Improving Explanation and Effectiveness of Interactions among Autonomous Vehicles and Pedestrians

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Abstract

In this paper we describe a study involving an autonomous vehicle based on planning and interaction situations with other road users (i.e. *pedestrians*). The paper presents the research framework and directions towards enriching the vehicle information about the moving objects on its way with formal, explicit and shared representation of available findings about pedestrian on-road behaviors. Among the advantages of the integration of empirical data achieved through behavioral studies about pedestrian dynamics, we claim that a research effort in this direction may significantly contribute to improve trust, transparency, and quality of communication between heterogeneous road users, mainly to avoid and solve obstruction situations.

In the paper we describe first steps of this multidiscilpinary research and we present a representation of concepts related to pedestrian crossing behaviours at unsignalized pedestrian crossings (based on ontology formalism and derived from the reference literature). After, we introduce the movement planning model of the autonomous vehicle and we overview experiments we are developing to collect useful insights to improve knowledge on perception and interpretation of actions in interaction situations (involving pedestrians crossing in the presence of an autonomous vehicle). Further developments of the vehicle behavior to improve its capability to interpret the scene at real-time, as well as effectiveness of the vehicle communication with other road users are then discussed.

Introduction

Nowadays, autonomous driving is gaining increasing importance, with some vehicles supposed to perform at the SAE-level 5, already circulating in some cities. In this context, proper and interaction between a vehicle and the pedestrians that could be present in its surroundings is fundamental.

Pedestrian-aware planning, that is, planning keeping into consideration the behavior of pedestrians, is a longly studied problem in the robotics world. Initially, most of the works concentrated on the scenario of a robot moving in a crowded indoor space. For example Bennewitz *et al.* (Bennewitz et al. 2005) developed an approach that uses the prediction of the movement of a person to produce a better plan for the robot (*i.e.*, a plan that would not interfere with the motion of the person). Pacchierotti *et al.* proposed a planner for traversing corridors with people coming from the opposite site (Pacchierotti, Christensen, and Jensfelt 2005). While these works focus on avoiding physical interference with a person, they do not address the important problem of the *perceived safety* of a plan (Kulkarni et al.). That is, the perceived level of danger induced by the robot motion. To allow a perception of safety, the robot should not move very close to a person, as this is perceived as dangerous by the person. This problem has been studied by Nonaka *et al.* and its solution is a fundamental step for the introduction of robotics in everyday world (Nonaka et al. 2004). It has also been addressed by Chen *et al.* who presented a method for the avoidance of the pedestrians whose trajectory is tracked (Chen, Ngai, and Yung 2008). The need of a predictive model of the movement of pedestrians is, for instance, discussed in (Nishino et al. 2016).

With the advent of autonomous driving vehicles, this topic gained an even larger importance as cars move much faster and can be more dangerous than small indoor service robots. For this reason safety and effectiveness in the interaction between pedestrian and autonomus vehicles are essential. Having a model capable to describe how to interact with the heterogenous types of pedestrians in the many different conditions is thus an essential part of an autonomous driving system: it would be not effective to deal similarly with an elderly person and with a group of teenagers; analogously, the vehicle behavior should change when the road is dry and there is, e.g., risk of black ice.

The variety of pedestrian behaviors observed at intersections has been the subject of interest of several researches (Evans and Norman 1998; Hamed 2001; Perumal and others 2014), aiming both at a better understanding and modeling of the behaviors of road users. Besides the understanding of human behaviors, pedestrians' movement models are studied also for several other objectives; for instance, for their integration into pedestrian simulation software platforms (Federici, Manenti, and Manzoni 2014) and for the improvement of the quality of crowd management support systems. Knowledge sources about pedestrian behaviors are thus quite fragmented and relates to several study areas.

