- Since mid 80ies
- Solved for highly restricted domains (highways)
- Few work for more complex domains, then only consideration of special cases
- Geometry only, no semantics

➔ Toy worlds?

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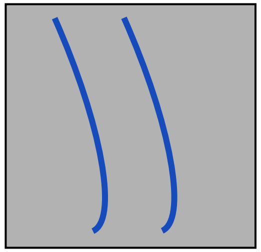
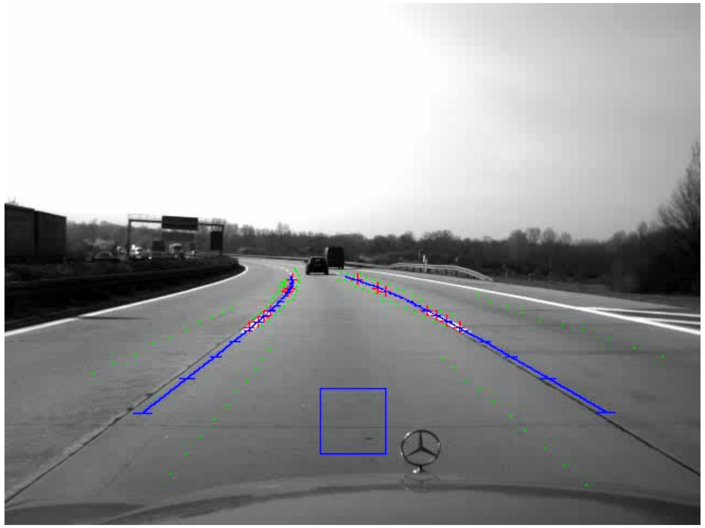
Common Approach to Road Recognition

1. Project



Low-dimensional geometry model (clothoid, …)



2. Compare with image cues

3. Update

→ Cannot be generalized to more complex domains

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Motivation

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1. **High-dimensional hypothesis space**
2. **Few features**
   - Narrow field of view
   - Massive occlusions
   - Omitted features
3. **Presence of noise**
   - Unmodelled objects
   - Decreased feature quality

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➔ Problem is ill-posed!

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What is needed?

1. Geometrical Model of arbitrary roads and intersections
2. Massive reduction of hypothesis space size
   - using prior knowledge
   - using large set of complementary sensor data: video object detectors, digital map, positioning sensors, …
3. Conceptual model of arbitrary roads and intersections
   - explicit representation (due to intensive HMI within a DAS)
4. Sound inference & retrieval services on the KB

→ Paradigm shift: Intersection recognition as
… scene understanding task
… ~~mid~~ high level vision task

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- **Decidable subset of 1st order logic**
- **Syntax:**

Name	*Description*	*Example*
Individuals	objects of the domain	*John*
Concepts	(≈classes) sets of individuals	Human
Roles	binary relations on individuals	hasChild
Constructors	to build complex expressions C, D → C ∩ D | C ∪ D | ¬C | ∃R.C | ∀R.C | T | ⊥ … R, S → R | R⁻ | R ∘ S	Man ∩ ∃hasChild.T

- **Semantics:** Set-theoretic

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Description Logic

- **Axioms** form sentences

Terminological Axioms	$C \equiv D$ $C \subseteq D$ $R \subseteq S$	Father ≡ Man ∩ ∃hasChild.T Father ⊆ Person hasChild ⊆ hasDescendent
Assertional Axioms	*i* : C *(i,j)* : R	*John*: Human (*John*, *Emily*) : hasChild

- A **DL Knowledge Base** consists of
  - **Tbox:** Set of terminological axioms
    ➔ state general domain knowledge here
  - **Abox:** Set of assertional axioms
    ➔ state knowledge about particular situation here
  - **(Rulebox)**

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- Classical DL **inference services**:

Satisfiability Check for TBox and Abox	(Mother ∩ Male) is inconsistent
Classification of Tbox and Abox	$\mathcal{KB} \models$ *John*: Father
Entailment	*John*: ∃hasChild.Female
Retrieval	Retrieve all individuals which are instance of: $\exists_{\geq 3}$hasChild ∩ ¬Female

- **Non-classical inference**

  ….

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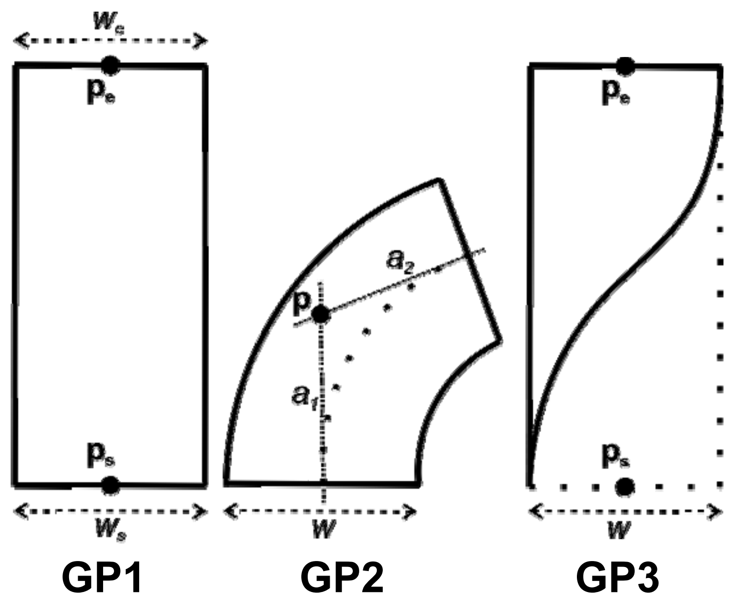
Road Network Hypothesis Space

