A Meta-Algorithm for Creating Fast Algorithms for Counting ON Cells in Odd-Rule Cellular Automata

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Abstract: By using the methods of Rowland and Zeilberger (2014), we develop a meta-algorithm that, given a polynomial (in one or more variables), and a prime p, produces a fast (logarithmic time) algorithm that takes a positive integer n and outputs the number of times each residue class modulo p appears as a coefficient when the polynomial is raised to the power n and the coefficients are read modulo p. When $p = 2$, this has applications to counting the ON cells in certain "Odd-Rule" cellular automata. (This article is accompanied by a Maple package, `CAcount`, as well as numerous examples of input and output files, all of which can be obtained from the web page for this article:
`http://www.math.rutgers.edu/~zeilberg/mamarim/mamarimhtml/CAcount.html`).

Preface

The number of ON cells in the nth generation of an "Odd-Rule" cellular automaton is found by raising the defining polynomial (in which the number of variables is equal to the dimension of the ambient space) to the nth power, reading the coefficients modulo 2, and counting the remaining monomials—or equivalently, setting all the variables equal to 1 (see [Sl] for a detailed discussion).

The purpose of this article is to describe a meta-algorithm, inspired by a recent paper of Eric Rowland and Doron Zeilberger [RZ], that takes such a polynomial as input, and outputs a recurrence scheme that enables the fast (logarithmic time) computation of terms of the sequence giving the number of ON cells at time n. This provides an alternative, computer proof of Theorems 4 and 5 of [Sl].

A toy example

Following the *Gelfand Principle*, let's illustrate the method with a simple example that can be done by hand. We will later describe how this method can be 'taught' to a computer, which will then be able to do far more complicated cases, impossible for humans.

Consider the sequence

$$a_1(n) := (1 + x + x^2)^n \bmod 2 \Big|_{x=1} \quad ,$$

(sequence A071053 in [OEIS]), and suppose we wish to compute $a_1(10^{100})$, or $a_1(n)$ for any very large n.

Of course, direct computation is hopeless, even if we reduce modulo 2 at each step and use the repeated squaring trick that makes RSA possible ($P^n = (P^{n/2})^2$ if n is even, $P^n = PP^{n-1}$ if n is odd), since the polynomials, before we set $x = 1$, are far too big for our modest universe. What we will do is adapt this trick so that we can also make the substitution $x = 1$ at intermediate steps.

First let's try to relate $a_1(2n)$ to $a_1(n)$, using the **Freshman's Dream** identity $P(x)^p \equiv P(x^p) \bmod p$:

$$a_1(2n) = (1+x+x^2)^{2n} \bmod 2 \Big|_{x=1} = ((1+x+x^2)^2)^n \bmod 2 \Big|_{x=1}$$

$$= (1+x^2+x^4)^n \bmod 2 \Big|_{x=1} = (1+x+x^2)^n \bmod 2 \Big|_{x=1} \qquad (EvenCase1)$$

(replacing x^2 by x). Hence

$$a_1(2n) = a_1(n) \quad . \qquad (Recurrence1even)$$

Now we do the same thing for $a_1(2n+1)$:

$$a_1(2n+1) \;=\; (1+x+x^2)^{2n+1} \bmod 2 \Big|_{x=1} = (1+x+x^2)\,((1+x+x^2)^2)^n \bmod 2 \Big|_{x=1}$$

$$= \; (1+x+x^2)\,(1+x^2+x^4)^n \bmod 2 \Big|_{x=1}$$

$$= \; (1+x^2)\,(1+x^2+x^4)^n \bmod 2 \Big|_{x=1} + x\,(1+x^2+x^4)^n \bmod 2 \Big|_{x=1} \quad . \qquad (OddCase1)$$

In the first term, once again, we can replace x^2 by x, getting an **uninvited guest**, $a_2(n)$, say:

$$a_2(n) := (1+x)\,(1+x+x^2)^n \bmod 2 \,\Big|_{x=1} \quad .$$

As for the second term of Eq. $(OddCase1)$, multiplying by x does not change anything, so this is equal to $(1+x^2+x^4)^n \bmod 2 \Big|_{x=1}$, which, again replacing x^2 by x, is our old friend $a_1(n)$. Hence

$$a_1(2n+1) = a_2(n) + a_1(n) \quad . \qquad (Recurrence1odd)$$

But this pair of recurrences is useless unless we can handle $a_2(n)$. So let's try the same technique on it. A priori, this may force us to introduce terms $a_3(n)$, $a_4(n)$, etc., and lead us into an infinite regression, also known as a *Ponzi scheme*, but let's hope for the best.