Among recent results on pedestrian crossing behavior, environmental, demographical, social and psychological factors have shown to have a relevant impact on risky crossing behavior (Sisiopiku and Akin 2003), such as pedestrian age (Gorrini, Vizzari, and Bandini 2016) and movement as part of a group (NT. Dang et al. 2016). The crossing be-

Figure 1: The autonomous vehicle involved in LONGEVICITY experimental research. It implements a two-level planner and it is able to detect and avoid obstacle that may be present on its surrounding. Previous experimentations have been conducted mainly in its natural application scenario of a crowded unstructured space (like a public square). Within the planned experimentation the cart will be involved in interactions with participants that will be asked to cross the road in the presence of the autonomous vehicle.

havior of elderly pedestrians, for instance, is affected by the progressive decline of motor and cognitive abilities linked to ageing (Dommès et al. 2015), and by a scarce level of assertiveness in communicating to drivers their intention to cross. Moreover, a pedestrian crossing decision is influenced also by the behavior of others who are crossing at the same time, as the simultaneous motion with other pedestrians reduces indeed cautiousness due to diffusion of responsibility, and successful of crossing is probably overestimated (Harrell 1991).

These observations, and the opportunity to collaborate within the LONGEVICITY[1] project, motivated us at including a multidisciplinary study involving developers of IRA lab autonomous vehicle (see Figure 1) and competences on crowd studies from CSAI research center. A dedicated experimentation has been designed to better investigate the behavior of crossing pedestrians in the presence of an autonomous vehicle and to assess potential advantages on trust, interaction and transparency of the vehicle activity (including actions performed for communication aims, i.e. inter-actions (Chakraborti, Dudley, and Kambhampati 2018)).

Pedestrians and vehicles can interact in many different ways, but they always have to comply with the road code and have safety in high regard (World Health Organization 2015). Among the many different scenarios of interactions we focused our studies on a zebra crossings not regulated by a traffc light (i.e. Unsignalized Pedestrian Crossing, from now denoted as UPC). In this case, interaction between vehicles and pedestrians is defined as *obstruction*, (Ferber 1999). As in any obstruction situation, interaction at UPCs require a conflict resolution strategy to grant the success of individual coordinated actions. In a non-automated vehicular-traffic system, the resolution of conflictual situations is delegated to traffic rules, but it is often influenced also by culture-influenced customs; several heuristics are often observed on real roads.

We claim that this work could contribute not only to safer driving behavior of autonomous vehicles, but also to improve the trust into its decision-making, and the effectiveness of its communication with the other road users (Fox, Long, and Magazzeni). With the shared general goal of improving the quality and shareability of available information, we aim at reducing risk of inappropriate vehicle behavior, improving vehicle knowledge on other road users behavior and exploiting this knowledge towards improvement of trustability of its activity. To realistically consider application scenarios where autonomous vehicles and humans interact, potentially also with other partially robotic road entities, acceptance (as trusted co-user of a shared space) is an unavoidable aspect. High-quality interactions are also required to effectively engage and realise a semantically rich exchange of information with other agents, such as pedestrians or cyclists. Moreover, transparency of vehicles activity will be advantaged by a set of shared regulations they can be used.

An ontological representation of available knowledge about pedestrian crossing behavior is described in the next section. The motion planning model of the autonomous vehicle that will be involved in the experimentation, and the experimentation aims and main steps are then summarised.

Pedestrian Behaviors at Intersections

The ontology described in the following is an explicit knowledge representation of available knowledge about pedestrian behavior at UPC (i.e. zebra crossing without traffic light coordination of flows). In this case, interaction between vehicles and pedestrians is defined as *obstruction*, (Ferber 1999): any agent involved in such situation has individual skills to employ autonomously the available resources to accomplish their goals, and agents' goals are compatible because one agent crossing the road will not compromise the capabilities

[1] The project "LONGEVICITY - Social inclusion for the Elderly through Walkability" has the objective to study the cities of the future as characterized by the growing presence of long-lived and active citizens and by the need to design technologically advanced infrastructures, considering the increasing role that autonomous vehicles will have in this scenario. The LONGEVICITY project is funded by Fondazione Cariplo, within the call Scientific Research 2017 "Aging and social research: people, places and relations" along the period between April 2018 and December 2020 (Grant No. 2017-0938).

of the other agents to go straight on their way and vice-versa. In crossing situations where paths overlap, the agents need to coordinate their actions in order to share the use of the limited resource (i.e. the road portion that both want to occupy at the same time). A conflict resolution strategy to grant the success of individual actions shall be introduced. In a non-automated vehicular-traffic system, the resolution of conflictual situations is delegated to traffic regulation laws, but it is often influenced also by culture-influenced customs and several heuristics are often observed.