A Geometrical Modelling

B Conceptual Modelling

1. Qualitative spatial relations
2. Road Network taxonomy
3. Geometric Constraints
4. Road building / Semantic Constraints



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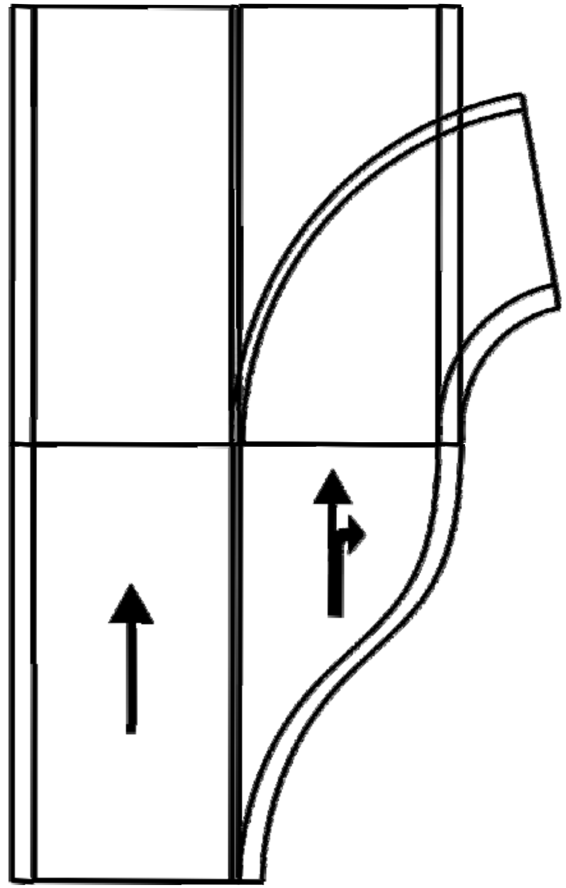

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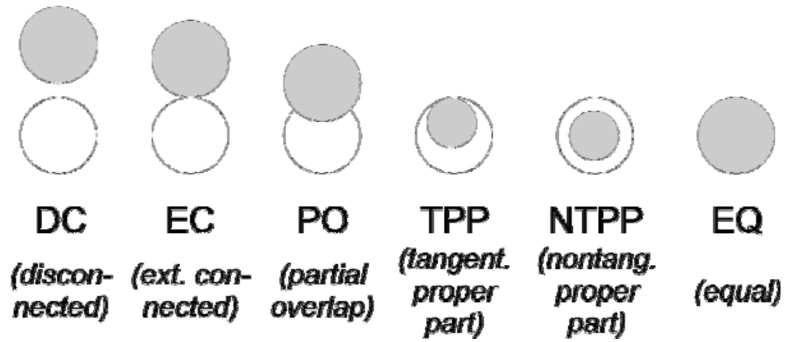
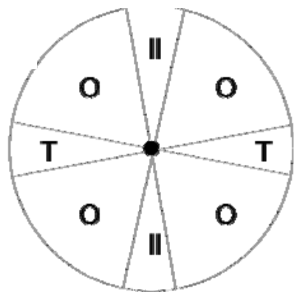
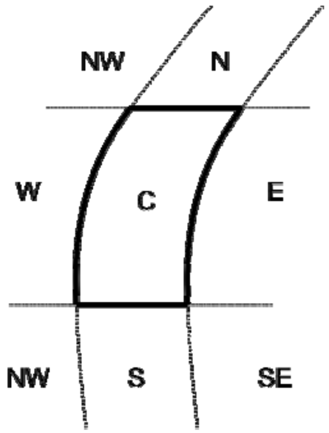


a) Degree of overlap (RCC-Calculus)





b) Rel. orientation c) Rel. position

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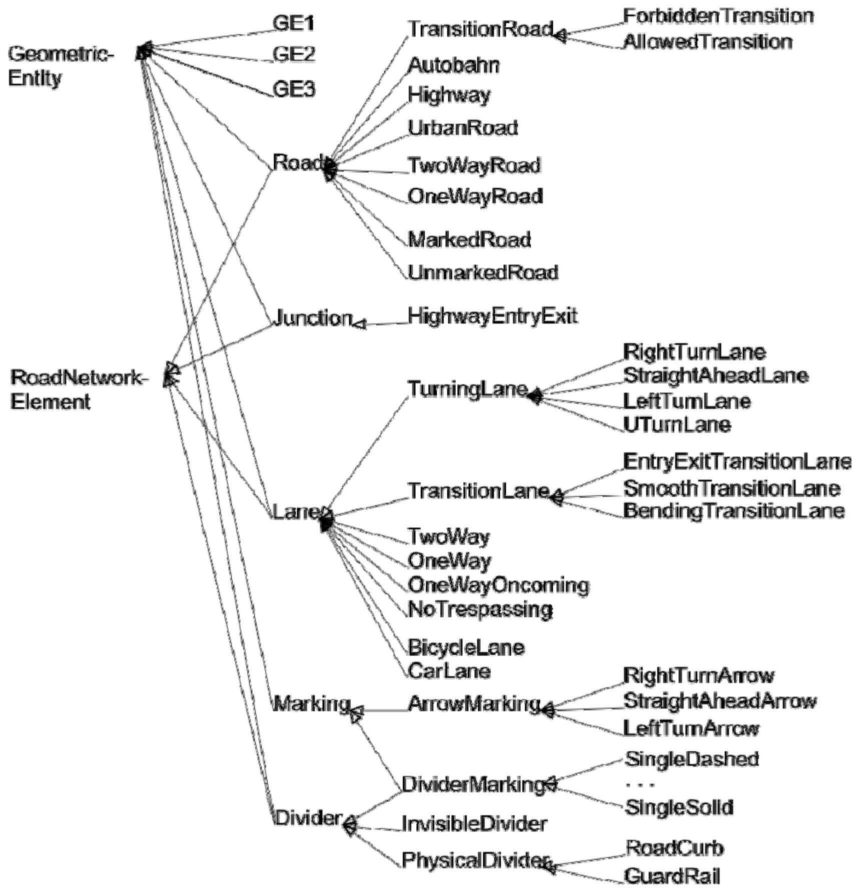

