Experimenting with the Dym-Luks Ball and Cell Game (almost) Sixty Years Later

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Dedicated to Harry Dym (b. Jan. 26, 1938) on his eighty-fifth birthday

Abstract: This is a symbolic-computational redux, and extension, of a beautiful paper, by Harry Dym and Eugene Luks, published in 1966 (but written in 1964) about a certain game with balls and cells.

Preface

When Harry Dym and Eugene Luks were graduate students at MIT (working with Henry P. McKean, Jr. and Kenkichi Iwasawa, respectively) they collaborated on a "*fun*" paper [DL] not directly related to their dissertation topics. Here is how they introduced it.

"Each of r balls is placed at random into one of n cells. A ball is considered "captured" if (after all r balls have been distributed) it is the sole occupant of its cell. Captured balls are eliminated from further play. This completes the first "trial." The remaining balls are recovered and the process repeated (trials, $2, 3, 4, \ldots$ etc.). The play continues until all balls have been captured. The number of trials required to achieve this state is called the duration of the game."

In this modest tribute, we implement (in Maple) and *extend* their beautiful paper.

This will show the power of *symbolic computation*. We will describe a Maple package, `DymLuks.txt`, written by DZ, and diligently executed by SBE, available from the front of this article:

`https://sites.math.rutgers.edu/~zeilberg/mamarim/mamarimhtml/dym.html` .

This web-page also has numerous input and output files referred to in this article.

Dym and Luks only considered the *expected duration*, but we will go further and compute the *variance*, and higher moments. We also compute the full *probability generating function* for *any* specific number of balls and number of cells. Also for a *fixed* number of balls r, we find explicit expressions, in n, for these quantities.

A Quick summary of the Dym-Luks paper

Dym and Luks viewed the game as a **Markov process**. Fix n (the number of cells) once and for all. If currently there are r balls, then after one iteration, assuming that t balls were removed, there are $r-t$ balls that remain, where $0 \le t \le r$. Calling this probability $P_{r,r-t}(n)$, invoking a clever inclusion-exclusion argument, they derived ([DL], p. 517)

$$P_{r,r-t}(n) \,=\, \sum_{j=t}^{n} (-1)^{j-t} \binom{j}{t} \binom{n}{j} \binom{r}{j} j! \frac{(n-j)^{r-j}}{n^r} \quad .$$

[This is implemented in procedure `Prt(n,r,t)` in our Maple package DymLuks.txt. Note that `Prt(n,r,t)` is $P_{r,r-t}(n)$.]

Then they focused on the case of a fixed number of cells, n, and arbitrary number of balls r, and looked at the behavior of $M_n(r)$, the expected duration, and proved that, for any fixed n, as $r \to \infty$, we have

$$M_n(r) = \sum_{j=1}^{r} j^{-1} \left(\frac{n}{n-1}\right)^{j-1} + O(1) \quad .$$

Probability Generating Functions and Moments for the Dym-Luks Ball and Cell Game

Rather than just talk about the expectation, we will compute the full **probability generating function**, let's call it, $F_{r,n}(x)$. This is the rational function whose coefficient of x^i (in its Maclaurin expansion) is the **exact** probability that the game will terminate in **exactly** i rounds. Once we have it, we easily get the expectation, $M_n(r)$, that equals $F'_{n,r}(1)$, and the higher moments (see below). We have

$$F_{r,n}(x) = x \left(\sum_{t=0}^{r} P_{r,r-t} F_{r-t,n}(x)\right) \quad .$$

Hence we have the **recurrence**

$$F_{r,n}(x) = \frac{x}{1 - P_{r,r}x} \left(\sum_{t=1}^{r} P_{r,r-t} F_{r-t,n}(x)\right) \quad .$$

