Physical Puzzles—A challenging spatio-temporal configuration problem

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Abstract

This paper serves to argue for spatio-temporal configurations problems in physical domains, called physical puzzled for short, as benchmark problems for qualitative representation and reasoning. The kind of physical puzzles we consider involves simple objects subject to the laws of physics. The physical laws needed to solve a physical puzzle are all known and belong to the fragment of laws commonly considered as common sense. However, the problem specification involves several unknowns. Thus, in order to construct a solution, tests need to be carried out to evaluate solution candidates. The objective is to find a solution and to minimize the number of tests required. This task is a solid platform for demonstrating the effectiveness of reasoning techniques capable of handling common sense knowledge of mainly spatial and temporal knowledge.

1 Introduction

Qualitative representations aim to capture human commonsense understanding and to enable efficient symbolic reasoning processes that yield rational decisions in complex tasks. Qualitative representations abstract from an overly detailed domain by only distinguishing an essential set of meaningful concepts. Qualitative approaches are widely acknowledged for their ability to abstract from uncertainty, for example an uncertain measurement of a location can become a certain notion of region membership. Naturally, different tasks may call for different qualitative concepts to describe the state of affairs. This task-dependency lead to development of a wide range of qualitative representations of space and time—see [Cohn and Renz, 2007] for an overview.

When benchmarking qualitative representation and reasoning it appears natural to jointly consider adequacy of representation and effectiveness and efficiency of reasoning. Since qualitative representations are meant to provide us with a formal model for common-sense reasoning, we argue for studying problems which are easy to solve for humans but hard for computers. To this end, we examined mainly spatial configuration problems in the physical domain, i.e., problems in which objects need to be arranged in a certain way in order to achieve the goal. As claimed by Bedeweg, "reasoning about, and solving problems in, the physical world is one of the most fundamental capabilities of human intelligence and a fundamental subject for AI" [**?**]. Problem solving in a physical context can thus be considered a well-suited benchmark domain for AI. The physical domain is also very relevant to qualitative reasoning. As Williams puts it, "[...] the heart of the qualitative reasoning enterprise is to develop computational theories of the core skills underlying engineers, scientists, and just plain folks's ability to hypothesize, test, predict, create, optimize, diagnose and debug physical mechanisms" [**?**]. The idea to study physical puzzles has some tradition is AI research. For example, the seminal poverty conjecture in qualitative representation [Forbus *et al.*, 1991] was illustrated in context of a bouncing ball scenario. In the light of today's state of the art in qualitative spatial, Cohn and Renz take a more differentiated point of view [Cohn and Renz, 2007]. Therefore, we regard physical puzzles to be the domain of choice to evaluate advances in qualitative reasoning.

2 The Physical Puzzle Domain

Our proposal has been inspired by computer games that, among other difficulties, confront the player with tricky physical problems that involve spatio-temporal reasoning as well as reasoning about action and change. Two games exemplify the genre of physical puzzles we propose to study: the game Deflector published by Vortex Software in 1987 (see Fig. 1 for a screenshot of the Commodore 64 version) requires the player to arrange a set of rotatable mirrors in such a way as to make a laser beam hit balloons. Hitting all balloons (and thereby making them burst) clears a level. This kind of puzzle is a purely spatial one. Obstacles placed in the level make it hard to foresee which mirror setup is required to point the laser to a specific point in space. Whilst this problem can be solved purely using computational geometry, the state space is too large to be enumerated by humans. Human players need to employ some means of heuristics and reasoning in order to construct solutions. The second game, called Crazy Machines developed by FAKT Software is similar but involves a complex physical domain (see Fig. 2 for a screenshot). The objective is to arrange objects in such a way that they exhibit certain functionality (again, usually making a set of balloons burst). This game is not only more complex as it involves a variety of physical laws (gravity, magnetism, etc.), but it also

Figure 1: Screenshot of the computer game Deflektor in which rotatable mirrors have to be arranged such that all balloons (grey) are destroyed by the laser beam (yellow).

involves many unknowns. No physical constants like friction coefficients, mass, or density are known.

