

# fn sample\_geometric\_exp\_fast

Michael Shoemate

May 21, 2025

This proof resides in “contrib” because it has not completed the vetting process.

Proves soundness of `fn sample_geometric_exp_fast` in `mod.rs` at commit `0be3ab3e6` (outdated<sup>1</sup>). This proof is an adaptation of subsection 5.2 of [CKS20].

## Vetting history

- Pull Request #519

## 1 Hoare Triple

### Precondition

$x \in \mathbb{Q} \wedge x > 0$

### Pseudocode

```
1 def sample_geometric_exp_fast(x) -> int:
2     if x == 0:
3         return 0
4
5     s, t = Rational.into_numer_denom(x)
6
7     while True:
8         u = Integer.sample_uniform_int_below(t) #
9         d = bool.sample_bernoulli_exp(Rational(u, t)) #
10        if d:
11            break
12
13        v = sample_geometric_exp_slow(1) #
14        z = u + t * v
15        return z // s
```

### Postcondition

For any setting of the input parameter  $x$  such that the given preconditions hold, `sample_geometric_exp_fast` either returns `Err(e)` due to a lack of system entropy, or `Ok(out)`, where `out` is distributed as  $Geometric(1 - \exp(-x))$ .

---

<sup>1</sup>See new changes with `git diff 0be3ab3e6..cde9e54 rust/src/traits/samplers/cks20/mod.rs`

## 2 Proof

Assume the preconditions are met.

**Lemma 2.1.** `sample_geometric_exp_fast` only returns `Err(e)` when there is a lack of system entropy.

*Proof.* `x` is of type `Rational`, there exists some non-negative integer  $s$  and positive integer  $t$  such that  $x = s/t$ . This is why `Rational.into_numer_denom` is infallible. Since  $t$  is a positive integer, the preconditions on `SampleUniformIntBelow` are met, `sample_uniform_int_below` can only return an error due to lack of system entropy, and  $u$  is a non-negative integer. Similarly, the preconditions on `sample_bernoulli_exp` and `sample_geometric_exp_slow` are met, and their definitions guarantee an error is only returned due to lack of system entropy. The only source of errors is from the invocation of these functions, therefore `sample_geometric_exp_fast` only returns `Err(e)` when there is a lack of system entropy.  $\square$

We now establish some lemmas that will be useful in proving the distribution of `out`.

- Let  $u$  be a realization of a random variable  $U \sim \text{Uniform}(0, t)$ , supported on  $[0, t)$ .
- Let  $d$  be a realization of a random variable  $D \sim \text{Bernoulli}(\exp(-u/t))$
- Let  $v$  be a realization of a random variable  $V \sim \text{Geometric}(1 - \exp(-1))$

**Lemma 2.2.** [CKS20] Conditioned on  $d = \top$ , if  $z = u + t \cdot v$ , then  $z$  is a realization of a random variable  $Z \sim \text{Geometric}(1 - \exp(-1/t))$ . Equivalently,  $P[Z = z | D = \top] = (1 - e^{-1/t})e^{-z/t}$ .

*Proof.* For any  $z$ , define  $u_z := z \bmod t$  and  $v_z := \lfloor z/t \rfloor$ , so that  $z = u_z + t \cdot v_z$ .

$$\begin{aligned}
 P[Z = z | D = \top] &= P[U = u_z, V = v_z | D = \top] && \text{since } z = u_z + t \cdot v_z \\
 &= P[U = u_z | D = \top] P[V = v_z] && \text{as } U \text{ and } V \text{ are independent} \\
 &= \frac{P[U = u_z]}{P[D = \top]} P[D = \top | U = u_z] \cdot (1 - e^{-1})e^{-v_z} && \text{by Bayes' theorem} \\
 &= \frac{1/t}{1/t \sum_{k=0}^{t-1} e^{-k/t}} e^{-u_z/t} \cdot (1 - e^{-1})e^{-v_z} && \text{since } P[D = \top] = \frac{1}{t} \sum_{k=0}^{t-1} e^{-k/t} \\
 &= \frac{(1 - e^{-1})}{\sum_{k=0}^{t-1} e^{-k/t}} e^{-(u_z/t + v_z)} \\
 &= (1 - e^{-1/t})e^{-(u_z/t + v_z)} \\
 &= (1 - e^{-1/t})e^{-z/t} && \text{since } z = u_z + t \cdot v_z
 \end{aligned}$$

$\square$

**Lemma 2.3.** [CKS20] Fix  $p \in (0, 1]$ . Let  $G$  be a  $\text{Geometric}(1 - p)$  random variable, and  $n \geq 1$  be an integer. Then  $\lfloor G/n \rfloor$  is a  $\text{Geometric}(1 - q)$  random variable with  $q = p^n$ .

*Proof.*

$$\begin{aligned}
 P[\lfloor G/n \rfloor = k] &= P[nk < G < (k+1)n] && \text{any } G \text{ in the interval maps to } k \\
 &= \sum_{l=nk}^{(k+1)n-1} (1-p)p^l \\
 &= (1-p^n)p^{nk} \\
 &= (1-q)q^k
 \end{aligned}$$

$\square$

**Theorem 2.4.** [CKS20] Given any  $s, t \in \mathbb{Z}_+$  and  $Z \sim \text{Geometric}(1 - \exp(-1/t))$ , define  $Y = \lfloor Z/s \rfloor$ . Then  $Y \sim \text{Geometric}(1 - \exp(-s/t))$ .

*Proof.*

$$\begin{aligned}
P[Y = y | D = \top] &= P[\lfloor Z/s \rfloor = y | D = \top] \\
&= (1 - p^s) p^{sk} && \text{by 2.3} \\
&= (1 - (e^{-1/t})^s) (e^{-1/t})^{sk} \\
&= (1 - e^{-s/t}) (e^{-s/t})^k
\end{aligned}$$

□

**Lemma 2.5.** If the outcome of `sample_geometric_exp_fast` is `Ok(out)`, then `out` is distributed as  $\text{Geometric}(1 - \exp(-x))$ .

*Proof.* As shown in 2.1, the preconditions for `SampleUniformIntBelow` on line 8, `sample_bernoulli_exp` on line 9, and `sample_bernoulli_exp_slow` on line 13 are met. Therefore, `u`, `d` and `v` follow the distributions necessary to apply 2.2. By 2.2, `z` is a realization of  $Z \sim \text{Geometric}(1 - \exp(-1/t))$ . Since `z` is a realization of  $Z \sim \text{Geometric}(1 - \exp(-1/t))$ , then by 2.4, `out` is distributed as  $\text{Geometric}(1 - \exp(-x))$ . □

*Proof.* 1 holds by 2.1 and 2.5. □

## References

[CKS20] Clément L. Canonne, Gautam Kamath, and Thomas Steinke. The discrete gaussian for differential privacy. *CoRR*, abs/2004.00010, 2020.