

Randomness properties of \mathbb{Z}_v ElGamal sequences

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Bounds for random ν -ary sequences

Bounds for ElGamal ν -ary sequences

Experimental results

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ElGamal Permutations

For p prime, $\mathbb{Z}_p^* = \{1, \dots, p-1\}$ is a cyclic group of order $p-1$ under multiplication. For g a generator, the ElGamal map $\gamma = g^x : \mathbb{Z}_p^* \rightarrow \mathbb{Z}_p^*$ is a permutation

- ▶ The ElGamal function is the basis of the ElGamal Signature Scheme
- ▶ The ElGamal function used in the Welch construction of Costas Arrays

Research challenge

In 2016 Joachim von zur Gathen posed this research challenge:

How random is the map $\gamma(x) = g^x$?

Cycle sizes in ElGamal Permutations

Example: The generators of \mathbb{Z}_5^* are 2 and 3.

x	g^x
1	$2^1 = 2$
2	$2^2 = 4$
3	$2^3 = 3$
4	$2^4 = 1$

$$\gamma = (1, 2, 4)(3)$$

x	g^x
1	$3^1 = 3$
2	$3^2 = 4$
3	$3^3 = 2$
4	$3^4 = 1$

$$\gamma = (1, 2, 3, 4)$$

Cycle sizes in ElGamal Permutations

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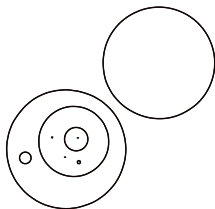
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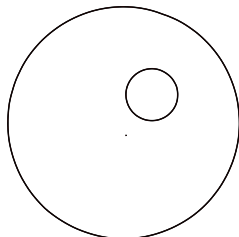
$$\gamma = (1, 2, 3, 4)$$

- ▶ Distinct g produce distinct permutations;
- ▶ Distinct g affect the cyclic structures.