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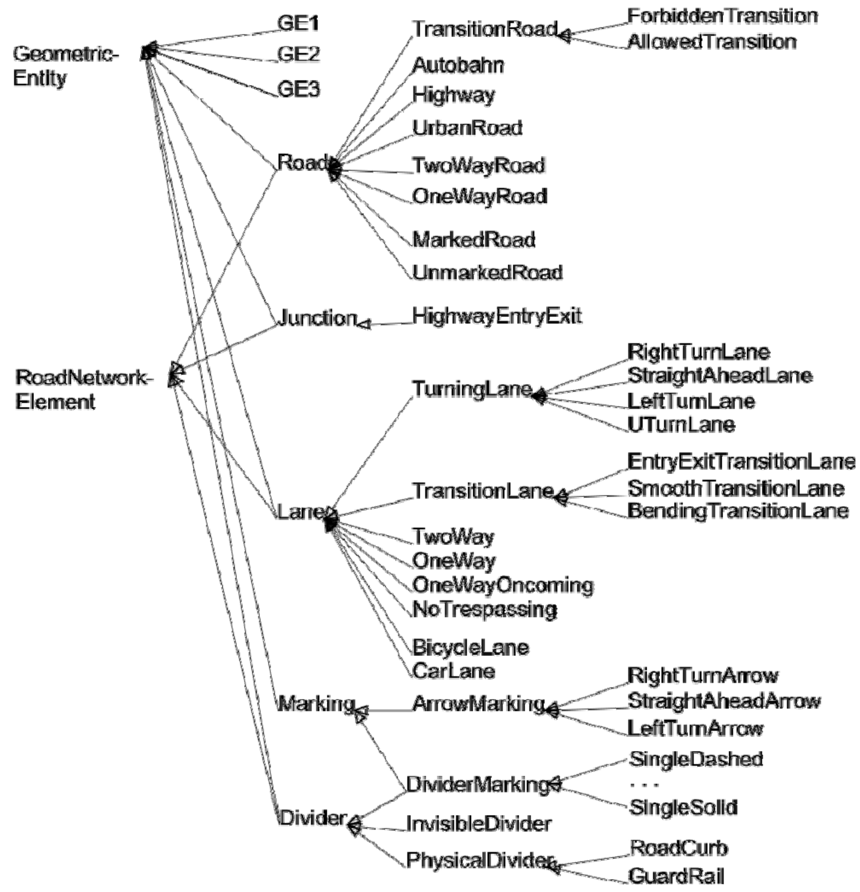

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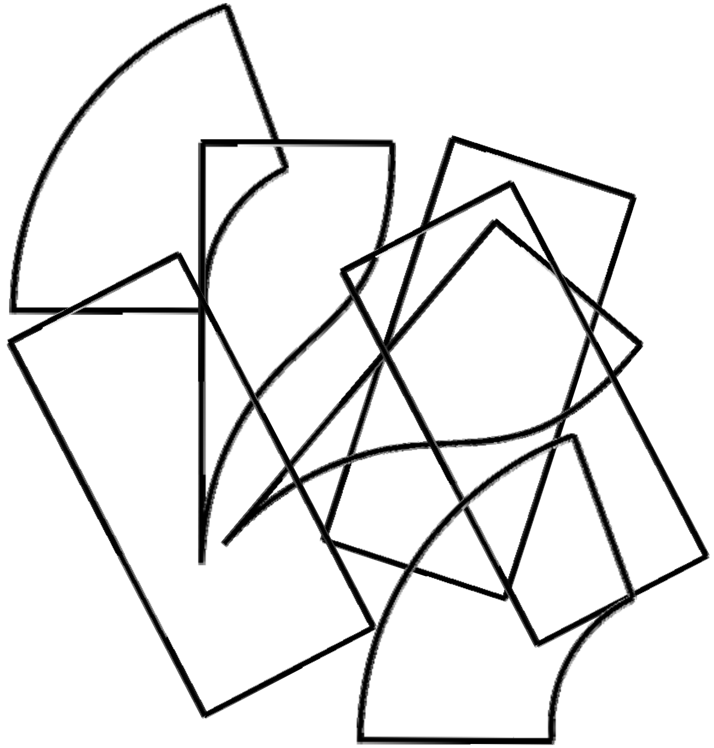

Arbitrary Sample

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// Lanes are externally connected

// only to lanes or dividers.