Again we start with $a_2(2n)$. Using the Freshman's Dream, and the fact that multiplying a polynomial by x (or any other monomial) does not affect the result if we are going to read it modulo 2 and set $x = 1$, we have

$$a_2(2n) \;=\; (1+x)\,(1+x+x^2)^{2n} \bmod 2 \Big|_{x=1} \;=\; (1+x)\cdot((1+x+x^2)^2)^n \bmod 2 \Big|_{x=1}$$

$$= \; (1+x)\cdot(1+x^2+x^4)^n \bmod 2 \Big|_{x=1} \;=\; 1\cdot(1+x^2+x^4)^n \bmod 2 \Big|_{x=1} + x\,(1+x^2+x^4)^n \bmod 2 \Big|_{x=1}$$

$$= \; 2\,(1+x^2+x^4)^n \bmod 2 \Big|_{x=1} \;=\; 2\,(1+x+x^2)^n \bmod 2 \Big|_{x=1} \;=\; 2a_1(n) \quad .$$

Hence

$$a_2(2n) = 2a_1(n) \quad . \qquad (Recurrence2even)$$

Now for $a_2(2n+1)$. We have

$$a_2(2n+1) \;=\; (1+x)\cdot(1+x+x^2)^{2n+1} \bmod 2 \Big|_{x=1}$$

$$= ((1+x)\cdot(1+x+x^2))\cdot((1+x+x^2)^2)^n \bmod 2\Big|_{x=1}$$

$$= (1+2x+2x^2+x^3)\cdot(1+x^2+x^4)^n \bmod 2\Big|_{x=1}$$

$$= (1+x^3)\cdot(1+x^2+x^4)^n \bmod 2\Big|_{x=1}$$

$$= 1\cdot(1+x^2+x^4)^n \bmod 2\Big|_{x=1} + x^3\cdot(1+x^2+x^4)^n \bmod 2\Big|_{x=1}$$

$$= (1+x^2+x^4)^n \bmod 2\Big|_{x=1} + (1+x^2+x^4)^n \bmod 2\Big|_{x=1}$$

$$= (1+x+x^2)^n \bmod 2\Big|_{x=1} + (1+x+x^2)^n \bmod 2\Big|_{x=1} = 2a_1(n) \quad .$$

Hence

$$a_2(2n+1) = 2a_1(n) \quad . \qquad (Recurrence2odd)$$

So the *uninvited guest*, $a_2(n)$, did not invite further guests, and now we have a super-fast way to compute $a_1(n)$ for large n, using the **system**

$$a_1(2n) = a_1(n) \quad , \quad a_1(2n+1) = a_1(n) + a_2(n) \quad ;$$

$$a_2(2n) = 2a_1(n) \quad , \quad a_2(2n+1) = 2a_1(n) \quad . \qquad (System)$$

For certain "odd-rule" cellular automata, the sequence $a_1(n), n \geq 0$ is completely determined by the subsequence $b_1(k) := a_1(2^k - 1), k \geq 0$ [Sl], and the $b_1(k)$, unlike the $a_1(n)$, often have simple generating functions, which we can derive (rigorously) by these methods. With $a_1(n)$ as defined above, let

$$f_1(t) := \sum_{k=0}^{\infty} b_1(k) t^k$$

be the generating function for $b_1(k)$, and similarly define $b_2(k) := a_2(2^k - 1)$ and

$$f_2(t) := \sum_{k=0}^{\infty} b_2(k) t^k \quad .$$

From Eq. ($System$), we have

$$b_1(k) = b_1(k-1) + b_2(k-1) \quad , \quad b_2(k) = 2b_1(k-1) \quad ,$$

and since by direct computation, $b_1(0) = 1$, $b_2(0) = 2$, we arrive at a system of two linear equations for the *unknowns* $f_1(t)$ and $f_2(t)$:

$$\{\, f_1(t) = 1 + t f_1(t) + t f_2(t) \quad , \quad f_2(t) = 2 + 2t f_1(t) \,\} \quad ,$$

whose solution is

$$f_1(t) = \frac{1\,+\,2t}{(1+t)(1-2t)} \quad , \quad f_2(t) = \frac{2}{(1+t)(1-2t)}$$