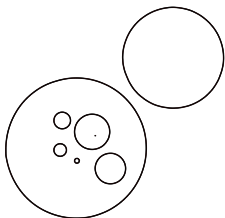
$$p = 1009$$



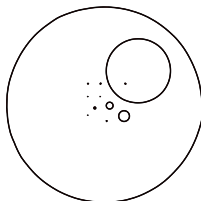
$$g = 11$$



$$g = 17$$

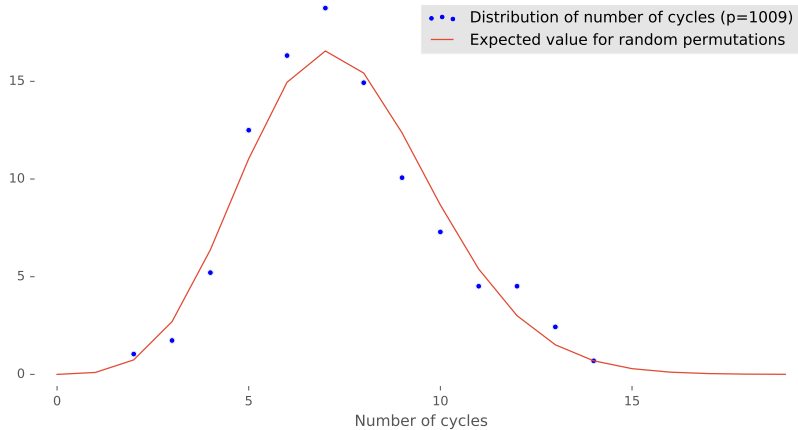


$$g = 22$$



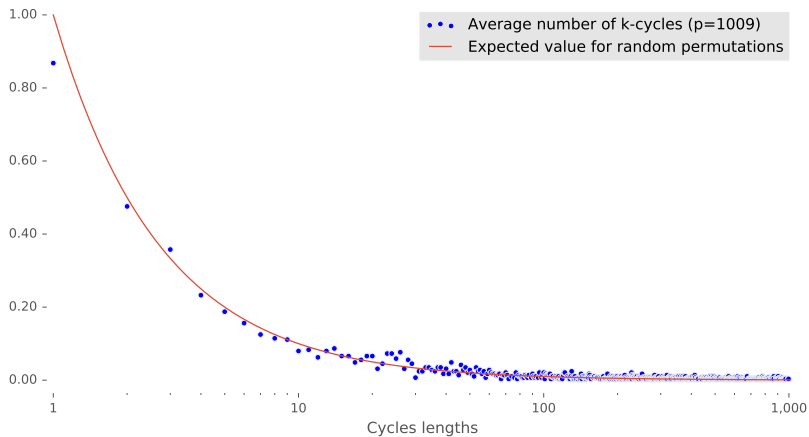
$$g = 26$$

Number of cycles



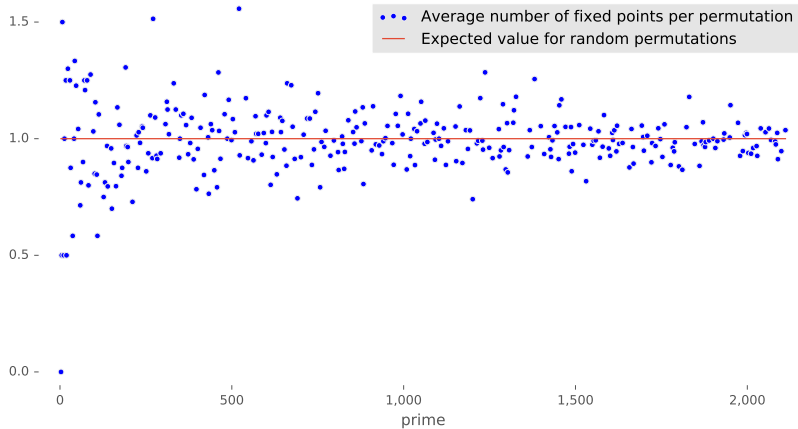
Distribution of number of cycles for all 288 generators of \mathbb{F}_{1009}

Number of k -cycles



Average number of k -cycles in \mathbb{F}_{1009}

Number of fixed points ($k = 1$)



Average number of fixed points in the generators of \mathbb{F}_p

Results with Sidon Sets

Let $S = \{(x, g^x) : x \in \mathbb{Z}_p^*\}$ be the graph of the ElGamal permutation.
Because S is a Sidon Set,

Theorem (Niehues, von zur Gathen, P, Zumalacárregui, 2020)

Let

$$B = [h_1, \dots, h_2] \times [k_1, \dots, k_2] \subset \mathbb{Z}_p^* \times \mathbb{Z}_p.$$

Then

$$\left| \#S \cap B - \frac{\#B}{p} \right| \leq 50p^{1/2} \log^2 p$$

Other randomness properties

- ▶ Drakakis et al. prove the ElGamal function is *Almost Perfect Nonlinear*
- ▶ Closer to PN than most APN functions in differential uniformity
- ▶ More linear than most Costas functions on a log-ratio test
- ▶ Less linear than random functions with a phase modulation test

Sequences from permutations

For any permutation π in \mathbb{Z}_p^* , make a sequence

$$\pi_v = (\pi_1 \% v, \dots, \pi_{p-1} \% v).$$

Sequences from permutations

For any permutation π in \mathbb{Z}_p^* , make a sequence

$$\pi_v = (\pi_1 \% v, \dots, \pi_{p-1} \% v).$$

Example: $p = 5$ and $g = 2$

$$\begin{aligned}\gamma &= ((2^0) \% 5) \% 2, \dots, (2^3) \% 5) \% 2 \\ &= (1, 2, 4, 3)\end{aligned}$$

$$\gamma_2 = (1, 0, 0, 1) \in \mathbb{Z}_2^4$$

Randomness properties of ElGamal Sequences?

How closely do ElGamal sequences compare to sequences from random permutations?

