Generalizing and Implementing
Michael Hirschhorn's AMAZING Algorithm for Proving Ramanujan-Type Congruences

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Preamble

Let $p(n)$ be the number of integer partitions of n. Euler famously proved that

$$\sum_{n=0}^{\infty} p(n)q^n = \prod_{i=1}^{\infty} \frac{1}{1-q^i} \quad .$$

Srinivasa Ramanujan famously discovered (by glancing at a table of $p(n)$ for $1 \leq n \leq 200$, computed by the *analytic machine*, Major Percy Alexander MacMahon's head) the three congruences

$$p(5m+4) \equiv 0 \pmod 5 \quad ,$$

$$p(7m+5) \equiv 0 \pmod 7 \quad ,$$

$$p(11m+6) \equiv 0 \pmod{11} \quad .$$

The first two are really easy, and the proofs that G.H. Hardy chose to present in his classic book "Ramanujan" ([Ha], pp. 87-88), slightly streamlined, go as follows.

First recall the (purely elementary and *shaloshable*) identities of Euler and Jacobi :

$$E(q) = \prod_{i=1}^{\infty}(1-q^i) = \sum_{n=-\infty}^{\infty} (-1)^n q^{(3n^2+n)/2} \quad , \quad and$$

$$E(q)^3 = \sum_{n=0}^{\infty}(-1)^n(2n+1)q^{(n^2+n)/2} \quad .$$

Also recall the obvious fact (but *extremely useful* [e.g. the AKS algorithm!]), that follows from the binomial theorem, that for every prime ℓ, and any polynomial, or formal power series, $f(q)$, $f(q)^\ell \equiv f(q^\ell) \pmod \ell$. In particular $E(q)^\ell \equiv E(q^\ell) \pmod \ell$.

p(5n+4) is divisible by 5

Since $\{(n^2+n)/2 \; mod \; 5 \; ; \; 0 \leq n \leq 4 \; , \; 2n+1 \not\equiv 0 \pmod 5\} = \{0,1\}$, we have:

$$E(q)^3 \equiv J_0 + J_1 \pmod 5 \quad ,$$

where J_i consists of those terms in which the power of q is congruent to i modulo 5. Now

$$\sum_{n=0}^{\infty} p(n)q^n = E(q)^{-1} = \frac{(E(q)^3)^3}{E(q)^{10}} = \frac{(E(q)^3)^3}{(E(q)^5)^2} \equiv \frac{(J_0+J_1)^3}{E(q^5)^2} \pmod 5 \quad .$$

Since $(J_0 + J_1)^3 = J_0^3 + 3J_0^2 J_1 + 3J_0 J_1^2 + J_1^3$, whose terms consist of powers of q that are $0, 1, 2, 3$ modulo 5, respectively, none of the powers of q that are congruent to 4 modulo 5 show up, and hence the coefficient of q^{5n+4} is always 0 modulo 5. $\Box$

p(7n+5) is divisible by 7

Since $\{(n^2 + n)/2 \; mod \; 7 \; ; \; 0 \le n \le 6 \; , \; 2n + 1 \not\equiv 0 \pmod 7\} = \{0, 1, 3\}$, we have:

$$E(q)^3 \equiv J_0 + J_1 + J_3 \pmod 7 \quad ,$$

where J_i consists of those terms in which the power of q is congruent to i modulo 7. Now

$$\sum_{n=0}^{\infty} p(n)q^n = E(q)^{-1} = \frac{(E(q)^3)^2}{E(q)^7} \equiv \frac{(J_0 + J_1 + J_3)^2}{E(q^7)} \pmod 7 \quad ,$$

Since $(J_0 + J_1 + J_3)^2 = J_0^2 + J_1^2 + J_3^2 + 2J_0J_1 + 2J_0J_3 + 2J_1J_3$, whose terms consist of powers of q that are $0, 2, 6, 1, 3, 4$ modulo 7, respectively, none of the powers of q that are congruent to 5 modulo 7 show up, and hence the coefficient of q^{7n+5} is always 0 modulo 7. $\Box$

At the bottom of page 88 of Hardy's above-mentioned classic "Ramanujan"[Ha], he states

"*There does not seem to be an equally simple proof that* $p(11n + 6)$ *is divisible by* 11".