The exploitation of ontology-based (Mizoguchi and Ikeda 1998) explicit representation of road rules, of driving behaviors and heuristics has demonstrated to be enough expressive and practicable to enable vehicle context understanding (Feld and Muller 2011; Armand 2016; Mohammad 2015; Zhao et al. 2015). The main references for this work have been: an ontology (Armand 2016) that includes context concepts such as Mobile Entity (Pedestrian and Vehicle), Static Entity (Road Infrastructure and Road Intersection), and Context Parameters (*isClose*, *isFollowing*, and *isToReach*) and an ontology-based framework (Mohammad 2015; Zhao et al. 2015) for assessing the degree of risk in a road scene taking into account several factors (e.g. risk from other mobile objects like vehicles, pedestrians, cyclists, environmental risk related to weather and visibility conditions and, road environmental risk that is, related to road quality, road traffic signs and road type). Applying rules written in *Semantic Web Rule Language* (SWRL), the ontology provides an informed interpretation of road contexts. An ontology is an explicit specification of conceptualization (Gruber 1995). It describes concepts and relationships that are relevant to model a domain of interest. It specifies the vocabulary that is necessary to make assertions, and which may be inputs/outputs of knowledge-based agents. Domain ontologies, when are based on *Description Logics* (DL) (Baader et al. 2003), are described by two functional parts: *Terminological Box* (TBox) and *Assertional Box* (ABox). In the following subsections, pedestrian ontology developed in an explicitly, formal and exploitable to improve vehicle scene interpretation and decision-making.

Ontology TBox

TBox consists of the definition of all the concepts and relations that the ontology aims to describe, in our case detectable scene objects and contextual information about vehicle observable scene. It specifies: **concepts** (or classes) of the domain that the ontology aims to describe, organised into a taxonomy; **roles** that are properties that can be defined and assigned to concepts. Roles can be either **object properties** that define axioms in the form of binary relationships between two concepts, or **data properties** used to assign properties to single classes or instances of classes in the form: Concept1 - *Data Property* - Property Value. **Relations** between concepts are defined by hierarchical relations (concepts taxonomy), axioms (classes linked by object properties) and rules.

Figure 2 shows part of ontology TBox about taxonomic relationships among road entities that may be perceived in a driving situation (on a single lane road), while Figure 3

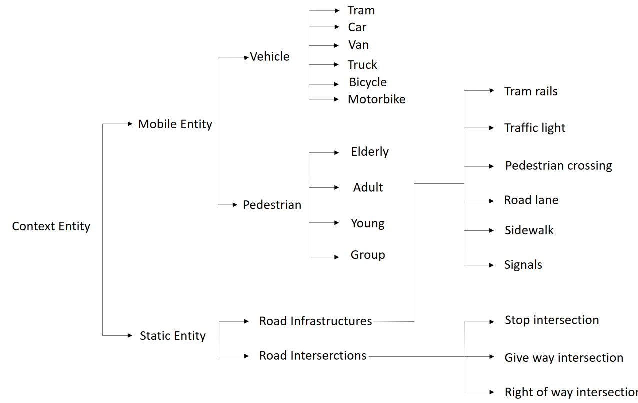


Figure 2: Graphical representation of TBox taxonomic relationships among road entities that may be perceived in a driving situation.

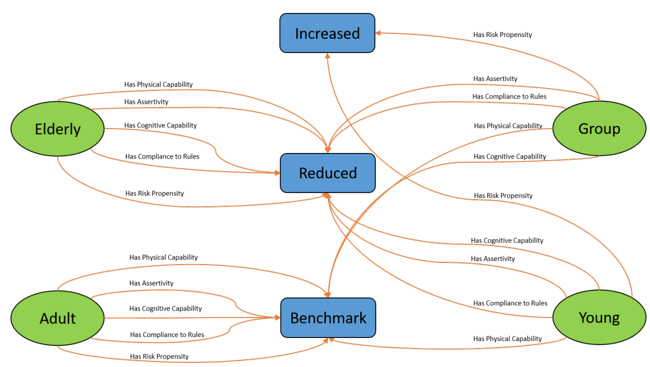


Figure 3: Graphical representation of TBox relationships between pedestrian profiles and relevant crossing features.