- ▶ Balance
- ▶ Period length
- ▶ Distribution of fixed t -tuples $z \in \mathbb{Z}_v^t$:

$$\lambda(z) = \#\{i \in [0, p-1] : \gamma_v(i +_n \iota) = z(\iota), 0 \leq \iota < t\}$$

- ▶ Distribution of *runs* of $b \in \mathbb{Z}_v$ and of length t :

$$\rho(b, t) = \#\{i \in [0, p-1] : \gamma_v(i -_n 1), \gamma_v(i +_n t) \neq b = \gamma_v(i +_n \iota), 0 \leq \iota < t\}$$

- ▶ $\rho(t) = v\rho(t+1)$

Other uses of Modulo operator in sequences

- ▶ The Legendre sequence

$$(\log_g(i)\%2, \log_g(i+1)\%2, \dots)$$

- ▶ Colbourn constructed covering arrays from the circulant matrix

$$(\log_g(i)\%v, \log_g(i+1)\%v, \dots)$$

- ▶ Tzanakis et al. formed covering array from circulant matrices of

$$(\log_g(\text{tr}(g^i))\%v, \log_g(\text{tr}(g^{i+1}))\%v, \dots)$$

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Balance

Proposition

Let π be a permutation in \mathbb{Z}_p^ , then π_v is a balanced sequence over \mathbb{Z}_v if and only if $v \mid p - 1$.*

Proof.

The number of $x \equiv a \pmod v$ in $[1, p - 1]$ is

$$|\pi_v|_a = \lceil (p - 1 - ((a - 1) \bmod v)) / v \rceil$$



Period

Lemma

If $p \equiv \alpha \not\equiv 1 \pmod{v}$, then π_v has period $N = p - 1$ for any π permutation of \mathbb{Z}_p^ .*

Proof.

The difference in the number of occurrences of any two symbols must be a multiple of $(p - 1)/N$. But

$$|\pi_v|_a = \begin{cases} \lceil (p - 1)/v \rceil & 0 \leq a < \alpha - 1, \\ \lfloor (p - 1)/v \rfloor & \text{otherwise.} \end{cases}$$



Period

Theorem

For every $\epsilon > 0$ there exists an n_ϵ so that for all $p \geq n_\epsilon$, the number T of balanced sequences π_v with period $p - 1$ satisfies

$$(p - 1)!(1 - \epsilon) \leq T \leq (p - 1)!. \quad (1)$$

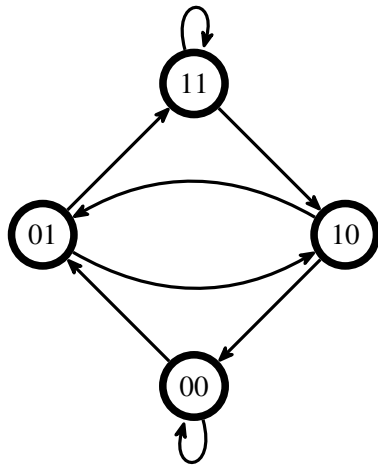
Special case

When q is prime and $p = vq + 1$,

$$\frac{(p-1)! - T}{(p-1)!} = \frac{v!(q!)^v}{(p-1)!}$$

This includes the case of Sophie Germain primes.

de Bruijn graph



Transfer Matrix

Transfer matrix is directed adjacency matrix of de Bruijn graph with variables

$$T = \begin{array}{c} \begin{array}{cc} & \begin{array}{cccc} & 00 & 01 & 10 & 11 \end{array} \\ \begin{array}{c} 00 \\ 01 \\ 10 \\ 11 \end{array} & \left(\begin{array}{cccc} ux_0 & ux_0 & 0 & 0 \\ 0 & 0 & x_0 & x_0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{array} \right) \end{array}$$

$$C = \begin{array}{c} \begin{array}{cc} & \begin{array}{cccc} & 00 & 01 & 10 & 11 \end{array} \\ \begin{array}{c} 00 \\ 01 \\ 10 \\ 11 \end{array} & \left(\begin{array}{cccc} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{array} \right) \end{array}$$

$$\sum_{\mathbf{k} \in \mathbb{N}^t} a_n(\mathbf{k}) x^{\mathbf{k}} = \sum_{z', z'' \in \mathbb{Z}_V^t} C_{z', z''} T_{z', z''}^n.$$

