ON THE PROBABILITY OF REACHING A GIVEN HEAD TO TAIL RATIO

Tamás Lengyel*
Department of Mathematics
Occidental College
Los Angeles, CA 90041, USA

The head to tail ratio converges to 1 with probability one when a fair coin is flipped. We show that the limit probability of reaching the ratio $\frac{q}{q+m}$ is $\frac{2}{2+m}$, as $q \to \infty$ and q and m are co-primes.

1. Introduction

We flip a balanced coin. Let X and Y denote the number of heads and tails, respectively. It is well known from the theory of random walks that the probability of ever visiting the line $Y = X - m$ is 1 for any integer m. For instance, if the line is reached when $Y = n$ then $X = n + m$ and the probability of this happening is $p_n = P(Y = X - m) = \binom{2n+m}{n}/2^{2n+m}$. It follows that $1 - 1/\bigl(1 + \sum_{n=1}^{\infty} p_n\bigr)$ is the probability that the line $Y = X - m$ is ever reached [3]. By binomial identities (cf. identities (5.72) and (5.78) in [4], p. 203), we obtain for $|x| < 1/2$ that

$$\sum_{n=0}^{\infty} \binom{2n+m}{n} x^{2n+m} = \left(\frac{1-\sqrt{1-4x^2}}{2x}\right)^m \Big/ \sqrt{1-4x^2}.$$

If $x = 1/2$, then the sum is divergent, therefore the line will be reached with probability 1. We might as well be interested in calculating the probability of reaching a given *ratio* instead of a difference. By the theory of recurrent events [3], the probability of reaching the ratio one (or equivalently, a difference of $m = 0$) is 1, though the expected number of flips needed is infinite. In this paper we discuss the extreme value of the probability of reaching a given head to tail ratio which is different from 1.

We note that the case of an unbalanced coin has been discussed in the literature ([3], Exercise 4, p. 339). In general, let h and t denote the probability of getting a head and a tail, respectively, where $h + t = 1$. The event that the accumulated number of heads equals λ times the accumulated number of tails is *persistent*, i.e., it has probability one, if and only if the head/tail probability ratio, h/t, is equal to λ. Other ratios are usually not discussed.

* Present address: T. Lengyel, Dept. Math., Occidental College, 1600 Campus Road, Los Angeles, CA 90041, USA

In this paper we consider the head to tail ratio X/Y for a balanced coin. We like to know how large the probability of ever reaching a given head to tail ratio, q/p, is where p and q are co-primes, i.e. the ratio q/p is given in lowest terms. We assume that $q < p$, since for a balanced coin, the ratios q/p and p/q can be reached with the same probability. We set $r = p + q$.

Numerical evidence suggests that the second largest probability is around 2/3 and it does not exceed 2/3. Hence there is a gap between 1 and the second largest probability of reaching a given ratio q/p. We prove that for every positive ϵ and integer m, this probability is less than $\frac{2}{2+m} + \epsilon \leq \frac{2}{3} + \epsilon$ for ratios of form $\frac{q}{p} = \frac{q}{q+m}$ with large values of q, where q and m are co-primes. Actually, the limit probability is $\frac{2}{2+m}$. Let $u(p,q) = \sum_{n=1}^{\infty} \binom{rn}{qn} 2^{-rn}$ be. The probability of ever reaching the ratio q/p is $w(p,q) = 1 - \frac{1}{1+u(p,q)}$. The infinite series $\sum_{n=1}^{\infty} \binom{rn}{qn} 2^{-rn}$ diverges if $p = q$, and it converges otherwise.

Note, that instead of the head to tail ratio we might consider the head to total ratio. The head to tail ratio 1 corresponds to the head to total ratio 1/2.

2. The result

Let $\gcd(q,m)$ denote the greatest common divisor of the positive integers q and m. We prove

THEOREM. $\lim_{q\to\infty} w(q+1,q) = 2/3$, *and in general, for every fix* $m \geq 1$,

$$\lim_{\substack{q\to\infty \\ \gcd(q,m)=1}} w(q+m,q) = \frac{2}{2+m}.$$

Theorem 1 shows the somewhat surprising fact that $u(p,q)$ is not a continuous function of the ratio q/p. To illustrate this, we compare two ratios that are close. Say, the first pair is $(q+1,q)$, i.e., $m=1$, while the other is $(q+2,q)$, with $m=2$. By selecting a sufficiently large odd q, the two ratios can be arbitrarily close, though the probabilities of reaching them stay apart since $w(q+1,q) \approx 2/3$, while $w(q+2,q) \approx 1/2$.