[This is implemented in procedure `GFrn(r,n,x)` in our DymLuks.txt]. For each **numeric** r and n we get a certain rational function in x. For example,

$$F_{1,1}(x) = x \quad , \quad F_{2,2}(x) = -\frac{x}{-2+x} \quad , \quad F_{3,3}(x) = \frac{2x\,(5x+3)}{(-3+x)\,(-9+x)} \quad ,$$

$$F_{4,4}(x) = -\frac{3x\,\left(25x^2+316x+64\right)}{(-4+x)\,(-16+x)\,(-32+5x)} \quad ,$$

$$F_{5,5}(x) = \frac{24x\,\left(767x^3+63115x^2+182125x+15625\right)}{(-5+x)\,(-25+x)\,(-125+13x)\,(-625+41x)} \quad .$$

To see the expressions for $F_{r,r}(x)$ for $r \leq 40$ (always rational functions of x, of course), see the output file:

`https://sites.math.rutgers.edu/~zeilberg/tokhniot/oDymLuks3.txt` .

From these we can deduce the diagonal sequence $\{M_r(r)\}$. It is not clear to us, with the available data, whether this sequence tends to a 'universal' constant, or whether it (very!) slowly increases to infinity. At any rate, we are almost sure that there is a *limiting distribution* (once you scale it). What is it?

To get an idea how this sequence starts, look at the output file

`https://sites.math.rutgers.edu/~zeilberg/tokhniot/oDymLuks5.txt` ,

that also gives the sequence of variances.

Probability Generating Functions for the Duration with a Fixed number of balls and General Number of Cells

When r is fixed , and we let n vary, we can get closed-form expressions, as rational functions in x **and** n,for the general $F_{r,n}(x)$. For example

$$F_{1,n}(x) = x \quad , \quad F_{2,n}(x) = \frac{x\,(n-1)}{n-x} \quad , \quad F_{3,n}(x) = \frac{x\left(n^3+2n^2x-3n^2-3nx+2n+x\right)}{(n-x)\,(n^2-x)} \quad ,$$

$$F_{4,n}(x) = \frac{x\left(n^6+5n^5x-6n^5-15n^4x+3n^3x^2+11n^4+9n^3x-2n^2x^2-6n^3+3n^2x-3n\,x^2-2nx+2x^2\right)}{(n-x)\,(n^2-x)\,(n^3-3nx+2x)} \quad ,$$

$$F_{5,n}(x) =$$

$$\frac{x}{(n-x)\,(n^2-x)\,(n^3-3nx+2x)\,(n^4-10nx+9x)} \cdot$$

$$(n^{10}+9n^9x-10n^9-39n^8x+59n^7x^2+35n^8-13n^7x-284n^6x^2+12n^5x^3$$

$$-50n^7+280n^6x+508n^5x^2-38n^4x^3+24n^6-494n^5x$$

$$-415n^4x^2+35n^3x^3+359n^4x+111n^3x^2+20n^2x^3-102n^3x+39n^2x^2-47n\,x^3-18n\,x^2+18x^3) \quad .$$

For expressions for $F_{r,n}(x)$ for $r \leq 40$, please consult the (large!) output file

`https://sites.math.rutgers.edu/~zeilberg/tokhniot/oDymLuks3.txt` .

Moments

Once we have an explicit expression for the probability generating function (always a rational function) we can let the computer compute, for each specific r, but general n, not only the expectation (the only concern in [DL]), but also the variance, and higher moments. Recall that the average, called $M_n(r)$ in [DL] is

$$M_n(r) = x\frac{d}{dx}F_{r,n}(x)|_{x=1} = F'_{r,n}(1) \quad .$$

Calling our random variable $X_{n,r}$ (so $M_n(r) = E[X_{n,r}]$), we have

$$E[X_{n,r}^i] = (x\frac{d}{dx})^i F_{r,n}(x)|_{x=1} \quad ,$$

and from this the computer can easily find the *moments about the mean*. Recall that the i^{th} moment about the mean, m_i, is $E[(X_{n,r}-M_n(r))^i]$. In particular the second moment about the mean is the *variance*, $Var_n(r)$. Also recall that the *scaled* moments (about the mean) are $m_i/m_2^{i/2}$.