$\mathsf{Lane} \sqsubseteq \forall \mathsf{EC}.(\mathsf{Lane} \sqcup \mathsf{Divider})$

// Lanes only have arrows

// as proper parts.

$\mathsf{Lane} \sqsubseteq \forall \mathsf{PP}.\mathsf{Arrow}$

...

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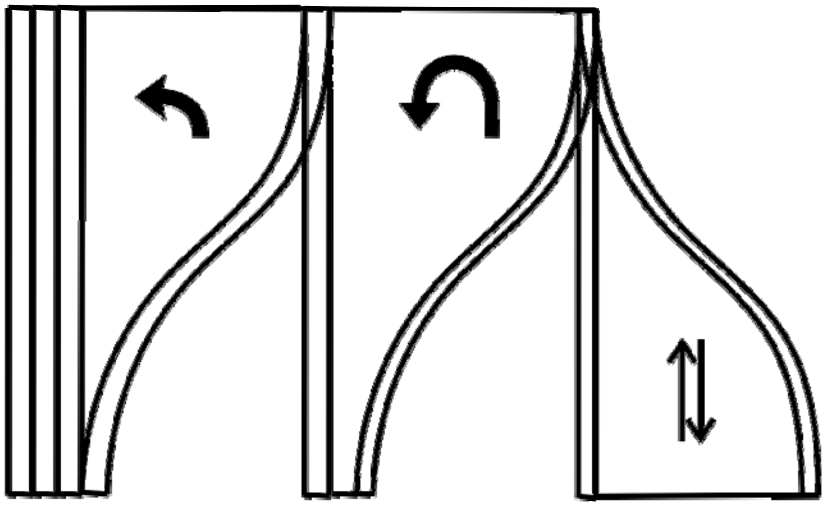

Arbitrary Road Sample

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// Only right turn lanes can be right of right turn len

$\mathsf{RightTurnLane} \sqsubseteq \forall\, \mathsf{hasEastNeighbor.RightTurnLane}$

// A one way road does not have a uturn lane.

$\mathsf{OneWayRoad} \sqsubseteq \forall\, \mathsf{NTPP}.\neg \mathsf{UTurnLane}$

// All autobahns and highways are one way roads.

$\mathsf{Autobahn} \sqcup \mathsf{Highway} \sqsubseteq \mathsf{OneWayRoad}$

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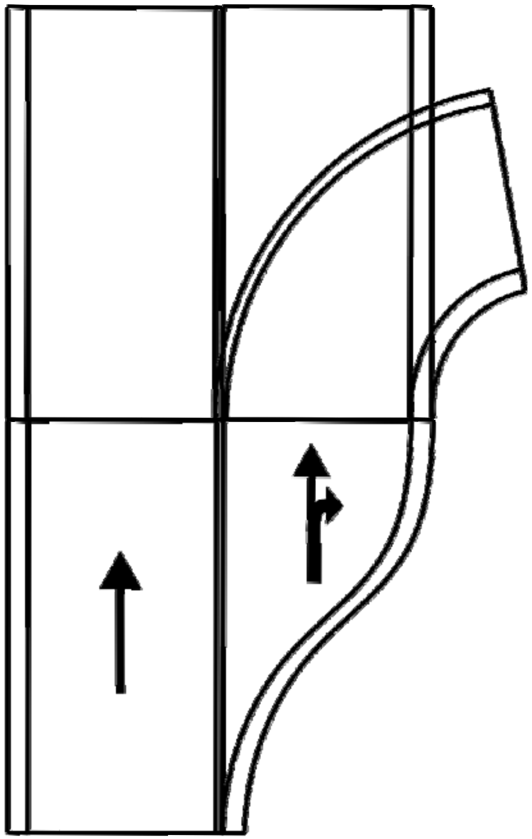

Arbitrary Sample

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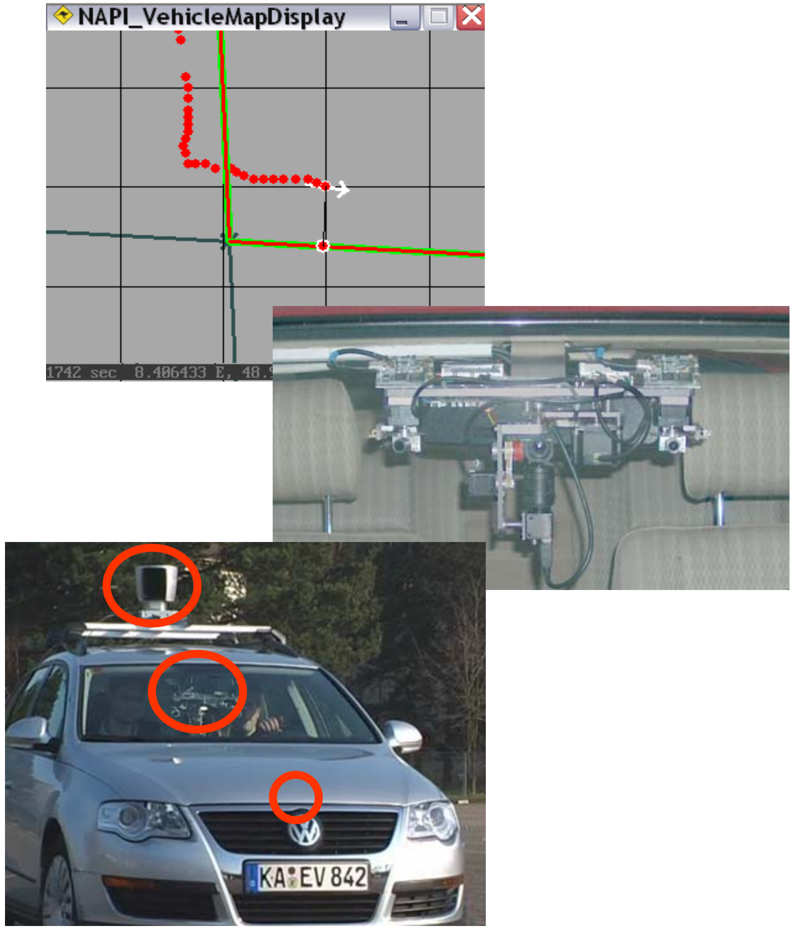
Sensor Data Input