Over the years there were many proofs, but **none** as **simple** and **elementary** and, most importantly, **beautiful!**, as the one recently found by Michael Hirschhorn [Hi].

Michael Hirschhorn's proof for p(11n+6)

The proof in [Hi] goes like this. It starts the same way.

Since $\{(n^2 + n)/2 \; mod \; 11 \; ; \; 0 \le n \le 10 \; , \; 2n + 1 \not\equiv 0 \pmod{11}\} = \{0, 1, 3, 6, 10\}$, we have:

$$E(q)^3 \equiv J_0 + J_1 + J_3 + J_6 + J_{10} \pmod{11} \quad ,$$

where J_i consists of those terms in which the power of q is congruent to i modulo 11. Now

$$\sum_{n=0}^{\infty} p(n)q^n = E(q)^{-1} = \frac{(E(q)^3)^7}{E(q)^{22}} \equiv \frac{(J_0 + J_1 + J_3 + J_6 + J_{10})^7}{E(q^{11})^2} \pmod{11} \quad .$$

Alas, now the part consisting of the powers that are congruent to 6 modulo 11 in the polynomial $(J_0 + J_1 + J_3 + J_6 + J_{10})^7 \pmod{11}$ is **not** identically zero modulo 11, but a certain polynomial of degree 7 in $\{J_0, J_1, J_3, J_6, J_{10}\}$, (over $GF(11)$) let's call it POL.

It is readily seen that, introducing an auxiliary variable t, that

$$POL(J_0, J_1, J_3, J_6, J_{10}) = Coeff_{t^6} \left(J_0 + J_1 t + J_3 t^3 + J_6 t^6 + J_{10} t^{10}\right)^7 \pmod{11} \pmod{t^{11} - 1} \quad ,$$

that is **not** identically zero.

But, Since $\{(3n^2+n)/2 \; mod \; 11 \; ; \; 0 \le n \le 10\} = \{0,1,2,4,5,7\}$, we have,

$$E(q) = E_0 + E_1 + E_2 + E_4 + E_5 + E_7 \quad ,$$

where E_i consists of those terms in which the power of q is congruent to i modulo 11, and

$$(E(q)^3)^4 = E(q)^{12} = E(q)^{11}E(q) \equiv E(q^{11})E(q) \pmod{11} \quad ,$$

so

$$(J_0 + J_1 + J_3 + J_6 + J_{10})^4 \equiv E(q^{11})(E_0 + E_1 + E_2 + E_4 + E_5 + E_7) \pmod{11} \quad .$$

By expanding the left side and extracting the complementary powers $\pmod{11}$ ($\{3,6,8,9,10\}$), we get five polynomials of degree 4, let's call them $Q_3, Q_6, Q_8, Q_9, Q_{10}$ that we know are 0 modulo 11 (once the J_i's are replaced by the formal power series they stand for). For $m \in \{3,6,8,9,10\}$, we have

$$Q_m(J_0, J_1, J_3, J_6, J_{10}) = Coeff_{t^m}\left(J_0 + J_1 t + J_3 t^3 + J_6 t^6 + J_{10} t^{10}\right)^4 \pmod{11} \pmod{t^{11}-1} \quad .$$

Then we ask our beloved computer to find five polynomials of degree 3, (in the variables $\{J_0, J_1, J_3, J_6, J_{10}\}$), let's call them $R_3, R_6, R_8, R_9, R_{10}$, such that

$$POL \equiv R_3Q_3 + R_6Q_6 + R_8Q_8 + R_9Q_9 + R_{10}Q_{10} \pmod{11} \quad .$$

Since it succeeded (*a priori* there was no guarantee!), we are done!! *Quod Erat Demonstratum.* $\square$

See the output file `http://www.math.rutgers.edu/~zeilberg/tokhniot/oHIRSCHHORN1v`, that contains the above three proofs, (and four other ones!), that was generated, by running the Maple package `HIRSCHHORN` (that accompanies this article), in three seconds!