In this paper we use the following notations and assumptions.

Let m be a fixed positive integer. Assume that $p = q + m$, i.e., $r = 2q + m$, such that $\frac{m^2}{2p} < 1$.

From now on, $c_1(p,m,n)$, $c_2(p,m,n)$, and $c_3(p,m,n)$ denote *bounded* functions of the variables p, m, and n. Similarly, $c_4(p,m,N)$, $c_5(p,m,N)$, $c_6(p,m,N)$, $c_7(p,m,N)$, $c_8(p,m,N)$, $c_9(p,m,N)$, and $c_{10}(p,m)$ are *bounded* functions of the variables indicated in parentheses.

Lemma 1 utilizes the Stirling formula in order to asymptotically evaluate $g(p,q,n) = \binom{rn}{qn} 2^{-rn}$. It will be applied to the sum $u(p,q) = \sum_{n=1}^{\infty} g(p,q,n)$.

Lemma 1. *In addition to the previous conditions on p, q, and m, let $q > m$ be. Then*

$$g(p,q,n) = \Big(\big(\frac{1}{2}\frac{p}{p-q}\big)^p \big(\frac{p-q}{q}\big)^q \Big)^n \sqrt{\frac{p}{2q(p-q)}} \sqrt{\frac{1}{n\pi}} \Big(1 + c_1(p,m,n)\frac{1}{pn}\Big).$$

We omit the proof of Lemma 1 but note that it can be proved similarly to the asymptotical formula

$$\binom{(a+b)n}{an} \sim \frac{(a+b)^{n(a+b)+1/2}}{a^{an+1/2} b^{bn+1/2}} \frac{1}{\sqrt{2\pi n}},$$

for positive integers a and b (cf. [1], Exercise 2, p. 292).

By introducing the notation $\frac{1}{2}\frac{q}{p} = \frac{1}{2} - \epsilon$, we get $\epsilon = \frac{m}{2p}$ and $2p\epsilon^2 = \frac{m^2}{2p} < 1$. Lemma 1 yields

$$g(p,q,n) = \\ \sqrt{\frac{2}{\pi}} \frac{1}{\sqrt{p}} \frac{\big(1 - 2\epsilon^2 + c_2(p,m,n)\epsilon^4\big)^{pn}}{\sqrt{n}} \Big(1 + c_1(p,m,n)\frac{1}{pn}\Big) \Big(1 + 2\epsilon^2 + c_3(p,m,n)\,\epsilon^4\Big). \tag{1}$$

We set $S_N(p,q) = \sum_{n=1}^{N} \binom{rn}{qn} \frac{1}{2^{rn}}$. The Theorem will be proven in three steps. We shall need Lemmas 2 and 3 to approximate the sum $u(p,q)$. We select a large N in identity (2) to get a close approximation to $u(p,q) = \sum_{n \ge 1} g(p,q,n)$ by the finite sum $S_N(p,q)$. Next, we need a sufficiently large p in equation (3) to approximate $S_N(p,q)$ by another sum which is easier to calculate. Formula (4) suggests that we choose large p and N in order to have a meaningful approximation when using Euler's formula. The proof follows as we combine identities (2) and (5).

By Lemma 1 we obtain

Lemma 2. *Let $p = q + m$ and $r = 2q + m$ be where $m > 0$ is a fixed integer such that $\frac{m^2}{2p} < 1$. Then*

$$u(p,q) = \sum_{n=1}^{\infty} \binom{rn}{qn} \frac{1}{2^{rn}} = S_N(p,q) + c_4(p,m,N)\Big(\frac{p}{N}\Big)^{1/2}\Big(1 - \frac{m^2}{2p}\Big)^N, \tag{2}$$

and

$$S_N(p,q) = \sqrt{\frac{2}{\pi}} \sum_{n=1}^{N} \frac{1}{\sqrt{p}} \frac{(1 - \frac{m^2}{2p})^n}{\sqrt{n}} + c_5(p,m,N)\frac{\ln N}{p}. \tag{3}$$

PROOF OF LEMMA 2.