(A001045, A014113 in [OEIS]). But we really don't care about $f_2(t)$, we just needed it in order to find $f_1(t)$, so *now* we can safely discard it, and get the

Theorem:

$$f_1(t) = \frac{1\,+\,2t}{(1+t)(1-2t)} \quad .$$

The general case

Fix once and for all a prime p and a polynomial $P = P(x_1, \ldots, x_k) \in \mathbf{Z}[x_1, \ldots, x_k]$. If $A(x_1, \ldots, x_k)$ is any element of $\mathbf{Z}[x_1, \ldots, x_k]$, we define the *functional*

$$A(x_1, \ldots, x_k) \to A(x_1, \ldots, x_k) \bmod p \Big|_{x_1=1,\ldots,x_k=1} \qquad (Reduce)$$

to mean "expand $A(x_1, \ldots, x_k)$ as a sum of monomials, reduce the coefficients modulo p to one of the numbers $\{0, 1, \ldots, p-1\} \in \mathbf{Z}$, and finally set all the variables x_i equal to 1".

For any polynomial $Q = Q(x_1, \ldots, x_k) \in \mathbf{Z}[x_1, \ldots, x_k]$ whose degree in each of the variables is less than p, define

$$a_Q(n) := QP^n \bmod p \Big|_{x_1=1,\ldots,x_k=1} \quad .$$

For $0 \leq i < p$, we have

$$a_Q(pn\,+\,i) \;=\; Q(x_1, \ldots, x_k)P(x_1, \ldots, x_k)^{pn+i} \bmod p \,\Big|_{x_1=1,\ldots,x_k=1}$$

$$=\;[\,Q(x_1, \ldots, x_k)P(x_1, \ldots, x_k)^i\,]P(x_1, \ldots, x_k)^{np} \bmod p \,\Big|_{x_1=1,\ldots,x_k=1}$$

$$=\;[\,Q(x_1, \ldots, x_k)P(x_1, \ldots, x_k)^i\,](P(x_1, \ldots, x_k)^p)^n \bmod p \,\Big|_{x_1=1,\ldots,x_k=1}$$

$$=\;[\,Q(x_1, \ldots, x_k)P(x_1, \ldots, x_k)^i\,]P(x_1^p, \ldots, x_k^p)^n \bmod p \,\Big|_{x_1=1,\ldots,x_k=1} \quad .$$

Now write

$$Q(x_1, \ldots, x_k)P(x_1, \ldots, x_k)^i \bmod p \;=\; \sum_{(\alpha_1,\ldots,\alpha_k)\in\{0,\ldots,p-1\}^k} x_1^{\alpha_1} \cdots x_k^{\alpha_k} R_{(\alpha_1,\ldots,\alpha_k)}(x_1^p, \ldots, x_k^p) \quad .$$

(Here again "mod p" applies just to the coefficients, not the variables.) Hence

$$a_Q(np+i) = \sum_{(\alpha_1,\ldots,\alpha_k)\in\{0,\ldots,p-1\}^k} x_1^{\alpha_1} \cdots x_k^{\alpha_k} R_{(\alpha_1,\ldots,\alpha_k)}(x_1^p, \ldots, x_k^p)P(x_1^p, \ldots, x_k^p)^n \bmod p \,\Big|_{x_1=1,\ldots,x_k=1}$$

$$= \sum_{(\alpha_1,\ldots,\alpha_k)\in\{0,\ldots,p-1\}^k} R_{(\alpha_1,\ldots,\alpha_k)}(x_1^p, \ldots, x_k^p)P(x_1^p, \ldots, x_k^p)^n \bmod p \,\Big|_{x_1=1,\ldots,x_k=1} \quad ,$$

$$= \sum_{(\alpha_1,\ldots,\alpha_k)\in\{0,\ldots,p-1\}^k} R_{(\alpha_1,\ldots,\alpha_k)}(x_1, \ldots, x_k)P(x_1, \ldots, x_k)^n \bmod p \,\Big|_{x_1=1,\ldots,x_k=1} \quad ,$$

$$= \sum_{(\alpha_1,\dots,\alpha_k)\in\{0,\dots,p-1\}^k} a_{R_{(\alpha_1,\dots,\alpha_k)}}(n) \quad .$$