Here are the first few expressions for $M_n(r)$ for small r.

$$M_n(1) \,=\, 1 \quad ,$$

of course, followed by:

$$M_n(2) \,=\, \frac{n}{n-1} \quad , \quad M_n(3) \,=\, \frac{n\,(n+3)}{n^2-1} \quad , \quad M_n(4) \,=\, \frac{\left(n^2+7n-2\right)n^2}{(n^3-3n+2)\,(n+1)} \quad ,$$

$$M_n(5) \,=\, \frac{n^2\left(n^5+12n^4-6n^3+48n^2-125n+10\right)}{(n^4-10n+9)\,(n^2+n-2)\,(n+1)} \quad .$$

Not surprisingly they all tend to 1 as n goes to infinity. After all, if you have many cells and only a few balls, they are all likely to lend in different cells, making them all removable.

For the explicit expressions for all $r \leq 20$, as well as expressions for the variance, *skewness*, and *kurtosis* (i.e. the scaled third and fourth moments, respectively), see the output file

`https://sites.math.rutgers.edu/~zeilberg/tokhniot/oDymLuks1t.txt` .

Fixed number of Cells and General Number of Balls

Except when there are two cells (i.e. $n = 2$), there is no *closed form* expression for $F_{r,n}(x)$ and even not for $M_r(n)$, but following Dym and Luks we can get very good approximations. It is easy to see that, with a fixed n, we have

$$P_{r,r}(n) = 1 - r(\frac{n-1}{n})^{r-1} \cdot (1 + O(\beta_1^r)) \quad ,$$

$$P_{r,r-1}(n) = r(\frac{n-1}{n})^{r-1} \cdot (1 + O(\beta_2^r)) \quad ,$$

$$P_{r,r-i}(n) = r(\frac{n-1}{n})^{r-1} \cdot O(\beta_3^r) \quad , \quad i \geq 2 \quad ,$$

where $0 < \beta_1, \beta_2, \beta_3 < 1, \beta_3 < \beta_2$. In other words, we can approximate the process by looking at a very simplified Markov process where the "particle" either moves one unit down (i.e. from r to $r-1$) with probability $r(\frac{n-1}{n})^{r-1}$, and stays in place otherwise. Let's consider the more general situation where for an *arbitrary* sequence $a(r)$, the particle either stays where it currently is, position r say, or goes down to $r-1$ with probability $a(r)$. For the Ball and Cell Game, and fixed number of cells n, we have $a(r) = r\,(\frac{n-1}{n})^{r-1}$.

Let's consider this more general scenario. Having fixed the sequence $a(r)$, let $F_r(x)$ be the probability generating function for the duration. We have:

$$F_r(x) = x \cdot ((1-a(r))\,F_r(x) + a(r)F_{r-1}(x)) \quad ,$$

hence

$$F_r(x) \,=\, \frac{a(r)\,x}{1-x(1-a(r))} \cdot F_{r-1}(x) \quad ,$$

that, in turn, implies that

$$F_r(x) = \prod_{i=1}^{r} \frac{a(i)\,x}{1 - x(1-a(i))} \quad .$$

By taking derivative, and then plugging-in $x = 1$ we immediately get that the expectation is

$$\sum_{i=1}^{r} \frac{1}{a(i)} \quad .$$

By taking the second derivative and doing some simple manipulations, we get that the variance is

$$\sum_{i=1}^{r} \frac{1}{a(i)^2} - \sum_{i=1}^{r} \frac{1}{a(i)} \quad .$$

We can get similar expressions for the higher moments, but for general $a(r)$ they won't be very useful. In the Dym-Luks case there is no "closed-form", but if we consider the closely analogous case of $a(r) = \alpha^r$, with $0 < \alpha < 1$, one (or rather one's computer) gets explicit expressions, not only for the expectation, but also for the variance and higher moments.

Explicit Expressions for the Moments of the Longevity of the Markov Process Where r goes to $r-1$ with probability α^r and stays at r with probability $1-\alpha^r$

We have that the expectation is

$$\frac{1-\alpha^r}{(1-\alpha)\alpha^r} \quad ,$$

and the variance is

$$\frac{(1-\alpha^r)\,(1-\alpha^{r+1})}{(1-\alpha^2)\,\alpha^{2r}} \quad .$$

In particular, the *coefficient of variation* (the standard deviation divided by the expectation) converges to

$$\sqrt{\frac{1-\alpha}{1+\alpha}} \quad .$$

Explicit formulas for the general higher moments, up to the tenth, can be gotten from:

`https://sites.math.rutgers.edu/~zeilberg/tokhniot/oDymLuks7.txt` .

