Tangibles for Graph Algorithmic Thinking: Research Questions and Work-in-Progress

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Abstract. Algorithmic thinking is at the hearth of the best known computational thinking. It requires the abilities to decompose and model a problem with a certain representation, and devise or understand an algorithm for making a computer solve it. Such abilities are rather abstract and thus algorithmic thinking is often neglected in primary and middle schools. This research picks up the challenge of designing interactive tangible objects, enhanced by Internet of Things technologies, that can help children in mastering algorithmic thinking. The research reported in this paper focusses on graph algorithmic thinking, the latest prototype of tangibles for graph algorithmic thinking and its usage in the field.

Keywords: Algorithmic Thinking; Interaction Design; Interactive Tangible Objects

1 Introduction

1.1 Setting

Computational Thinking (*CT*) [18] refers to a pool of abilities necessary to abstract away a problem and represent it in a format amenable for computers to process. It takes four main abilities: decomposition and modelling; pattern recognition; pattern generalisation and abstraction; algorithm design. At the core of CT abilities, one can recognise the less known *Algorithmic Thinking* (*AT*) abilities. Thinking algorithmically means being able to decompose a problem into essential components and model it with a certain representation, so as to give step-by-step instructions to make a computer solve it (an algorithm) [11].

Graph AT is the focus of the PhD work presented in this paper. In short, a(n undirected) *graph* is a rather general representation format. It consists in an ordered pair $G = (V, E)$, with $V = \{v_1, \ldots, v_n\}$ the set of *nodes*, and $E = \{\{v_i, v_j\} \mid v_i, v_j \in V\}$ the set of *edges* between pairs of nodes. Graph AT requires to decompose and model a problem with a graph, and to explore or envisage algorithms for resolving it. Example problems, familiar to all, are given by social networks, of Facebook friends or classmate friends. Problems concerning such social networks can be decomposed and modelled with graphs. People can be modelled as nodes, and edges between nodes can be used to represent friendship relations. Possible problems are: is there a way to connect a person, A, to another, B, through a chain (a path) of mutual friends? If not, how can one connect all the given people? In other words, how can one devise an algorithm for that?

1.2 Research Problem and Rationale

As the above examples show, understanding graphs and modelling problems with graphs are prerequisites for exploring and devising graph algorithms. However, they are rather abstract things for primary and middle school children to carry out. And yet CT and AT in particular are nowadays considered fundamental skills for those children as well.

For primary and middle school children, interactive tangibles for teaching graph AT can be of help: tangibles could foster the interplay between abstraction and concreteness, thus helping even the youngest to learn through multi-sensory experiences, and be actively engaged in the experiences. This paper is based on the idea of designing and using *interactive tangible objects for graph algorithmic thinking* (briefly, *graph AT tangibles*), with and for primary and middle schools, so as to promote multi-modal learning of graph AT and engaging all children actively in the process. Such tangibles can be developed so as to exploit current *Internet of Things* (IoT) technologies.

The design of graph AT tangibles is however highly complex: they should help children grasp abstract concepts, promote multi-modal learning and be engaging. It takes a specific design methodology that brings tangibles in the field, which makes design advance through children's usage of tangibles, and children learn through the process. In other words, it takes a design approach that moves into specific real contexts and brings all participants clear benefits.

1.3 Paper Outline

The paper starts presenting current work in the area of AT learning and tangible design with users. Starting from this, it frames the main research questions of the PhD. Then it overviews and explains the adopted design methodology and process. It presents the current prototype design and the latest usage in the field, with primary and middle school children. Results are still under analysis and thus the reported findings are work in progress. The paper concludes with reflections for future work in the area of tangible design and AT for children.

2 Related Research Work

2.1 Computational and Algorithmic Thinking

Literature on computer science education highlights three main categories of approaches to teaching CT, in general, and AT, in particular: (1) without computers; (2) by coding, with computers; (3) with interactive tangible objects.