When details of the underlying physical model are unknown or cannot be handled computationally[1], a solution cannot be determined in by a single computation. Instead it becomes necessary to first construct trial solutions and study how they perform. In order to make a ball running a ramp hit a trampoline (see Fig. 3) it is necessary to first observe where the ball hits the ground. Then the trampoline can then be placed accordingly. Aside from such simple variations of where exactly to place the trampoline between objects O_1 and O_2, more complex relationships need to be assessed too. Again considering Figure 3, it is by no means easy to see whether placing a trampoline on the ground between O_1 and O_2 would help to make the ball bounce over the obstacle O_2 in order to reach the goal area. In conclusion, unknowns introduce uncertainty on two levels, on the numerical level of fine-tuning a solution and on the qualitative level.

2.1 Reasoning in Physical Puzzles

Reasoning can help in different ways to solve a physical puzzle. First of all, qualitative assessment of a trial can help to guide the search for the right choice of parameters. To this end, a representation of some basic physical knowledge is required. From such background knowledge one can infer whether a parameter like the position of a trampoline needs to be shifted to the left or to the right. The same approach can also help to recognize that fine-tuning parameters will not lead to a solution. For example, if the trampoline does not make the ball jump high enough (top vertex of the parabola-like trajectory is not above O_2) , than it becomes pointless to fine-tune how the trampoline bounces back the ball.

More importantly, reasoning on the qualitative level can also help to identify solution candidates. To this end any solution to the physical puzzle also needs to be a solution of the qualitative abstraction of the puzzle. This allows for a generate-and-test approach based on qualitative reasoning. First, solution candidates are generated on the qualitative level

[1] for example, if inverse kinematics cannot be handled analytically

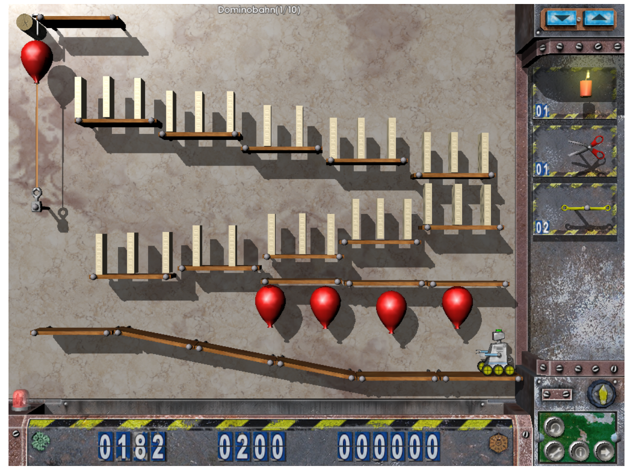

Figure 2: An exemplary physical puzzles from the computer game Crazy Machines. The objects to the right (including a burning candle and several levers) have to placed such that all balloons burst. The robot in this puzzle is capable of carrying an object and will only move straight on, eventually falling off the platform.

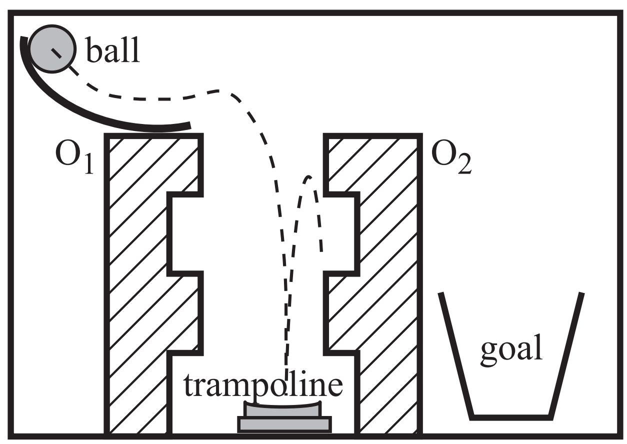

Figure 3: A physical puzzle in which trampolines need to placed to make a ball reach a goal area

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Figure 4: Specialized (extended) Bouncing Ball Puzzles BBP^0 (left) and $eBBP^0$ (right)

and then it is studied by trials whether it the solution candidate is realizable in the concrete physical context given.