is a graphical representation of TBox relationships between pedestrian profiles and the following pedestrian profile properties: **cognitive capability** of subject's to estimate relevant motion coordination features (like distance from the subject and speed); **physical capability** to safely cross the road; **assertivity**, the ability to comunicate (more or less intentionally) the intention to cross; **compliance** with road rules; **propensity to risk**. Physical capability and propensity to risk are described as inversely proportional to age, while cognitive capability, assertivity and compliance decreases as the age diverges from the one of a reference pedestrian fully compliant to road traffic rules and with full capabilities and assertivity; for the present work, an adult person in the range of [25...50] years old.
The involvement of a child or of an elderly person in an interaction situation suggests its interpretation as potentially risky since, according to the reference ontology both pedestrian profiles are described as *less assertive and less respectful of traffic laws* and potentially less perceptive about communicative audio-visual signals. Rules like the ones exemplified in the Table manage this part of scene understading.

Each relationship refers to a pedestrian property and indicates whether the profile differs (with a reduction or increase) from a reference profile. Witin the T-Box ontology, these relationships are described in the form of axioms.

Ontology ABox

The ABox consists of instances of classes previously defined in the TBox, commonly called Individuals, that represent real life scenario, according to ontology interpretation. The ABox represents objects that are observed, and are understood thanks to prior knowledge available and explicitly described by TBox relationships (i.e. taxonomic relationships, axioms in the form of objects or data properties, or rules).

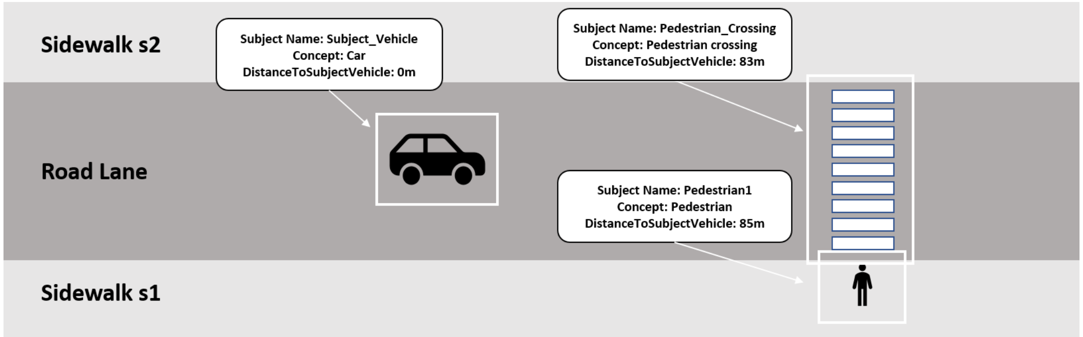
Figure 4 exemplifies an interaction situation at a unsignalized pedestrian crossing, with zebra crossing road infrastructure and right of way to pedestrians. Its description according to the above sketched TBox is shown. Information about detected road infrastructures, plausible profile of pedestrians and contextual information are available to be logged and exploited at, first real-time for improving decision making about actions to undertake in order to coordinate conflict resolution with pedestrian going to cross, as well. Moreover, this semantically rich contextual information is also available to improve explanation of vehicle decisions.

Vehicle(?v0) ∧ Adult(?p1) ∧ Road_lane(?rl1) ∧ IsCloseTo(?v0,?rl1) ∧ IsToReach(?v0,?p1) → HasToAlert(?v0,?p1)	The adult pedestrian *p1* is close to road lane and want to cross, so the vehicle *v0* alert *p1* that can't cross because *v0* is upcoming
Vehicle(?v0) ∧ Elderly(?p1) ∧ Road_lane(?rl1) ∧ IsCloseTo(?p1,?rl1) ∧ IsToReach(?v0,?p1) → HasToDecelerate(?v0,?p1)	The elderly pedestrian *p1* is close to road lane and want to cross, so the vehicle *v0* doesn't alert because elderly have be a reduced cognitive capability.*v0* has to decelerate because *p1* has a higher risk profile than the standard.
Vehicle(?v0) ∧ Young(?p1) ∧ Pedestrian_crossing(?pc1) ∧ Sidewalk(?s1) ∧ Road_lane(?rl1) ∧ IsOn(?v0,?rl1) ∧ IsOn(?p1,?s1) ∧ IsToReach(?v0,?pc1) ∧ IsToReach(?p1,?pc1) → HasToDecelerate(?v0,?p1)	The young pedestrian *p1* is to reach pedestrian crossing, the vehicle *v0* is to reach the pedestrian crossing, *v0* has to decelerate because *p1* is a risk profile of pedestrian and so is more difficult to predict his action.