1. **Digital Map**
2. **GPS & Map Matching**
3. **Video/Laser-based object detectors**



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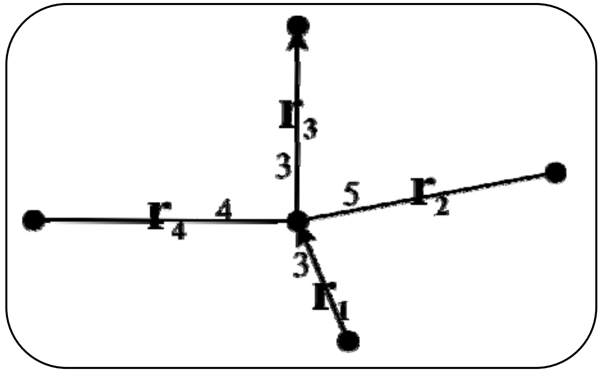

Symbol Grounding

[…] *// r4: not(OneWayRoad)*
[…] *// r4: has 4 Lanes*
[…] *// r4: leads to junction with 4 branches*
[…] *// Closed World Assumption*

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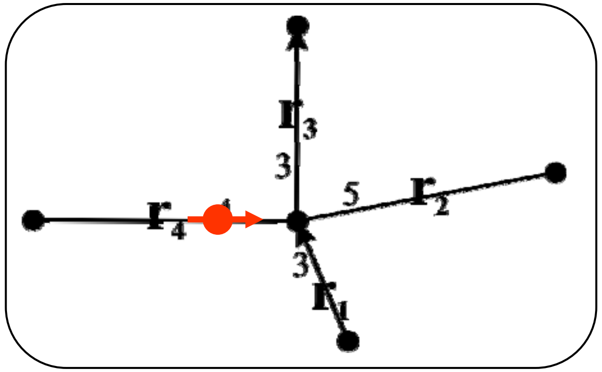

Symbol Grounding

$egovehicle : \mathsf{Vehicle}$	// create new vehicle
$(egovehicle, r_4) : \mathsf{NTPP}^{-}$	// is inverse proper part of road r_4
$(egovehicle, r_4) : \parallel$	// is parallel to road r_4

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Sensor Data Input

1. **Digital Map**
2. **GPS & Map Matching**
3. **Video/Laser-based object detectors**

Symbol Grounding

[…] // *i1: RoadCurb*

[…] // *i2: StraightAheadArrow*

[…] // *i3: DividerMarking50-20*

[…] // *state spatial relations*

[…] // *Open World Assumption*

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Inference

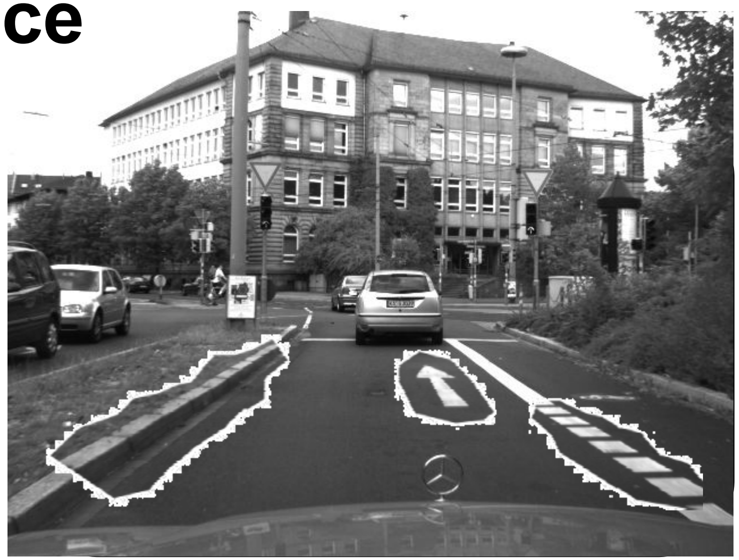
1. Draw all conclusions, given the KB (i.e. prior knowledge & sensor data)