Perhaps the best known approaches to AT education are based on *coding*, with programming environments for children, such as Scratch [17]. Proposals such as *CS-unplugged* by Bell [2], instead, teach CT without computers: they require physical activities, using everyday materials like paper and pencil. CS-unplugged has inspired several researchers, including Gibson, who taught graph modeling and algorithms through physical non-interactive objects [15].

Relevant related work for AT education can also be found in the area of *interaction design of tangibles*, e.g., [3,16]. Proposals to teach algorithms through the use of tangibles have increased in recent years. A significant reference is [14], where a gamified tangible for primary schools is presented, BALA, for the scaffolding of a sorting algorithm. Therein, gamification is used for creating probe versions of tangibles for children as in [12,9,13].

2.2 Tangible Design with Users

Design solutions for social contexts, such as school contexts, are subject to evolution, and meta-design has been proposed as a suitable design approach for them [10]. Meta-design and other end-user development approaches, such as [7], do not provide fixed solutions but a framework within which end users and designers alike can continuously contribute to the development. An interesting study of meta-design for end-user development of smart environments is reported in [8].

In spite of their potentials, so far meta-design or other end-user development approaches have been scarcely used for tangibles over long periods of time, in a continuous manner, as done for instance in [14]. The former is a participatory design study over time with children and teachers of tangibles for socio-emotional learning. The latter describes the CoDICE software that enables designers to trace the rationale of co-design decisions. The participatory design of this paper shares the same concern of enabling a continuous evolution of graph AT tangibles over time, by working with the users of tangibles and bringing them benefits: children and teachers.

The adopted participatory design of graph AT tangibles is essentially an action-research process, evolving over time through rapid prototype solutions and usage in the field with users. The related research questions and process are discussed in the following.

3 Research Questions and Methodology

3.1 Research Questions

The primary goal of my Ph.D. research is how to design graph AT tangibles for primary and middle school children, focusing on the Italian context. To achieve my research goal, my research work is framed around two main research questions: **(RQ1)** How can one rapidly design graph AT tangibles for children, focusing on Italian contexts, so as to provide the involved children with an engaging learning experience during the design process? **(RQ2)** What are the characteristics of graph AT tangibles adequate for different learning contexts?

The first research question, RQ1, is tackled by adopting the research methodology and design process explained in the following. The second research question, RQ2, will be tackled at the end of the PhD by cumulating over the research experience and drafting guidelines for the design of such tangibles.

3.2 Research Methodology and Design Process

Given the aforementioned research goals, the PhD research involves users continuously, so as to transform learning "by empowering all people to become active contributors" [10]. Design is based on action research, which aims at bringing benefits to all participants, especially users of tangibles. In case of graph AT tangibles, users are teachers and their 9–13 years old pupils, from primary and middle schools.

The design process spirals through: (1) *planning* of tangibles, (2) *acting in the field* for (3) *reflecting about their users' usage*. It proceeds through prototype solutions, conceived as intermediary objects in the sense of [6], which are used in studies with designers and users for detecting usability issues, exploring novel design possibilities as well as creating learning possibilities for users.

To this end, tangibles are open-ended for unexpected usage and with few functionalities, critical to assess. Early solutions take the form of probes, which should be cheap and easy to abandon solutions, or solutions that can rapidly evolve into interactive prototypes over time, introducing small changes. The rationale for this spiral process is that solutions like graph AT tangibles, which are for social contexts, can be studied best by introducing small changes into these processes and observing the effects of these changes in it over time [1].

The design process started with an exploratory context of use analysis, which triggered the first alternative design ideas, assessed with interaction design experts. After building a first vertical prototype of a tangible for AT (with few critical functionalities implemented and open for appropriations and rapid changes), designers and users participated in two studies in informal learning contexts, see [4,5] respectively. Tangibles were rapidly assessed and redesigned according to the results of studies. For instance, new learning scenarios for primary and middle schools were developed together with teachers. New design features were added after studies with children.