Asymptotic Normality

Theorem (Bender, Richmond, Williamson 1983)

Suppose $\mathbf{a}_n(k)$ is admissible at 1 for $n \equiv n_0 \pmod{d}$ and that Λ is d -dimensional. Then $\mathbf{a}_n(k)$ satisfies a central limit theorem for $n \equiv n_0 \pmod{d}$ with means and covariance matrix asymptotically proportional to n . Let \mathbf{q} be such that $\mathbf{q}\mathbf{c} \in \Lambda$ for all $\mathbf{c} \in \mathbb{Z}^v$. Then $\mathbf{a}_n(k)$ satisfies a local limit theorem modulo Λ for $n \equiv n_0 \pmod{dq}$

Asymptotic Normality

Theorem

Let $z \in \mathbb{Z}_v^t$ and $t(\kappa)$ be the number of balanced circular sequences of length n over \mathbb{Z}_v for which $\lambda(z) = \kappa$. There exists a $m_\lambda, b_\lambda, c_\lambda \in \mathbb{R}$ such that

$$\sup_{\kappa} \left| \frac{\sqrt{2\pi b_\lambda} t(\kappa)}{\binom{v}{l, l, \dots, l}} - c_\lambda e^{(\kappa - m_\lambda)^2 / b_\lambda} \right| = o(1).$$

Let $b \in \mathbb{Z}_v$, $t \in \mathbb{N}$ and $r(\kappa)$ be the number of balanced circular sequences of length n over \mathbb{Z}_v for which $\rho(b, t) = \kappa$. There exists a $m_\rho, b_\rho, c_\rho \in \mathbb{R}$ such that

$$\sup_{\kappa} \left| \frac{\sqrt{2\pi b_\rho} r(\kappa)}{\binom{v}{l, l, \dots, l}} - c_\rho e^{(\kappa - m_\rho^2) / b_\rho} \right| = o(1).$$

Mean for tuples

$$\begin{aligned} \frac{n}{v^t} \left(1 + \frac{-(t^2 - 2tv + v^2 - t)(v - 1)}{2n} \right) + O\left(\frac{1}{n}\right) \\ \leq E(\lambda(z)) \leq \\ \frac{n}{v^t} \left(1 + \frac{t(v - 1)}{2n} \right) + O\left(\frac{1}{n}\right) \end{aligned}$$

Variance for tuples

$$\begin{aligned} \frac{n}{v^{2t}} \left(\frac{2v^t}{2} + \frac{-12t^2v^t}{24n} \right) + O\left(\frac{1}{n}\right) \\ \lesssim \text{VAR}(\lambda) \lesssim \\ \frac{n}{v^{2t}} \left(\frac{2v^t(v+1)}{2(v-1)} + \frac{12v^{t+2}t}{24n(v-1)} \right) + O\left(\frac{1}{n}\right) \end{aligned}$$

Runs

$$\begin{aligned}E(\rho(b, t)) &= \frac{(l(v-1)-1)(v-1)l(l)_t}{(n-1)_{t+1}}, \\ \text{VAR}(\rho(b, t)) &= \frac{(l(v-1)-1)(v-1)l(l)_t}{(n-1)_{t+1}} \\ &\quad + \frac{(v-1)l(l)_{2t}(l(v-1)-1)^2(l(v-1)-2)}{(n-1)_{2t+2}} \\ &\quad - \left(\frac{(l(v-1)-1)(v-1)l(l)_t}{(n-1)_{t+1}} \right)^2.\end{aligned}$$

Where $l = n/v$.

Runs

$$E(\rho(b, t)) = \frac{n(v-1)}{v^{t+2}} \left((v-1) - \frac{(v-1)^2 t^2 - (v+3)(v-1)t + 2}{2n} \right) + O\left(\frac{1}{n}\right)$$

$$\text{VAR}(\rho(b, t)) \approx \frac{n(v-1)^2}{v^{t+2}} \left(1 + \frac{-(v-1)t^2}{2n} \right) + O\left(\frac{1}{n}\right)$$

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Proposition

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Period

Theorem

The ElGamal sequence γ_v has period $N = p - 1$.