We get an upper bound on $\sum_{n=N+1}^{\infty} g(p,q,n)$ by using the identity $\sum_{i=N}^{\infty} z^i = \frac{z^N}{1-z}$ with any z exceeding $\left(1-\frac{m^2}{2p}\right)$. It follows from identity (1) that $u(p,q) - S_N(p,q) = \sum_{n=N+1}^{\infty} g(p,q,n) = c_6(p,m,N)\frac{1}{(pN)^{1/2}}\left(1-\frac{m^2}{2p}\right)^N \frac{2p}{m^2}$. Similarly, identity (1) gives an upper bound on the error term's contribution to $\sum_{n=1}^{N} g(p,q,n)$. The error is of magnitude $\ln N/p$.

We shall need

LEMMA 3. *Under the conditions of Lemma 2,*

$$\sum_{n=1}^{N} \frac{1}{\sqrt{p}} \frac{\left(1-\frac{m^2}{2p}\right)^n}{\sqrt{n}} = \frac{\sqrt{2\pi}}{m} + c_7(p,m,N)\Big(\frac{1}{\sqrt{p}} + \sqrt{\frac{p}{N}}\Big). \tag{4}$$

Therefore,

$$S_N(p,q) = \sum_{n=1}^{N} \binom{rn}{qn} \frac{1}{2^{rn}} = \frac{2}{m} + c_5(p,m,N)\frac{\ln N}{p} + c_7(p,m,N)\Big(\frac{1}{\sqrt{p}} + \sqrt{\frac{p}{N}}\Big)\sqrt{\frac{2}{\pi}}. \tag{5}$$

REMARK. Lemma 3 shows that $S_N(p,q)$ can get arbitrarily close to $\frac{2}{m}$, for large p and N. In fact, we select a sequence $N = N(p)$ so that $p/N(p) \to 0$ and $\ln N(p)/p \to 0$, as $p \to \infty$. By Lemma 2, it follows that $\sum_{n=1}^{\infty} \binom{rn}{qn} \frac{1}{2^{rn}}$ converges to $\frac{2}{m}$, as $q \to \infty$ and $\gcd(q,m) = 1$.

PROOF OF LEMMA 3.

We shall need an application of *Euler's summation formula* ([5], p. 108 or [2]) to derive identity (4). Let $f(k) = \frac{1}{\sqrt{p}} \frac{\left(1-\frac{m^2}{2p}\right)^k}{\sqrt{k}}$ be. Euler's method yields formula (6) for the difference between $\int_1^n f(x)dx$ and $\sum_{1\le k<n} f(k)$ if $f(x)$ is differentiable, i.e.,

$$\sum_{1\le k<n} f(k) = \int_1^n f(y)dy - \frac{1}{2}\big(f(n) - f(1)\big) + \int_1^n B_1(\{y\})f'(y)dy, \tag{6}$$

where $B_1(y) = y - 1/2$ and $\{y\} = y - \lfloor y \rfloor$.

We apply this formula to function $f(k)$. Clearly, $f(n)$ converges to 0 at a rate faster than $\frac{1}{\sqrt{n}}$ as $n \to \infty$, and $f(1) < \frac{1}{\sqrt{p}}$. We set $\frac{1}{s} = (1 - \frac{m^2}{2p})$. Here $s > 1$, since p is large enough to make $\frac{m^2}{2p} < 1$. We note that $f'(y) = \frac{1}{\sqrt{p}} \frac{\left(1-\frac{m^2}{2p}\right)^y}{\sqrt{y}}(-\ln s - \frac{1}{2y})$. Observe that $\ln s \sim \frac{m^2}{2p}$ as $p \to \infty$.