To foster reasoning we treat the physical world as a black box and aim to minimize the number of trials required. We note that the necessity of performing trials is not an artificial burden but it is also common in engineering problems. Even when all physical effects involved are known, one might not be able to create reliable computer models. It is up to the researcher developing a reasoner (or up to the engineer, respectively) to minimize the amount of experiments necessary.

Even simple physical puzzles involve a dense and complexly structured search space that does not become tractable until reasoning is applied. The level of difficulty can easily be fine-tuned by changing the number of static obstacles and by limiting the set of objects that can be placed. We conclude that physical puzzles are an excellent problem to study the utility of approaches to qualitative representation and reasoning.

3 Problem Specification

The physics considered in this proposal are the physic of rigid objects including gravity. For the sake of simplicity we only consider the task of throwing a ball into a basket. In order to solve a puzzle, one can change how the ball is thrown from a fixed start position (by choosing the initial velocity vector) and one may alter a given scene by placing objects from a given set of objects.

Definition 1. *Let S be a function that maps a parameter a tuple $P \in \mathfrak{P}$to a continues path T, where a path if a function $T : [0;1] \mapsto \mathbb{R}^n$. Let $G \subset \mathbb{R}^n$ be the set of goal positions. $P^\star$ is a solution iff $G(T^\star(1)) = \top$ with $T^\star = S(P^\star)$. A **physical puzzle** is then the tuple $< S, G, \mathfrak{P} >$.*

The function S is the physical *black box* and usually contains internal parameters that are unknown to the solver of the physical puzzle. S can used by the solver to evaluate trials and the evaluations of S are counted. All known information is part of the parameter $P =< p_1, \ldots, p_m, x, a_1, \ldots, a_k >\in \mathfrak{P}$, where p_i are the free parameters over fixed domains D^i , x is the starting point, which is usually fixed and a_i denotes other fixed *attributes*, such as the objects in the world. We now list a set of distinct types of physical puzzle problems order by increasing difficulty.

The Bouncing Ball Puzzle (BBP) In this puzzle only two free parameters are available: the angle and the strength of the initial force applied to the ball. A scoring function counts how many tries, i.e., calls to the S function, a given approach requires. For comparison purposes an approach should be evaluated on a number of such puzzles and the resulting statistics should be given.

Some special cases of these puzzles can be identified:

BBP^0 in this scenario the goal area is contained be obstacles but can be entered freely by the ball from the top, no other obstacles are present (see Figure 4).

BBP^{-1} this is the normal BBP but without gravity

The extended Bouncing Ball Puzzle (eBBP) In this problem a number of objects can be placed to alter the path of the ball. Some special cases of these puzzles can be identified:

eBBP^0 in this scenario the goal area is contained be obstacles but can be entered freely by the ball from the top, no other obstacles are present. But the ball has a fixed initial force applied and can only be guided into the goal area by placing objects (see Figure 4).

eBBP^{-1} this is the normal eBBP but without gravity

4 Conclusion

In this proposal we argue for solving configuration problems in the physical domain to benchmark qualitative representation and reasoning techniques. Solving problems in physics of rigid objects is largely of spatio-temporal nature, but it involves unknowns, resulting in a steep scaling behavior with respect to problem complexity. We have chosen the physical world as our domain as it covers spatial, temporal, and general qualitative reasoning. Furthermore, it gives rise to the ultimate benchmark: to defeat human problem solvers in computer games. Using a physical simulator that takes quantitative input parameters and produces a quantitative output we allow different qualitative representations to be applied and successful puzzle solvers can be expected to be relevant for serious practical applications.

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References

[Cohn and Renz, 2007] Anthony G. Cohn and Jochen Renz. Qualitative spatial representation and reasoning. In F. van Harmelen, V. Lifschitz, and B. Porter, editors, *Handbook of Knowledge Representation*, pages 551–596. Elsevier, 2007.

[Forbus *et al.*, 1991] Kenneth D. Forbus, P. Nielsen, and B. Faltings. Qualitative spatial reasoning: The clock project. *Artificial Intelligence*, 51:417–471, 1991.