Proof.

1. $p \not\equiv 1 \pmod{v}$: Use balance
2. $p \equiv 1 \pmod{v}$: Suppose period $N < p - 1$: $g^{i+N \% p} \equiv_v g^{i \% p}$
3. Let $i = 0$: $g' = g^{N \% p} \equiv_v 1$.
4. Let $p = kg' + r$, $x = k + 1$ ($p < xg' < 2p$). Let $i = \log_g(x)$:

$$x \equiv_v xg' \% p = xg' - p \equiv_v xg' - 1$$

5. $x(g' - 1) \equiv_v 1 \equiv_v g'$ is a contradiction.



Tuples

Theorem

Let γ_v be an ElGamal sequence and $p = qg^{t-1} + r$, then

$$\left\lfloor \frac{g}{v} \right\rfloor^{t-1} \left\lfloor \frac{q}{v} \right\rfloor \leq \lambda(z) \leq \left\lceil \frac{g}{v} \right\rceil^{t-1} \left(\left\lfloor \frac{q}{v} \right\rfloor + 1 \right).$$

Proof

$$X = \{x \in [1, p-1] : (g^i x) \% p \equiv_v z_i, 0 \leq i < t\}$$

Let $c_i = g^i z_0 - z_i$, $0 \leq i < t$.

$$D = \{d \in \mathbb{Z}^t : d_0 = 0, d_i \equiv_v \alpha^{-1} c_i \text{ and } g d_{i-1} \leq d_i < g(d_{i-1}+1) \text{ for } 0 < i < t\}.$$

For $d \in D$, let

$$X_d = \left\{ x \in \mathbb{Z} : x \equiv_v z_0, \frac{d_i p}{g^i} \leq x < \frac{(d_i + 1)p}{g^i}, \text{ for } 0 \leq i < t \right\}.$$

Claim:

$$X = \bigcup_{d \in D} X_d$$

$$X_d \subset X$$

If $x \in X_d$, then $x \equiv_v z_0$ and

$$d_i p \leq g^i x < (d_i + 1)p$$

Thus

$$g^i x \% p = g^i x - d_i p \equiv_v g^i x - \alpha d_i \equiv_v g^i z_0 - c_i \equiv_v g^i z_0 - (g^i z_0 - z_i) = z_i,$$

So $x \in X$.

$$X \subset \cup X_d$$

For $x \in X$, define $g^i x = q_i p + r_i$:

$$q_0 = 0$$

$$r_i = g^i x - q_i p = (g^i x) \% p \equiv_v z_i$$

$$\frac{q_i p}{g^i} \leq x < \frac{(q_i + 1)p}{g^i}$$

So $x \in X_{(q_0, \dots, q_{t-1})}$

$$X \subset \cup X_d$$

$$q_i \equiv_v \alpha^{-1} q_i p = \alpha^{-1} (g^i x - r_i) \equiv_v \alpha^{-1} (g^i z_0 - z_i) = \alpha^{-1} c_i.$$

Then,

$$\begin{aligned} q_i &= \frac{g^i x - r_i}{p} = \frac{g(g^{i-1} x) - r_i}{p} = \frac{g(q_{i-1} p + r_{i-1}) - r_i}{p} \\ &= gq_{i-1} + g\frac{r_{i-1}}{p} - \frac{r_i}{p} < g(q_{i-1} + 1), \end{aligned}$$

and

$$gq_{i-1} = \frac{gq_{i-1}p}{p} \leq \frac{g(q_{i-1}p + r_{i-1})}{p} = \frac{g(g^{i-1}x)}{p} = \frac{g^i x}{p} = q_i + \frac{r_i}{p}.$$

Since $gq_{i-1}, q_i \in \mathbb{Z}$ and $r_i/p < 1$, $\Rightarrow q_i \geq gq_{i-1}$.

Thus $(q_0, \dots, q_{t-1}) \in D$.

