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# Tag systems and the complexity of simple programs<sup>\*</sup>

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**Abstract.** In this mini-survey we discuss time complexity and program size results for universal Turing machines, tag systems, cellular automata, and other simple models of computation. We discuss results that show that many of the simplest known models of computation including the smallest known universal Turing machines and the elementary cellular automata Rule 110 are efficient simulators of Turing machines. We also recall a recent result where the halting problem for tag systems with only 2 symbols (the minimum possible) is proved undecidable. This result has already yielded applications including a significant improvement on previous undecidability bounds for the Post correspondence problem and the matrix mortality problem.

## 1 Introduction

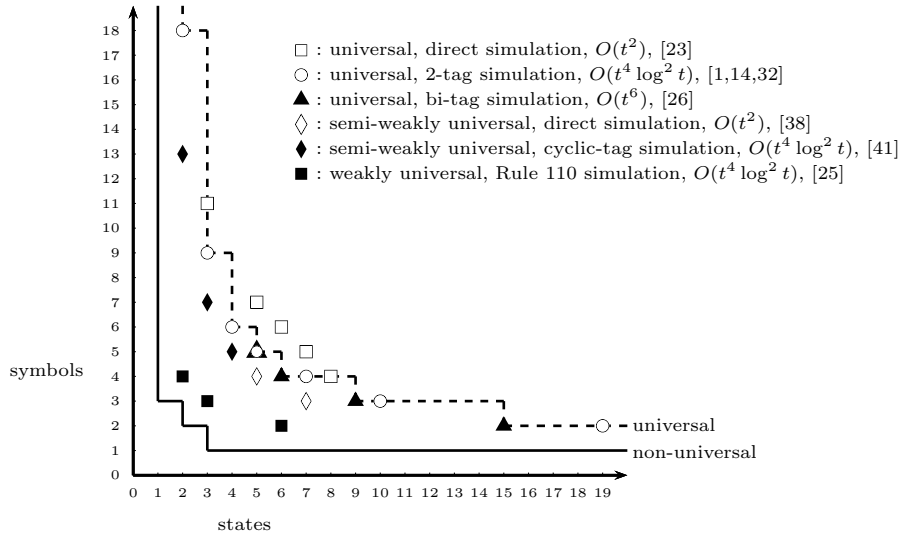
This brief survey is concerned with time complexity and program size results for universal Turing machines, tag systems, cellular automata and other simple models of computation. We pay particular attention to tag systems as they are at the center of many of the results we discuss. Here we provide only a brief glimpse at the above mentioned topics and we direct the reader who wishes to learn more to other related surveys [17,27].

## 2 Program size of small universal machines

In 1956 Shannon [35] considered the question of finding the smallest possible universal Turing machine, where size is the number of states and symbols. Figure 1 summarises the state of the art for the smallest known standard, weakly and semi-weakly universal Turing machines. Here we say a machine is standard

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**Fig. 1.** State-symbol plot of small universal Turing machines. The type of simulation is given for each group of machines. For example, each machine plotted as a hollow circle simulates 2-tag systems, a technique introduced by Minsky [20]. The technique of Rule 110 simulation was devised by Cook [4] and later improved upon in [26] to give the weakly universal machines plotted as solid squares. Direct simulation indicates that a machine was proved universal by simulating Turing machines directly rather than via some other system. Simulation time overheads are given in terms of simulating a single-tape deterministic Turing machine that runs in time  $t$ .

if it is deterministic and has a single-tape. Semi-weakly universal machines generalise the standard model by allowing an infinitely repeated word on one side of the input, and the (standard) infinitely repeated blank symbol on the other. Weakly universal machines are a further generalisation on the standard model as they allow an infinitely repeated word to the left of the input, and another infinitely repeated word to the right. It is often the case that generalising the model allows us to find smaller universal programs. This notion is borne out when we compare the standard, weak and semi-weak machines in Figure 1.

In Figure 1 the machines with the state-symbol pairs (2, 18), (3, 9), (4, 6), (5, 5), (6, 4), (9, 3), and (15, 2) are the smallest known standard machines and these machines define the universal curve (dashed line). Figure 1 also gives a non-universal curve. This curve is a lower bound that gives the state-symbol pairs for which it is known that the halting problem is decidable [11,13,28,29]. It is currently unknown whether all of the lower bounds in Figure 1 hold for weak and semi-weak machines. For example, the non-universality results of Pavlot-skaya [28,29] were proven under the assumption that the (standard) blank symbol is infinitely repeated to the left and right of the input.