More Ramanujan Type Congruences

Let's consider, more generally,

$$\sum_{n=0}^{\infty} p_{-a}(n)q^n = \prod_{i=1}^{\infty} \frac{1}{(1-q^i)^a} \quad .$$

(Note that $p_{-1}(n) = p(n)$ and $p_{24}(n) = \tau(n-1)$, where $\tau(n)$ is Ramanujan's τ-function).

There are many known Ramanujan-type congruences for $p_{-a}(n)$. Matthew Boylan [B] (Theorem 1.3, where our $p_{-a}(n)$ is denoted by $p_a(n)$, and the entry $r = 27, l = 31$ is erroneous) has found all of them for a odd and ≤ 47.

The first few are (here we restricted our search to primes $\ge 2a+1$).

$$p_{-1}(5n+4) \equiv 0 \pmod{5} \quad , \quad p_{-1}(7n+5) \equiv 0 \pmod{7} \quad , \quad p_{-1}(11n+6) \equiv 0 \pmod{11} \quad ,$$

(Ramanujan's)

$$p_{-2}(5n+2) \equiv 0 \pmod 5 \quad , \quad p_{-2}(5n+3) \equiv 0 \pmod 5 \quad , \quad p_{-2}(5n+4) \equiv 0 \pmod 5 \quad ,$$

$$p_{-3}(11n+7) \equiv 0 \pmod{11} \quad , \quad p_{-3}(17n+15) \equiv 0 \pmod{17} \quad ,$$

$$p_{-5}(11n+8) \equiv 0 \pmod{11} \quad , \quad p_{-5}(23n+5) \equiv 0 \pmod{23} \quad ,$$

$$p_{-7}(19n+9) \equiv 0 \pmod{19} \quad ,$$

$$p_{-9}(19n+17) \equiv 0 \pmod{19} \quad , \quad p_{-9}(23n+9) \equiv 0 \pmod{23} \quad ,$$

$$p_{-21}(47n+42) \equiv 0 \pmod{47} \quad .$$

Thanks to the impressive algorithm of Silviu Radu[R1], every such congruence (and even more general ones, see [R1]), is effectively (and fairly efficiently!) decidable. Let's hope that Radu would post a public implementation of his method. Since no such an implementation seems to exist, we Emailed Radu, who kindly[R2] showed us how to deduce these (except for the last two, that we are sure can be done just as easily) from his powerful algorithm, by specifying the N_0 for which checking them for $0 \leq n \leq N_0$ would imply them for *all* $0 \leq n < \infty$.

As impressive as Radu's algorithm is, it is **not** elementary. It uses the 'fancy', and intimidating, theory of modular functions, that being analytic, is not quite legitimate according to our finitistic philosophy of mathematics. Hence it is still interesting (at least to us!) to find elementary, Hirschhorn-style proofs. Also, by the *principle of serendipity* our extension and implementation of Hirschhorn's method may lead to new things that even modular functions can **not** do.

Extending Hirschhorn's Method

Suppose that, for some prime ℓ and some integer r $(0 \leq r < \ell)$, we want to prove a congruence of the type

$$p_{-a}(\ell n + r) \equiv 0 \pmod{\ell} \quad .$$

We first find the smallest integer α such that $b := (\alpha\ell - a)/3$ is an integer, noting that

$$E(q)^{-a} = \frac{(E(q)^3)^b}{E(q)^{\alpha\ell}} \equiv \frac{(E(q)^3)^b}{E(q^\ell)^\alpha} \pmod{\ell} \quad .$$