Final step

$$\begin{aligned}
 X &= \bigcup_{d \in D} X_d = \bigcup_{d \in D} \left(\{x \equiv_v z_0\} \cap \left(\bigcap_{0 \leq i < t} \left\{ \frac{d_i p}{g^i} \leq x < \frac{(d_i + 1)p}{g^i} \right\} \right) \right) \\
 &= \bigcup_{d \in D} \left(\{x \equiv_v z_0\} \cap \left\{ \frac{d_{t-1} p}{g^{t-1}} \leq x < \frac{(d_{t-1} + 1)p}{g^{t-1}} \right\} \right).
 \end{aligned}$$

$$\begin{array}{ccccc}
 \lfloor g/v \rfloor^{t-1} & \leq & \#D & \leq & \lceil g/v \rceil^{t-1} \\
 q & \leq & \#[d_{t-1}p/g^{t-1}, (d_{t-1} + 1)p/g^{t-1}) & \leq & q + 1 \\
 \lfloor q/v \rfloor & \leq & \#X_d & \leq & \lceil (q + 1)/v \rceil
 \end{array}$$

$$\left\lfloor \frac{g}{v} \right\rfloor^{t-1} \left\lfloor \frac{q}{v} \right\rfloor \leq \lambda(z) \leq \left\lceil \frac{g}{v} \right\rceil^{t-1} \left(\left\lfloor \frac{q}{v} \right\rfloor + 1 \right).$$

□

Observations

- ▶ When $g = mv$ bounds differ by at most m^t
- ▶ When $g = v$, $\lfloor \frac{g}{v} \rfloor \leq \lambda(z) \leq \lfloor \frac{g}{v} \rfloor + 1$
- ▶ If $p \geq vg^{t-1}$ and $g \geq v$, then $\lambda(z) > 0$ for all $z \in \mathbb{Z}_v^t$
- ▶ If $\lambda(z) > 0$ for all $z \in \mathbb{Z}_v^t$, then $g \geq v$ and $p \geq v^t + 1$.
- ▶ Coincide when $g = v$
- ▶ $\gamma_v(i+1) \equiv_v g\gamma_v(i) - s$ for some $0 \leq s < g$.

Runs

Theorem

Let γ_v be an ElGamal sequence and $p = qg^{t-1} + r$. For $z \in \mathbb{Z}_v^t$, let

$$\mu(z) = \#\{i \in [1, p-1] : g^{i+j} \% p \equiv_v z_j, 0 \leq j < t-1, g^{i+t-1} \% p \not\equiv_v z_{t-1}\}.$$

Then

$$\left\lfloor \frac{g}{v} \right\rfloor^{t-2} \left\lfloor \frac{(v-1)g}{v} \right\rfloor \left\lfloor \frac{q}{v} \right\rfloor \leq \mu(z) \leq \left\lceil \frac{g}{v} \right\rceil^{t-2} \left\lceil \frac{(v-1)g}{v} \right\rceil \left(\left\lfloor \frac{q}{v} \right\rfloor + 1 \right).$$

Corollary

Let $p = q_t g^t + r_t$ and $p = q_{t+1} g^{t+1} + r_{t+1}$. Then

$$\begin{aligned} \left\lfloor \frac{g}{v} \right\rfloor^{t-1} \left\lfloor \frac{(v-1)g}{v} \right\rfloor \left\lfloor \frac{q_t}{v} \right\rfloor - \left\lfloor \frac{g}{v} \right\rfloor^t \left\lfloor \frac{(v-1)g}{v} \right\rfloor \left\lfloor \frac{q_{t+1} + 1}{v} \right\rfloor \\ \leq \rho(b, t) \leq \\ \left\lfloor \frac{g}{v} \right\rfloor^{t-1} \left\lfloor \frac{(v-1)g}{v} \right\rfloor \left\lfloor \frac{q_t + 1}{v} \right\rfloor - \left\lfloor \frac{g}{v} \right\rfloor^t \left\lfloor \frac{(v-1)g}{v} \right\rfloor \left\lfloor \frac{q_{t+1}}{v} \right\rfloor, \end{aligned}$$

and

$$(v-1) \left\lfloor \frac{g}{v} \right\rfloor^t \left\lfloor \frac{(v-1)g}{v} \right\rfloor \left\lfloor \frac{q}{v} \right\rfloor \leq \rho(b, t) \leq (v-1) \left\lfloor \frac{g}{v} \right\rfloor^t \left\lfloor \frac{(v-1)g}{v} \right\rfloor \left\lfloor \frac{q+1}{v} \right\rfloor.$$