   ➔ **Deduction**

2. Generate all intersection hypotheses

   ➔ **Model construktion**

➔ **Video-based hypothesis test / Deformable Model matching**



$$\mathcal{KB} \models l_{4.1} : \mathsf{OneWayN} \sqcap \mathsf{BicycleLane} \sqcap \mathsf{StraightAheadLane}$$

$$l_{4.2} : \mathsf{OneWayN} \sqcap \mathsf{CarLane} \sqcap \mathsf{StraightAheadLane}$$

$$l_{4.3} : \mathsf{OneWayS}$$

$$l_{4.4} : \mathsf{OneWayS}$$

$$\mathcal{KB} \models (egovehicle, l_{4.2}) : \mathsf{NTPP}^{-}$$

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   ➔ **Model construction**

➔ **Video-based hypothesis test / Deformable Model matching**

$$\mathcal{H} = \begin{pmatrix} \text{Abox } \mathcal{A}_1 \\ \vdots \\ \text{Abox } \mathcal{A}_n \end{pmatrix}$$

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1. Draw all conclusions, given the KB (i.e. prior knowledge & sensor data)

   ➔ **Deduction**

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   ➔ **Model construktion**

➔ **Video-based hypothesis test / Deformable Model matching**

Abox $\mathcal{A}_k$

Symbol Grounding

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Demo: Video

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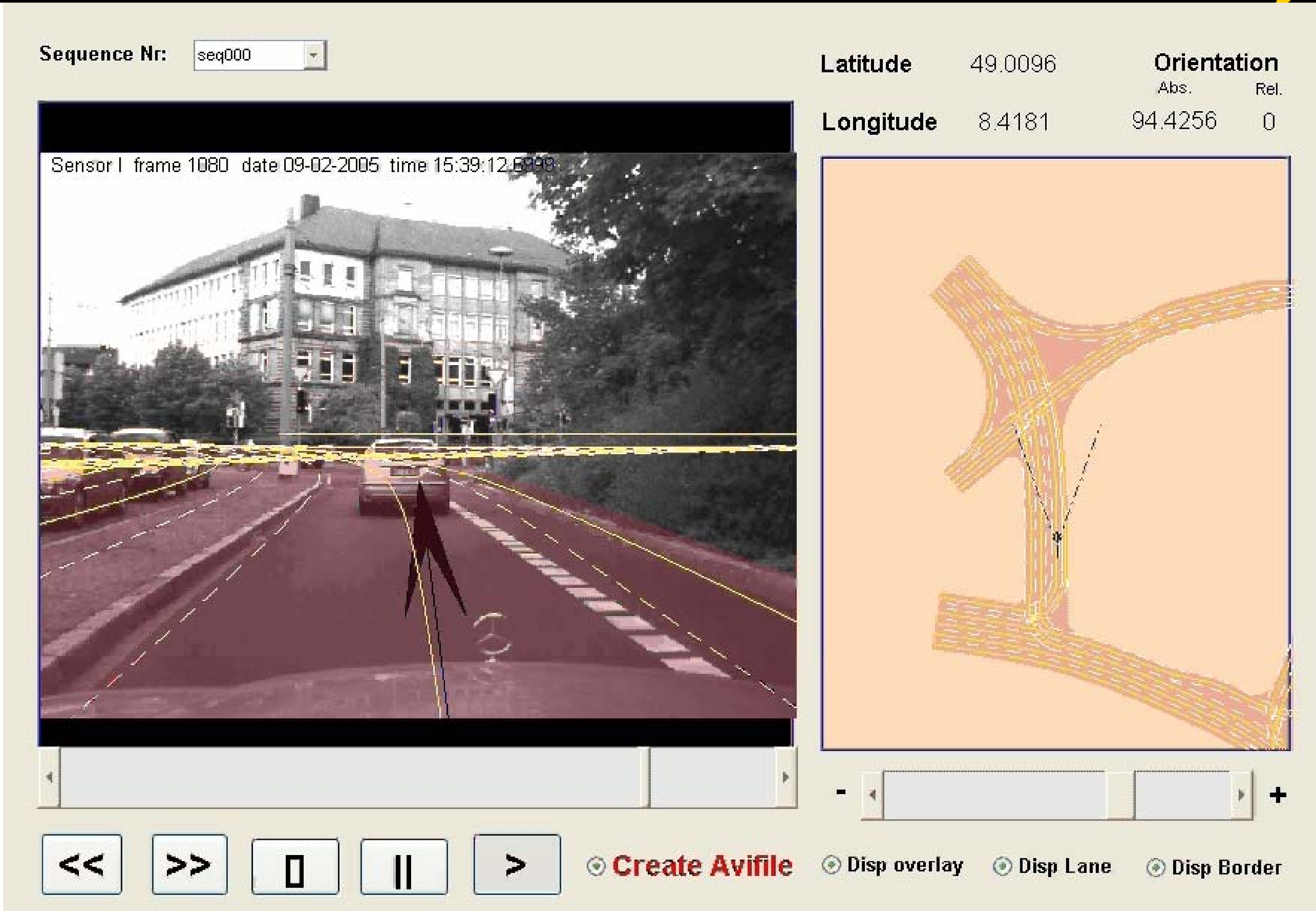

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Summary

Motivation:

- Road recognition works in toy worlds only
- A massive augmentation of prior knowledge is needed

Knowledge Representation:

- Introduction of DL as a formal, explicit, and readable knowledge representation formalism for real-world high-level scene interpretation
- Development of a DL RoadNetwork KB
  - High-level conceptual constraints
  - Map, Positioning, Video/Laser sensors

  } constrain hypothesis space

Inference:

- Deductive reasoning for querying the KB
- Model Construction for returning the set of intersection hypotheses
- Natural handling of partial observability, differing abstraction layers and incremental additions

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Outlook

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- **Hypothesize & Test**
- **Migration to probabilistic logic (MLN, SLP)**
- **Rule Learning from Training Data**

Thanks…

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Thanks for your attention.