### 3 Time efficiency of small universal machines

Cocke and Minsky [3] proved 2-tag systems universal via an exponentially slow simulation of Turing machines. So for many years the smallest known universal Turing machines were also exponentially slow. However, following the introduction of a new efficient 2-tag system algorithm for simulating Turing machines [40], the smallest known universal machines were found to be efficient simulators of Turing machines. To be more exact, given a single tape Turing machine  $M$  that runs in time  $t$  the small machines given by hollow circles in Figure 1 simulate  $M$  in time  $O(t^8 \log^4 t)$  (this overhead was later improved [21] to  $O(t^4 \log^2 t)$ ). Another consequence of this result is that many other systems [10,12,15,16,33,34,36] that simulate 2-tag systems, either directly or via a chain of simulations, are polynomial (instead of exponential) time simulators of Turing machines.

Rule 110 was proved universal by Matthew Cook via an impressive and intricate simulation of cyclic tag systems, the result is described in [39] and a full proof is given in [4]. Unfortunately, cyclic tag systems simulated Turing machines via Cocke and Minsky's exponentially slow 2-tag algorithm and so Rule 110 and the small weakly universal machines mentioned earlier were exponentially slow simulator of Turing machines. However, in [22] it was shown that cyclic tag systems simulate Turing machines in polynomial time. As a result, the following problem is now P-complete for Rule 110: Given a number  $t$  in unary, an initial configuration of Rule 110 and a cell  $c_i$ , predict the state of  $c_i$  after  $t$  timesteps. Rule 110 is the simplest (one-dimensional, nearest neighbour) cellular automaton that has been shown to have a P-complete prediction problem.

### 4 Universality of binary tag systems

Tag systems are a type of rewriting system that use a very simple form of rule. A tag system acts on a dataword, which is a string of symbols taken from a finite alphabet  $\Sigma$ . There is a fixed set of rules  $R : \Sigma \rightarrow \Sigma^*$  and a deletion number  $\beta \in \mathbb{N}$ . In a single timestep, the leftmost symbol  $\sigma_j$  of the dataword is read, if there is a rule  $\sigma_j \rightarrow \alpha_j$  then the string  $\alpha_j$  is appended to the right of the dataword and the leftmost  $\beta$  symbols are deleted. As an example we give the first 4 steps of Post's [31] binary tag system with deletion number 3 and the rules  $0 \rightarrow 00$  and  $1 \rightarrow 1101$  on the input 0101110.

0101110  $\vdash$  111000  $\vdash$  0001101  $\vdash$  110100  $\vdash$  1001101  $\vdash$  ...

A tag system computation halts if its dataword is shorter than its deletion number. Surprisingly, the halting problem for the simple tag systems given above (which Post discovered in the 1920s) remains open to this day [6]. Another remarkably simple tag system with an open halting problem was found by De Mol [5] when she reduced the well known Collatz problem to the halting problem for a tag system with only 3 rules and deletion number 2.

Tag systems were introduced by Post [30,31] and proved universal by Minsky [19]. Soon after this Cocke and Minsky [3] proved 2-tag systems (tag systems with deletion number 2) universal. As mentioned earlier, 2-tag systems

have been used to prove universality for many of the smallest known universal Turing machines [1,14,20,32] and are central to many other universality results [10,12,15,16,33,34,36]. Given that tag systems have been so useful in the search for new simple universal systems, it is surprising that there have been no attempts to simplify tag systems since the 1960s. All known universal tag systems [3,4,37] have a large number of symbols and thus a large number of rules. Recently [24] it was shown that tag systems with only 2 symbols (the minimum possible) are universal by showing that they simulate cyclic tag systems. Applications have already been found for this result. The undecidable halting problem for binary tag systems reduces to the Post correspondence problem for 5 pairs of words. The previous bound for undecidability in this problem, which is due to Matiyasevich and Sénizergues [18], was 7 pairs. Following this new result, only the cases for 3 and 4 pairs of words remain open, as the problem is known to be decidable for 2 pairs [7]. Applying the reductions of Halava and Harju [8], and Cassaigne and Karhumäki [2] to the Post correspondence problem for 5 pairs of words shows that the matrix mortality problem is undecidable for sets with six  $3 \times 3$  matrices and for sets with two  $18 \times 18$  matrices. The previous bounds for the undecidability in this problem was seven  $3 \times 3$  matrices and two  $21 \times 21$  matrices [9].

Looking to the future, we expect that binary tag systems will have an important role in proving further undecidability results and in the search for new simple models of computation.

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