Comparison to random balanced sequences

From theoretical results

- ▶ Balance matches exactly
- ▶ Periodicity matches very closely
- ▶ To first order, the number of tuples and runs matches
- ▶ To first order $\rho(t) \approx v\rho(t+1)$

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Experimental setting

We run experiments over two distinct data sets of pairs (p, v) with $p > 1,000,000$ and $2 \leq v \leq 8$.

all primes: Primes where $v \mid p - 1$.

$g = v$ primes: Primes where $v \mid p - 1$ and v is a generator.

Experimental setting

We run experiments over two distinct data sets of pairs (p, v) with $p > 1,000,000$ and $2 \leq v \leq 8$.

all primes: Primes where $v \mid p - 1$.

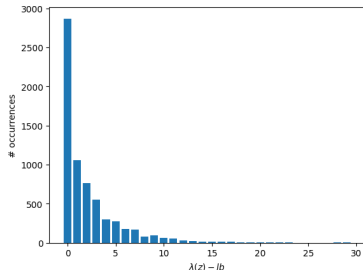
$g = v$ primes: Primes where $v \mid p - 1$ and v is a generator.

	all	$g = v$
# pairs (prime v)	715	400
# distinct primes	322	323
# distinct v	7	4
# v per prime (average)	4.51	1.48

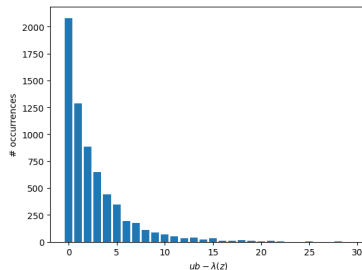
- ▶ We run experiments over *all primes* for the smallest 10 generators.
- ▶ If $v \in \{4, 5, 8\}$ then $v \neq g$.

ElGamal Sequences t -tuple bound gap distribution

Lower bound $\lambda(z) > 0$
 $t = 2$ and 12% outliers.



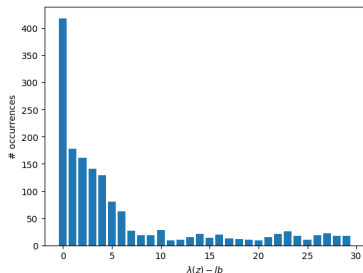
Upper bound
 $t = 2$ and 5% outliers



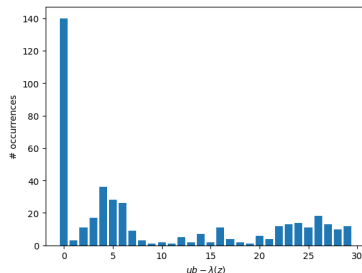
Distribution of gaps between $\lambda(z)$ and lower and upper bounds.

ElGamal Sequences t -tuple bound gap distribution

Lower bound $\lambda(z) > 0$
 $t = 7$ and 59.75% outliers.



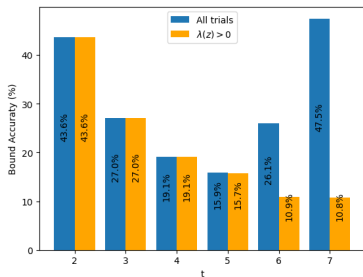
Upper bound
 $t = 7$ and 93.56% outliers.



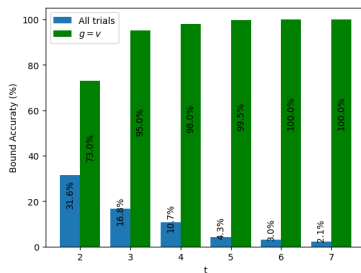
Distribution of gaps between $\lambda(z)$ and lower and upper bounds.