Table 1: Rules to describe relationship between observed pedestrians approaching unsignalized crossing, and its interpretation by taking into account pedestrian profiles.

Vehicle Movement Planning

The autonomous vehicle involved in this experimental research (see Figure 1) is able to detect and autonomously avoid obstacles by computing its trajectories according to a two-level planning (i.e. global and local). Previous experimentations have been conducted (with a maximum speed of about 10 km/h) mainly in its natural application scenario of a crowded unstructured space (like a public square). Within the planned experimentation the cart will be involved in interactions with participants that will be asked to cross the road in the presence of the autonomous vehicle. A speed



Subject_Vehicle:
Object Property Assertions:

- **IsCloseTo** Pedestrian_crossing
- **IsCloseTo** Pedestrian1
- **IsOn** Road Lane

Data Property:

- **DistanceToSubjectVehicle** 0m
- **HasSpeedValue** 50 km/h

Pedestrian1:
Object Property Assertions:

- **IsCloseTo** Road Lane
- **IsCloseTo** Pedestrian_Crossing
- **IsCloseTo** Subject_Vehicle
- **IsOn** Sidewalk s1

Data Property:

- **DistanceToSubjectVehicle** 85m
- **HasSpeedValue** 3.7 km/h
- **IsAppraising** True

Pedestrian_Crossing:
Object Property Assertions:

- $\emptyset$

Data Property:

- **DistanceToSubjectVehicle** 83m

Action: Subject_Vehicle *has to stop* before Pedestrian_Crossing.

Figure 4: Example of a pedestrian crossing scenario (scale is not respected) and its interpretation according to ontology TBox rules, axioms (object and data properties) and concepts taxonomy.

profile between 20 km/h and 30 km/h will be designed properly. The best path to reach the goal is computed, first, taking into account only a previously determined static map (global plannig). This step is very similar to what a car navigation system does, although it does not have to necessarily use a topological map. The global planner calculates a path that the vehicle should follow. However, in practice, the vehicle will not be able to precisely stick to it. Dynamic objects, like pedestrians, cars or other movable objects are taken into account by local planner. Local planner takes as input a path calculated by the global planner and generates the best commands in order to follow it, taking into consideration any obstacle that the vehicle can perceive. Of course, it may happen that the vehicle has to deviate from the path, in order to avoid an unexpected obstacle.

During local planning, various feasible trajectories are generated, scored according to various criteria and the best one is chosen. Trajectories that should pass through occupied cells are obviously discarded (Figure 5(b)). A drawback of this type of local planning is that, while a trajectory represents an anticipation of future world state, its evaluation is taken into account only considering current environment state. If a trajectory intersects the current position of a crossing pedestrian, it is discarded, even though that person is moving and will not be there at the time the vehicle reaches that position. In this case, trajectory would be perfectly feasible. On the other hand, a local planner could choose a trajectory that passes through currently free space, but that would be occupied in the future because a person is moving (Figure 5(b)). This problem severely decreases the performance of a local planner, known for both indoor robots and autonomous vehicles. A performance study on our vehicle is object of current research.

Global planning is usually performed only once, unless the path reveals to be infeasible for some previously unexpected reason. On the other hand, local planning is performed cyclically, usually at a fixed rate, because it has to control the vehicle in order to avoid obstacles and keep moving to the goal. Finally, the commands computed by the local planner are used as set points for the control loops of the actuators, which run at a fixed and much higher frequency.

On this vehicle, the availability of semantically unambigous knowledge on pedestrian motion could improve local planner in both its decision-making and interaction with