Example: Proof of Result 5

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Results 1-4:

$$\mathcal{KB} \models l_{4.1} : \mathsf{OneWayN} \sqcap \mathsf{BicycleLane} \sqcap \mathsf{StraightAheadLane}$$
$$l_{4.2} : \mathsf{OneWayN} \sqcap \mathsf{CarLane} \sqcap \mathsf{StraightAheadLane}$$
$$l_{4.3} : \mathsf{OneWayS}$$
$$l_{4.4} : \mathsf{OneWayS}$$

Result5:

// The vehicle is on lane $l_{4.2}$.

$$\mathcal{KB} \models (egovehicle, l_{4.i}) : \mathsf{NTPP}^{-} \text{ , iff } i = 2 \text{ .}$$

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Proof sketch: The TBox of the $\mathcal{KB}$ contains the following statements:

// Marking50-20 is a divider for bicycle lanes.

$\mathsf{Marking50\text{-}20} \sqsubseteq \exists \mathsf{isLaterallyConnectedTo.BicycleLane}$

// This type of arrow only occurs on car lanes.

$\mathsf{Arrow} \sqsubseteq \forall \mathsf{NTPP}^{-}.\mathsf{CarLane}$

// Bicycle lanes are not next to each other.

$\mathsf{BicycleLane} \sqsubseteq \forall \mathsf{hasNeighbor.CarLane}$

Example: Proof of Result 5

These deductively lead to:

Result 5a:

// The driver's lane is a car lane (fortunately :)),

// and right of it, there is a bicycle lane.

$\mathcal{KB} \models \mathit{egovehicle} : \exists \mathsf{NTPP}^{-}.(\mathsf{CarLane} \sqcap$

$\exists \mathsf{hasEastNeighbor}.\mathsf{BicycleLane})$

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Example: Proof of Result 5

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Result 5b:

// Right of the bicycle lane there can only be a car lane.

$\mathcal{KB} \models egovehicle : \exists \mathsf{NTPP}^{-}.(\mathsf{CarLane} \sqcap$

$\exists \mathsf{hasEastNeighbor}.(\mathsf{BicycleLane} \sqcap$

$\forall \mathsf{hasEastNeighbor}.\mathsf{CarLane}))$

Example: Proof of Result 5

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// A lane with a straight ahead arrow is a straight ahead lane

[…]

// Right neighbors of straight ahead lanes are straight ahead or right turn lanes only.

[…]

// Bicycle lanes do not occur between lanes of the same turning lane type

[…]

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Result 5c:

// Right of the bicycle lane can only be a right turn lane.

$\mathcal{KB} \models \textit{egovehicle} : \exists \mathsf{NTPP}^{-}.(\mathsf{CarLane} \sqcap$

$\exists \mathsf{hasEastNeighbor}.(\mathsf{BicycleLane} \sqcap$

$\forall \mathsf{hasEastNeighbor}.\mathsf{RightTurnLane}))$

Example: Proof of Result 5

- Intermediate result:

  As r1 is a OneWayRoad towards the junction, r4 cannot have a right turn lane.

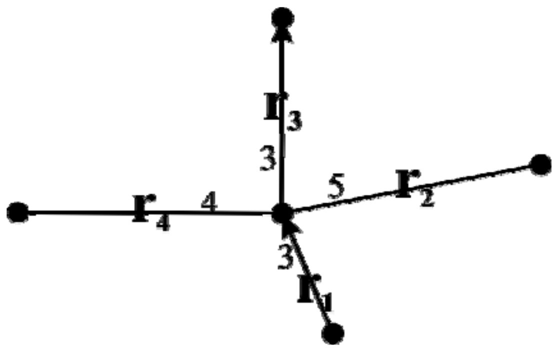
Result 5d:

// There is no more lane right of the bicycle lane.

$\mathcal{KB} \models egovehicle : \exists \mathsf{NTPP}^{-}.(\mathsf{CarLane} \sqcap$

$\exists \mathsf{hasEastNeighbor}.(\mathsf{BicycleLane} \sqcap$

$\neg\exists \mathsf{hasEastNeighbor}))$



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Example: Proof of Result 5

- *Closed World Assumption* for map data

==>

// The vehicle is on lane $l_{4.2}$.

$$\mathcal{KB} \models (egovehicle, l_{4.i}) : \mathsf{NTPP}^{-} \text{ , iff } i = 2 \;. \quad \Box$$

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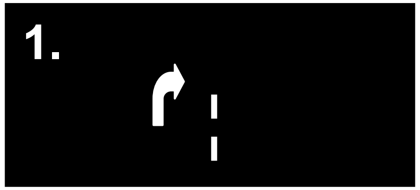
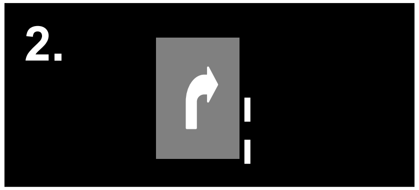
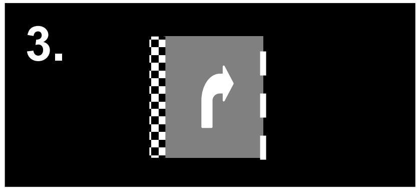
Hypothesize&Test