We now define the subset of $\{0, 1, \ldots, \ell - 1\}$:

$$Jset(\ell) := \{(n^2+n)/2 \ mod\ \ell \ ; \ 0 \leq n \leq \ell - 1 \ , \ 2n+1 \not\equiv 0 \pmod{\ell}\} \quad ,$$

and write

$$E(q)^3 \equiv \sum_{i \in Jset(\ell)} J_i \pmod{\ell} \quad ,$$

where J_i consists of those terms in which the power of q is congruent to i modulo ℓ. Next we define POL to be the polynomial, in the set of variables $\{J_i\,;\, i \in Jset(\ell)\}$,

$$POL(\{J_i\,;\, i \in Jset(\ell)\}) = Coeff_{t^r}\left[\left(\sum_{i \in Jset(\ell)} J_i t^i\right)^b\right] \pmod{\ell} \pmod{t^\ell - 1} \quad .$$

Now, if we are **lucky**, the polynomial $POL(\{J_i\})$ would be identically zero (modulo ℓ). In that case we have a *Ramanujan-style* proof, since the powers of q that are congruent to r modulo ℓ in $((E(q)^3)^b$, and hence in $E(q)^{-a}$, do not show up!

Otherwise, we need to resort to *Hirschhorn's* enhancement.

Analogously to $Jset(p)$, let's define

$$Eset(\ell) := \{(3n^2 + n)/2 \ mod\ \ell\ ;\ 0 \le n \le \ell - 1\} \quad ,$$

the set of residue classes modulo ℓ that show up as powers in the sparse Euler Pentagonal Theorem expression for $E(q)$.

Now let c be the reciprocal of 3 modulo ℓ, and let $d = (3c - 1)/\ell$. Then

$$(E(q)^3)^c = E(q)E(q)^{3c-1} = E(q)E(q)^{d\ell} \equiv E(q)(E(q^\ell))^d \pmod{\ell}.$$

Now define a set of polynomials, for each $0 \le m < \ell$ that is **not** in $Eset(\ell)$ (i.e. for the members of the complement of $Eset(\ell)$):

$$Q_m := Coeff_{t^m}\left[\left(\sum_{i \in Jset(\ell)} J_i t^i\right)^c\right] \pmod{\ell} \pmod{t^\ell - 1} \quad , \quad m \notin Eset(\ell) \quad .$$

We know that all the $Q_m(\{J_i\})$ $[m \notin Eset(\ell)]$ are 0 modulo ℓ (once the $J_i's$ are replaced by the formal power series, in q, that they stand for).

Finally, we decide whether the polynomial POL (that lives in the polynomial ring over the Galois Field $GF(\ell)$ in the J_i's), or one of its powers, belongs to the **ideal** generated by the polynomials Q_m. This can be done (for small ℓ) either directly, using *undetermined coefficients*, and for larger ℓ, using Gröbner bases.

The Big Disappointment

We naively hoped that Hirschhorn's method, as explicated and generalized above, would work for all of these other congruences. To our dismay, it failed to prove the congruence $p_{-3}(17n + 15) \equiv 0 \pmod{17}$.

It turns our that for the specialization

$$J_0 = 1\,,\ J_1 = 1\,,\ J_3 = 2\,,\ J_4 = 10\,,\ J_6 = 9\,,\ J_{10} = 11\,,\ J_{11} = 15\,,\ J_{15} = 12 \quad ,$$

all the Q_m are zero (modulo 17) **but** $POL \equiv 6 \pmod{17} \neq 0$. So, of course, POL is not in the ideal generated by the Q_m in $GF(17)[J_0, J_1, J_3, J_4, J_6, J_{10}, J_{11}, J_{15}]$.

But there is Hope

The Euler and Jacobi identities are but the first two in an *infinite* sequence of identities, the *Macdonald identities*[M] made famous in Freeman Dyson's[D] historic 1972 Gibbs Lecture.

In fact, the next-in-line in Macdonald's identities, earlier found by Winquist[W], was already used to give "a Ramanujan-style proof" of $p(11m+6) \equiv 0 \pmod{11}$. We strongly believe that *every Ramanujan-type congruence* that can be proved using Radu's[R1] beautiful algorithm (that relies on the theory of modular functions), has either a "Ramanujan-style", or "Hirschhorn-style" proof, by using one of the Macdonald identities, that in spite of their "fancy" pedigree (Lie theory) are **purely elementary**.