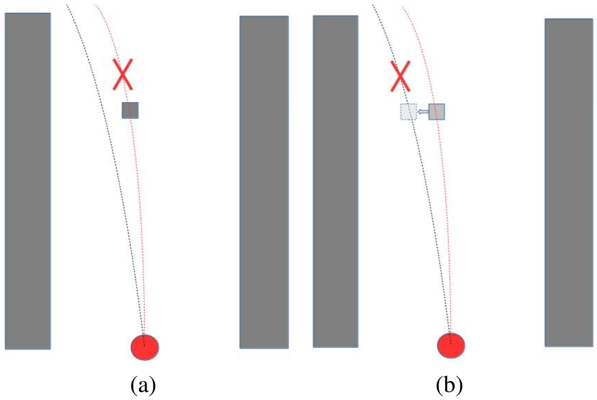


Figure 5: (a) An example of grid map with obstacles (in grey). The robot (in red) discards a trajectory that passes through an obstacle. (b) An example of the same scenario when the robot knows that the obstacle is a pedestrian and has a model of her/his motion, it can choose much better trajectories. The one on the left, indeed, is discarded not because it intersects an obstacle at the time of planning, but because it will intersect the path of the pedestrian.

other road users, for instance adapting its behavior (movement and online communicative actions) to different pedestrian profiles.

Experiments on Vehicle-Pedestrian Interaction at UPS

Within the LONGEVICITY project, the Complex Systems and Artificial Intelligence research center and Informatics and the Robotics for Automation laboratory of the University of Milano-Bicocca are sharing their competences with the aim of developing a cross-disciplinary approach to study pedestrian-autonomous vehicles interactions at UPC by means of the execution of an experimental campaign. In this methodological framework, a set of experiments will measure the interactions between a large sample of adult and elderly pedestrians and the autonomous vehicles developed by the IRA lab. The experiments will be executed with the authorisation of the Ethics Committee of the University of Milano-Bicocca, and they will be carried out in a private road of the campus of the university. Participants will be asked to cross the road in the presence of the autonomous vehicle; the crossing episodes will be video recorded from a zenithally point of view to facilitate video tacking analysis, focused on measuring the crossing behaviour of pedestrians by considering their trajectories, speed and crossing decision. In analogy with the results of the video-recorded observation performed in 2015 by the CSAI research center (Gorrini, Vizzari, and Bandini 2016), data analysis will be focused on measuring:

- the *appraising phase of pedestrians*: the pedestrian approaching the cross-walk decelerates to evaluate the distance and speed of oncoming autonomous vehicle;
- their *crossing decision*: the pedestrian decides to cross and speed up;
- the *safety gap accepted by pedestrians to safely cross*: the relation between the distance and speed of oncoming autonomous vehicles, when pedestrians decided to cross.

Achieved results will be compared with data from the literature, to highlight differences between the crossing behaviour of pedestrians in case of interaction with autonomous and human-driven vehicles. The experimental design includes several procedures to test the impact of different variables on the crossing behaviour of pedestrians (e.g., different braking patterns of the vehicles in terms of deceleration magnitude and distance from the pedestrian; presence of a driver supervising the autonomous vehicles; presence of the passenger only). Moreover, the experiments will aim at testing the effectiveness of a breaking light actuator on the front of the vehicle as a visual communication system to support the crossing decision of pedestrians. The final aim of the experiments is to collect useful insights to support the further development of the vehicles, through the exploitation and integration of the above described pedestrian ontology into the autonomous vehicle movement planning model, in order to improve its capability to interpret the scene at real-time.

Conclusions

The paper refers to an multidiscplinary research conducted at University of Milano-Bicocca towards the integration of available findings and knowledge about pedestrian dynamics at unsignalized pedestrian crossing to improve quality of scene interpretation, communication, and trustability of vehicle actions into the movement planner of the IRA lab autonomous vehicle.

The paper has presented the pedestrian ontology (in its T-Box and A-Box components) we developed to collect into a well-formed, machine readable and semantically rich framework part of available knowledge about behavioral studies findings about pedestrian dynamics. Vehicle-pedestrian interactions at UPCs is the reference case study here described. The adoption of an ontology as knowledge representation framework is due to advatages provided by any (formal, in the sense of semantically well-defined) tool to manage explicit knowledge. Evaluations about computational costs of pedestrian knowledge ontology implementation will be object of future investigation.

A possible direction towards the development of a learning behavior of the vehicle in interaction situations with pedestrians may consider several approaches as reasonable: Goal Reasoning (Wilson et al.), or Case-Based Reasoning (CBR (Kolodner 1993)), like for instance in (Floyd and Aha 2017) where stored information about previously adapted behaviors is used with the aim of taking into account human trustworthy of previous plan adaptations, is one of our preliminary preferred directions for further investigations.

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