4 Recent Prototype and Scenarios

The latest prototype of graph AT tangibles is made of wood, cables and micro-electronics components. The prototype adopts a distributed client-server architecture, with a WiFi connection.

The server is a computer that verifies graph properties according to an envisioned learning scenario. Prototypes of graph AT tangibles, in fact, are used together with learning scenarios: scenarios challenge children to model or algorithmically solve with tangibles specific problems, e.g., friendship relations among people and how to connect isolated people. Moreover, besides verifying the properties envisioned by a learning scenario, the server implements a graphical user interface (GUI) for teachers, which allows them to select a specific learning scenario. The GUI is not discussed in this paper as it is not the main research focus of this contribution.

Clients, which are the tangibles for children, interact with the server and children through micro-electronic components. Currently, each node is equipped with an RGB node LED and three RGB edge LEDs, besides other microelectronics components. RGB node LEDs are activated for giving specific types of feedback, e.g., RGB node LEDs of a strongly connected component switch on with the same color. Each node has three sockets for cables, and in parallel three RGB edge LEDs. The edge LEDs are activated when a cable is inserted in its socket, or for delivering other types of feedback concerning edges, e.g., in a simple graph there is only one edge between a pair of nodes. Edges, which are Ethernet cables, are just passive links, and presently provide no interaction. A confirmation button is also part of the prototype; it can only be pressed by children for signalling that they think that they have concluded their learning scenario. See Fig. 1.

Example learning scenarios are compactly presented below.

> The first scenario aims at making children construct a **simple** graph. Children are presented a situation to model, e.g., friendship relations in their class. Children start labelling nodes with classmates' names, e.g., see Fig. 2. When a child introduces a loop or parallel edges, LED lights switch on, blinking red, to signal error.

> The second scenario aims at making children construct a **connected** graph. Children are presented a situation modelled with graph AT tangibles, e.g., friendship relations in their class, with isolated classmates. Children are not told that there are isolated classmates and are instead asked to push the confirmation button: strongly connected components, that is, isolated groups of classmates, blink with different colours, e.g., see Fig. 1. Children are then asked to tell what that means in relation to the given problem. Then Children can connect strongly connected components by means of cables. In order to verify that the graph is finally connected, children can push again the confirmation button and see that the graph AT tangibles are all coloured green.

The scenarios were used in two studies: one with 8 middle school children, all in the age range 12–13 years old; another one with 3 primary school children, all in the age range 10–11 years old. See Fig. 2.

Qualitative data were gathered via designers' field notes and videos, concerning children's user experience with tangibles, their understanding of graph AT and engagement in the experience. Understanding of graph AT was further investigated through a written survey delivered at the end of the experience.

The results of the studies are still under analysis but preliminary findings are available and generally positive. All children succeeded in using tangibles for modelling the situation proposed by the first learning scenario. However, primary-school children required scaffolding support by designers to understand what simple graphs are: designers asked them to repeat the learning scenario with examples until children understood what simple graphs are. Interestingly, whereas middle-school children did not notice LED lights for edges, primary-school children immediately noted them and recognised them as pertaining to edges.

In relation to the second scenario, again, no critical usability issue was reported. All children understood that differently coloured nodes were isolated groups of friends, that is, different strongly connected components. Interestingly, only one child from the middle school, on his own, devised an optimal strategy for connecting the graph—working on a single node per strongly connected component.

Fig. 1: Nodes of a graph with two strongly connected components

5 Conclusions

The paper elaborated on the notion of graph AT tangibles, which can aid in the scaffolding of AT through an active multi-modal experience. The design of such tangibles is based on action-research approach, spiralling through rapid prototype solutions and studies with users. Teachers, children (users) and designers co-discover design and learning possibilities by using and modifying tangibles and scenarios.

Currently, were are moving the design and usage of such tangibles one step forward: towards more complex learning scenarions requiring spanning trees.

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Fig. 2: Children using the graph AT tangibles for modelling friendship relations in their class

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