ElGamal Sequences t -tuple bound accuracy

Lower bound



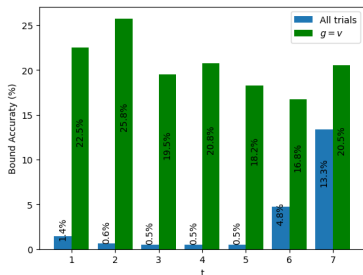
Upper bound



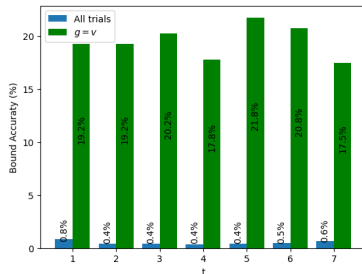
Percentage of trials with $z \in \mathbb{Z}_v^t$ s.t. $\lambda(z)$ matches lower and upper bounds.

ElGamal Sequences run bound accuracy

Lower bound



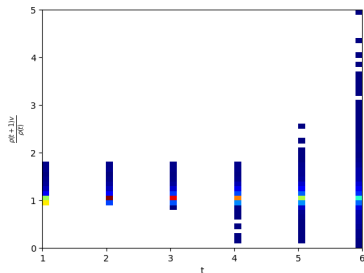
Upper bound



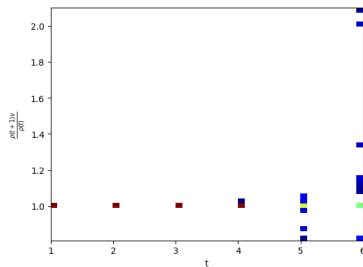
Percentage of trials with $b \in \mathbb{Z}_v$ s.t. $\rho(b, t)$ matches lower and upper bounds.

ElGamal Sequences run ratio Experiment

All primes.



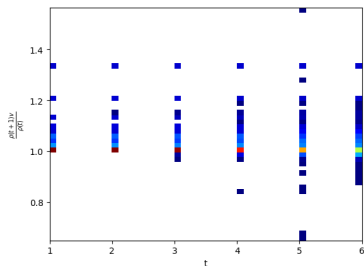
$g = v$ primes.



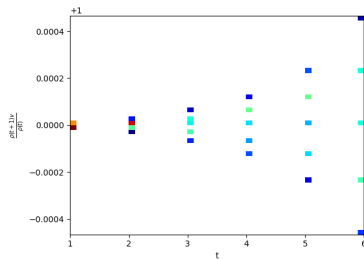
Distribution of $\rho(t+1)v/\rho(t)$ as a heat map with $2 \leq v \leq 8$

ElGamal Sequences run ratio Experiment

All primes.



$g = v$ primes.



Distribution of $\rho(t+1)v/\rho(t)$ as a heatmap with $v = 2$

Linear Complexity

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Conclusions

- ▶ ElGamal permutations behave like random for cycle sizes and distribution of graph
- ▶ ElGamal permutations are close to random permutations for nonlinearity
- ▶ ElGamal sequences have balance and periodicity close to random
- ▶ Tuples in ElGamal sequences are distributed as in random balanced sequences
- ▶ Run lengths in ElGamal sequences satisfy Golomb's Randomness Postulate

Next steps

- ▶ Experiments indicate that $\lambda(z)$ bounds are tight. So any improvements will be conditional
- ▶ Prove properties of the distribution of $\lambda(z)$
- ▶ Prove linear complexity results for ElGamal sequences
- ▶ Determine expected linear complexity for random balanced random sequences
- ▶ Further investigate auto-correlation
- ▶ Will these be enough to justify cryptographic utility?

Obrigado
Thanks
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Outline

Contextualization

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References

References I



Boppré Niehues, L., von zur Gathen, J., Perin, L. P., & Zumalacárregui, A. (2020). Sidon sets and statistics of the elgamal function. *Cryptologia*, 44(5), 438–450.