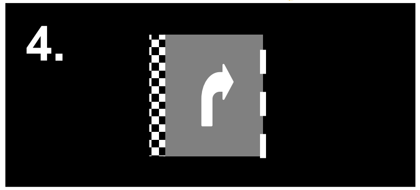
Evidence (ABOX):
```
RightTurnArrow(
  arrow1);
SingleLongDashed
  Divider(divi-
  der1);
```



Hypothesization:
```
Lane(lane1);
hasMarking(
     lane1,
     arrow1);
```

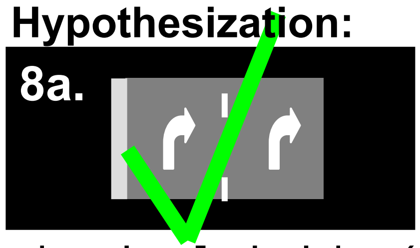


Hypothesization:
```
isConnectedWith-
     RightDivider(
     divider1);
isConnectedWith-
     LeftDivider(
     divider2);
```

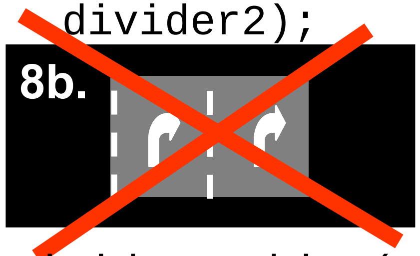


Hypothesization:
```
Road(road1);
isPartOf(lane1,
  road1);
```

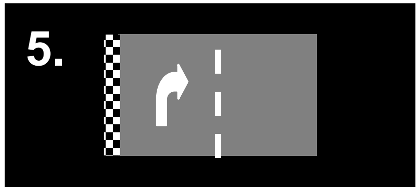
non-trivial Hypothesization:



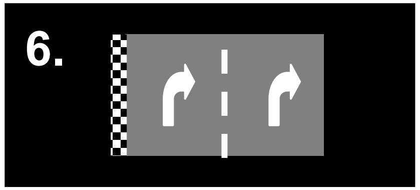

```
PhysicalDivider(
  divider2);
```



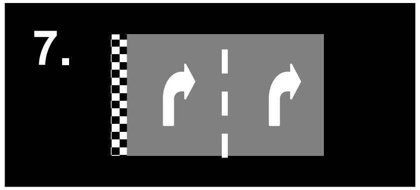

```
DividerMarking(
  divider2);
```



Hypothesization:
```
Lane(lane2);
hasRightNeighbor
  (lane1,lane2);
```



Deduction:
```
isPartOf(lane2,
   road1);
RightTurnLane(
   lane2);
```



Deduction:
```
MarkedRoad(
  road1);
```

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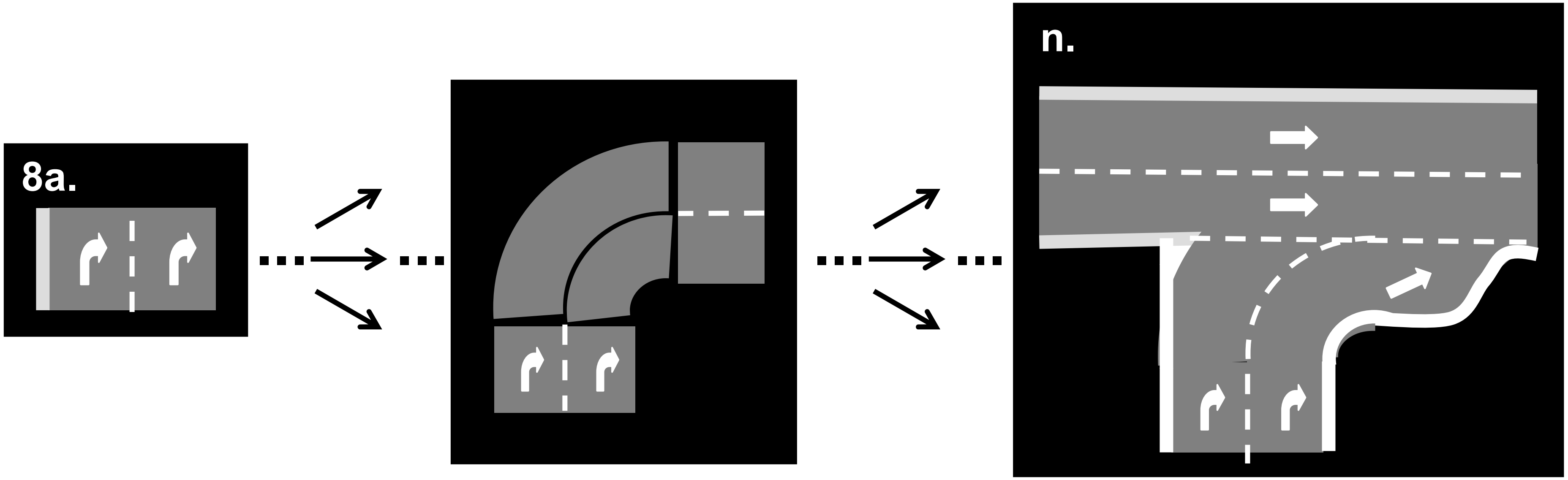

model complete

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