Let's just state the limiting expressions as r goes to infinity.

The limiting *skewness* (i.e. the scaled third-moment about the mean), as r goes to infinity, is

$$\sqrt{\frac{4\,(1-\alpha)\,(\alpha+1)^3}{(\alpha^2+\alpha+1)^2}} \quad .$$

The limiting *kurtosis* (i.e. the scaled fourth-moment about the mean) is

$$\frac{3\,(3-\alpha^2)}{\alpha^2+1} \quad .$$

The limiting *scaled fifth-moment* (about the mean) , as r goes to infinity, is

$$\sqrt{\frac{16\,(1-\alpha)\,(\alpha^4+\alpha^3-5\alpha^2-11\alpha-11)^2\,(\alpha+1)^3}{(\alpha^2+\alpha+1)^2\,(\alpha^4+\alpha^3+\alpha^2+\alpha+1)^2}} \quad .$$

The limiting *scaled sixth-moment* (about the mean) , as r goes to infinity, is

$$\frac{5\alpha^8+5\alpha^7-45\alpha^6-130\alpha^5-180\alpha^4-50\alpha^3+135\alpha^2+265\alpha+265}{(\alpha^2+1)\,(\alpha^2-\alpha+1)\,(\alpha^2+\alpha+1)^2} \quad .$$

How good are the Luks-Dym Approximations of $M_n(r)$?

At the very end of [DL], the authors define the error

$$E_n(r) := M_n(r) \;-\; \sum_{j=1}^{r} j^{-1} \left(\frac{n}{n-1}\right)^{j-1} \quad .$$

Of course, as they noted, $E_2(r)=0$, and with a 1964 computer, they found out that $|E_3(r)| \leq 0.25$, and that it approaches 0.042 as r approaches infinity. Using simulation they noticed that $E_n(r)$ seems to be less than one in magnitude, at least in the range $r \leq 5n$. With a 2023 computer we corroborated this. See the output file.

`https://sites.math.rutgers.edu/~zeilberg/tokhniot/oDymLuks4.txt` .

We estimate that

$$\lim_{r \to \infty} E_3(r) \approx .04213658385 \quad ,$$

(as already computed in [DL])

$$\lim_{r \to \infty} E_4(r) \approx .254461 \quad ,$$

$$\lim_{r \to \infty} E_5(r) \approx .5312 \quad .$$

Since $M_n(r)$ is so large, a more meaningful measure of the quality of the approximation is not the difference between $M_n(r)$ and its approximation, $\sum_{j=1}^{r} j^{-1} \left(\frac{n}{n-1}\right)^{j-1}$, but rather the ratio. See the output file

`https://sites.math.rutgers.edu/~zeilberg/tokhniot/oDymLuks4R.txt` ,

that also contains ratios of the variance with its approximation $\sum_{j=1}^{r} j^{-2}\,(\frac{n}{n-1})^{2j-2} - \sum_{j=1}^{r} j^{-1}\,\left(\frac{n}{n-1}\right)^{j-1}$. As you can see, they all converge to 1 very fast.

Simulation

Out Maple package also has simulation procedures. Try `DL(r,n)`, and `DLv(r,n)` for a verbose version. To see ten examples starting with 1000 balls and 1000 cells, consult the output file https://sites.math.rutgers.edu/~zeilberg/tokhniot/oDymLuks6.txt .

Conclusion

Happy (early) 85^{th} birthday, Harry, and Happy (late) 83^{th} birthday, Gene. Keep up the good work!

References

[DL] Harry Dym and Eugene M. Luks, *On the mean duration of a Ball and Cell game; a first passage problem*, The Annals of Mathematical Statistics **37** (1966), 517-521.
https://sites.math.rutgers.edu/~zeilberg/akherim/DymLuks.pdf .

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