The Maple package HIRSCHHORN

Everything (and more) is implemented in the Maple package `HIRSCHHORN` available from

`http://www.math.rutgers.edu/~zeilberg/tokhniot/HIRSCHHORN` .

The webpage

`http://www.math.rutgers.edu/~zeilberg/mamarmim/mamarimhtml/mh.html`

contains several computer-generated articles outputted by that package.

Gröbner via special cases

For $\ell > 11$, both POL and the $\{Q_m\}$ get too big for Maple. But by doing sufficiently many specializations (mod ℓ) for a subset of the variables $J_i's$ one can get a **fully rigorous** proof of ideal membership. See procedures `TerseMikeProof, TerseMikeProofG, TerseMikeProofGviaSC`, that use, respectively, undetermined coefficients, Groöbner bases, and Groöbner bases via special cases. As we already pointed out above, we are not always guaranteed success.

Future Directions

We believe that our extension of Hirschhorn's method could be generalized to more general q-series, including those that are *not* modular functions.

FIRST Encore: The Maple package BOYLAN

The Maple package `BOYLAN` available from

`http://www.math.rutgers.edu/~zeilberg/tokhniot/BOYLAN`

reproduces and extends Theorem 1.3 of [Bo], albeit empirically.

See

`http://www.math.rutgers.edu/~zeilberg/tokhniot/oBOYLAN1`

for a reproduction of the original (in less than two seconds), and

`http://www.math.rutgers.edu/~zeilberg/tokhniot/oBOYLAN2`

for many more congruences (going as far as $a = 399$).

SECOND Encore: Infinitely Many Congruences (*All having Ramanujan-style proofs!*)

Now that, thanks to Radu[R1], any *specific* congruence of the form $p_{-a}(\ell n + r) \equiv 0 \pmod{\ell}$, is *purely routine* (or, more politely, *algorithmically provable*, or *shaloshable*), the next stage would be to come up with "infinitely many congruences".

There is, of course, a *cheap* way to get "infinitely many" such congruences, namely when $a = \ell - 3$, since

$$\frac{1}{E(q)^{\ell-3}} \equiv \frac{E(q)^3}{E(q^\ell)} \pmod{\ell},$$

and since the set $Jset(\ell)$ is about one half of all residue classes, we get many r's (all the members of the complement of $Jset(\ell)$).

But, a little less trivially, we can generalize the Ramanujan proof of $p(7n+5) \equiv 0 \pmod{7}$, to the following proposition (we hesitate to call it a theorem, for two reasons. First it is a bit shallow, and second we only have a sketch of a proof [that we are sure can be easily completed, but we have better things to do]).

Proposition: Let ℓ be a prime that is either 7 or 11 modulo 12 and let $r := (\ell-6)/24 \pmod{\ell}$, then

$$p_{-(\ell-6)}(n\ell + r) \equiv 0 \pmod{\ell} \quad .$$

Sketch of a Ramanujan style proof. It is easy to see that $r := (\ell-6)/24 \pmod{\ell} \notin Jset(\ell) + Jset(\ell) \pmod{\ell}$, thanks to the following (presumably elementary lemma, verified empirically for $\ell \leq 2000$).

Elementary Lemma: Let ℓ be a prime that leaves remainder 7 or 11 when divided by 12. Then for any $0 \leq n_1, n_2 < \ell$ such that

$$\frac{n_1(n_1+1)}{2} + \frac{n_2(n_2+1)}{2} \equiv r \pmod{\ell} \quad ,$$

we must have either $n_1 = (\ell-1)/2$ or $n_2 = (\ell-1)/2$.

Using the lemma it follows that

$$\frac{1}{E(q)^{\ell-6}} = \frac{(E(q)^3)^2}{E(q^\ell)} \equiv \frac{(\sum_{i \in Jset(\ell)} J_i)^2}{E(q^\ell)} \pmod{\ell}$$

and the powers that are r modulo ℓ do not show up. $\square$

It would be interesting to come up with an infinite family provable by Hirschhorn-style proofs!

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