First we asymptotically evaluate the first term on the right side in formula (6). A well known integral equation for the gamma function [5] says that for all $\alpha > -1$

$$\int_0^\infty x e^{-xv} v^\alpha dv = \frac{1}{x^\alpha}\int_0^\infty e^{-t} t^\alpha dt = \frac{1}{x^\alpha}\Gamma(\alpha+1). \tag{7}$$

By setting $x = \ln s$ and $\alpha = -1/2$, it follows that

$$\int_0^\infty f(y)dy = \int_0^\infty \frac{1}{\sqrt{p}}\frac{e^{-y\ln s}}{\sqrt{y}}dy = \frac{1}{\sqrt{p}}(\ln s)^{-1/2}\sqrt{\pi}. \tag{8}$$

Therefore, if p is sufficiently large then $\ln s \sim \frac{m^2}{2p}$ and the above integral is asymptotically equal to $\frac{\sqrt{2\pi}}{m}$. Hence the term $\int_1^n f(y)dy$ contributes $\frac{\sqrt{2\pi}}{m} + c_8(p,m,n)\frac{1}{\sqrt{p}} + c_9(p,m,n)\sqrt{\frac{p}{n}}$ to $\sum_{1\le k<n} f(k)$ in formula (6).

For the last term of identity (6) we obtain

$$\begin{aligned}\left|\int_1^n B_1(\{y\})f'(y)dy\right| &\le \int_1^\infty |f'(y)|dy \le \int_1^\infty \frac{1}{\sqrt{p}}\frac{\left(1-\frac{m^2}{2p}\right)^y}{\sqrt{y}}(2\frac{m^2}{2p}+\frac{1}{2y})dy \\ &\le 2\int_0^\infty \frac{1}{\sqrt{p}}\frac{\left(1-\frac{m^2}{2p}\right)^y}{\sqrt{y}}\frac{m^2}{2p}dy + \int_1^\infty \frac{1}{\sqrt{p}}\frac{\left(1-\frac{m^2}{2p}\right)^y}{\sqrt{y}}\frac{1}{2y}dy.\end{aligned} \tag{9}$$

Similarly to equation (8), identity (7) yields

$$\int_0^\infty \frac{1}{\sqrt{p}}\frac{\left(1-\frac{m^2}{2p}\right)^y}{\sqrt{y}}\frac{m^2}{p}dy = c_{10}(p,m)\frac{1}{m}\frac{m^2}{p}. \tag{10}$$

For the second term, we get

$$\int_1^\infty \frac{1}{\sqrt{p}}\frac{\left(1-\frac{m^2}{2p}\right)^y}{y^{3/2}}dy \le \frac{1}{\sqrt{p}}\int_1^\infty \frac{1}{y^{3/2}}dy = \frac{2}{\sqrt{p}}.$$

These inequalities provide us with an upper bound on $\int_1^n B_1(\{y\})f'(y)dy$.

From here it follows that for fixed m, $\sum_{1\le k<n} f(k) = \frac{\sqrt{2\pi}}{m} + c_7(p,m,n)\left(\frac{1}{\sqrt{p}} + \sqrt{\frac{p}{n}}\right)$. In fact, we get $\lim_{q\to\infty} u(q+m,q) = \frac{2}{m}$ and for the probability that the ratio q/p will ever be reached, we conclude that $\lim_{q\to\infty} 1 - \frac{1}{1+u(q+m,q)} = 1 - \frac{1}{1+2/m} = \frac{2}{2+m} \le \frac{2}{3}$, where the limit is taken over the set of (q,m)-pairs that are co-primes.

Acknowledgment

The problem discussed in this paper has been brought to the author's attention by Professor J. Shavlik of the University of Wisconsin-Madison.

References

[1] L. Comtet (1974), *Advanced Combinatorics*, D. Reidel, Dordrecht

[2] N. G. De Bruijn (1970), *Asymptotic Methods in Analysis*, North-Holland, Amsterdam, 3rd edition

[3] W. Feller (1968), *An Introduction to Probability Theory and Its Applications, vol. I*, Wiley, 3rd edition

[4] R. L. Graham, D. E. Knuth, and 0. Patashnik (1988), *Concrete Mathematics*, Addison-Wesley, Reading, MA

[5] D. E. Knuth (1973), *The Art of Computer Programming, vol. 1*, Addison-Wesley, Reading, MA, 2nd edition