In other words for any $Q(x_1,\dots,x_k)$ and each of the residue classes i, $0 \le i \le p-1$, we can find a multiset of polynomials, let's call it $S_i(Q)$, such that

$$a_Q(np+i) \ = \sum_{R\in S_i(Q)} a_R(n) \quad .$$

We really only care about the case $Q=1$, but the algebra forces us to consider other Q's, and they in turn force us to treat still other Q's, and so on. However, by the **pigeon-hole principle**, this process must terminate, and we obtain a **finite** recurrence scheme, containing say m equations. Placing all the Q's that appear into some arbitrary order, with $Q_1=1$, we get a (logarithmic-time) **recurrence scheme**:

$$a_j(np+i) \ = \sum_{l\in S_i(j)} a_l(n) \quad ,$$

for $1 \le j \le m$, that enables the fast calculation of $a_1(n)$ for any n.

Furthermore, by focusing only on $i=p-1$, and defining $c_j(k) := a_j(p^k-1)$, we have, for $1 \le j \le m$,

$$c_j(k) \ = \sum_{l\in S_{p-1}(j)} c_l(k-1) \quad .$$

Define the **generating functions**

$$f_j(t) := \sum_{k=0}^{\infty} c_j(k)t^k \quad (1 \le j \le m) \quad .$$

Standard manipulations of generating functions convert the above recurrences into a system of m *linear* equations for the m unknowns $f_1(t),\dots,f_m(t)$:

$$f_j(t) = c_j(0) + t\sum_{l\in S_{p-1}(j)} f_l(t) \quad , \quad 1 \le j \le m \quad ,$$

that can be solved, at least in principle, yielding **rigorous** explicit expressions for *all* the $f_j(t)$, and in particular for $f_1(t)$, the one in which we are most interested. Note that this proves that the generating function, $f_1(t)$, is always a **rational function**. If m is too large, and the system of equations cannot be solved, then one may try to use the recurrences to generate sufficiently many terms of the sequence $c_1(k)$, and then *guess* the rational function $f_1(t)$, using for example the Maple packgage `gfun` [SaZ]. It may then be possible to justify that guess, *a posteriori*, by finding upper bounds on the degree of the generating function.

Keeping track of the individual coefficients

If instead of the functional Eq. (*Reduce*), one uses, for some formal variables $s_1,\dots,s_{p-1}$,

$$\sum_\alpha c_\alpha \mathbf{x}^\alpha \to \sum_\alpha s_{c_\alpha} \quad ,$$

one can modify the above arguments and keep track of the number of occurrences of each i ($i = 1, \ldots, p-1$) as coefficients in the expansion of $P(x_1, \ldots, x_k)^n \bmod p$.

The Maple package CAcount

Everything discussed above is implemented in the Maple package `CAcount`, which can be downloaded from the web page for this article:
`http://www.math.rutgers.edu/~zeilberg/mamarim/mamarimhtml/CAcount.html` , where there are also many samples of input and output files that readers can use as templates for further computations.

To see the list of the main procedures, type

`ezra();` ,

or to see the list of procedures that handle the more refined case, where one keeps track of the individual coefficients (only useful for $p > 2$), type

`ezraG();` .

To get instructions on using a particular procedure, type

`ezra(ProcedureName);` .

For example. procedure `CAaut` finds the recurrence 'automaton', and to get help with it, type

`ezra(CAaut);` .

For our toy example, type

```
CAaut([1+x+x**2,1],[x],2,2);
```

which produces as output the pair

`[[[[1], [2, 1]], [[1, 1], [1, 1]]], [1, 2]]` ,

where the first component,

`[[[1], [2, 1]], [[1, 1], [1, 1]]]` ,

is Maple's way of encoding the recurrence

$$a_1(2n) = a_1(n) \quad , \quad a_1(2n+1) = a_2(n)+a_1(n) \quad ; \quad a_2(2n) = a_1(n)+a_1(n) \quad , \quad a_2(2n+1) = a_1(n)+a_1(n) \quad .$$

The second component

`[1, 2]`

is Maple's way of encoding the initial conditions

$$a_1(1) = 1 \quad , \quad a_2(1) = 2 \quad .$$

Procedure `SeqF` uses the scheme, once found, to compute as many terms as desired, while procedure `ARLT` (for *anti-run-length-transform*, see [Sl]) computes the sparse subsequence in the places $p^i - 1$. Procedure `GFsP` finds the **proved** generating function for that subsequence, and if the size of the system is too big, `GFsG` guesses it faster, and as we mentioned above, the guess can be justified *a posteriori*.

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