

# Stochastic Models for blockchain analysis

## Simple models for blockchain performance analysis

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# The three dimensions of blockchain analysis

- 1 Security of PoW blockchain
- 2 Decentralization in PoS blockchain
- 3 Blockchain efficiency

# Double spending attack

## Security of PoW blockchain

- 1 Mary transfers 10 BTCs to John
- 2 The transaction is recorded in the public branch of the blockchain and John ships the good.
- 3 Mary transfers to herself the exact same BTCs
- 4 The malicious transaction is recorded into a private branch of the blockchain
  - Mary has friends among the miners to help her out
  - The two chains are copycat up to the one transaction

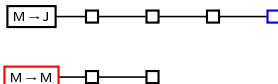
Fact (Bitcoin has only one rule)

The longest chain is to be trusted

# Double spending in practice

## Security of PoW blockchain

Vendor are advised to wait for  $\alpha \in \mathbb{N}$  of confirmations so that the honest chain is ahead of the dishonest one.



In the example, vendor awaits  $\alpha = 4$  confirmations, the honest chain is ahead of the dishonest one by  $z = 2$  blocks.

### Fact (PoW is resistant to double spending)

- Attacker does not own the majority of computing power
- Suitable  $\alpha$

Double spending is unlikely to succeed.



S. Nakamoto, "Bitcoin : A peer-to-peer electronic cash system." Available at <https://bitcoin.org/bitcoin.pdf>, 2008.

# Mathematical set up

## Security of PoW blockchain

Assume that

- $R_0 = z \geq 1$  (the honest chain is  $z$  blocks ahead)
- at each time unit a block is created
  - in the honest chain with probability  $p$
  - in the dishonest chain with probability  $q = 1 - p$

The process  $(R_n)_{n \geq 0}$  is a random walk on  $\mathbb{Z}$  with

$$R_n = z + Y_1 + \dots + Y_n,$$

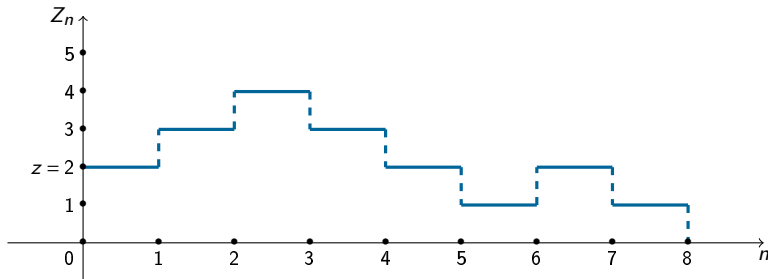
where  $Y_1, \dots, Y_n$  are the **i.i.d.** steps of the random walk.

# Double spending rate of success

Security of PoW blockchain

Double spending occurs at time

$$\tau_z = \inf\{n \in \mathbb{N}; R_n = 0\}.$$



Double spending theorem

If  $p > q$  then the double-spending probability is given by

$$\phi(z) = \mathbb{P}(\tau_z < \infty) = \left(\frac{q}{p}\right)^z.$$

# Proof of the double spending theorem I

## Security of PoW blockchain

Analogy with the gambler's ruin problem. Using a first step analysis, we have

$$\phi(z) = p\phi(z+1) + (1-p)\phi(z-1), \quad z \geq 1. \quad (1)$$

We also have the boundary conditions

$$\phi(0) = 1 \text{ and } \lim_{z \rightarrow +\infty} \phi(z) = 0 \quad (2)$$

Equation (1) is a linear difference equation of order 2 associated to the following characteristic equation

$$px^2 - x + 1 - p = 0$$

which has two roots on the real line with

$$r_1 = 1, \text{ and } r_2 = \frac{1-p}{p}.$$

The solution of (1) is given by

$$\phi(z) = A + B \left( \frac{1-p}{p} \right)^z,$$

# Proof of the double spending theorem II

Security of PoW blockchain

where  $A$  and  $B$  are constant. Using the boundary conditions (2), we deduce that

$$\phi(z) = \left( \frac{1-p}{p} \right)^z$$

as announced.



# Refinements of the double spending problem

## Security of PoW blockchain

The number of blocks  $M$  found by the attacker until the honest miners find  $\alpha$  blocks is a negative binomial random variable with **pmf**

$$\mathbb{P}(M = m) = \binom{\alpha + m - 1}{m} p^\alpha q^m, \quad m \geq 0.$$

The number of block that the honest chain is ahead of the dishonest one is given by

$$Z = (\alpha - M)_+.$$

Applying the law of total probability yields the probability of successful double spending with

$$\mathbb{P}(\text{Double Spending}) = \mathbb{P}(M \geq \alpha) + \sum_{m=0}^{\alpha-1} \binom{\alpha + m - 1}{m} q^\alpha p^m.$$



M. Rosenfeld, "Analysis of hashrate-based double spending," *arXiv preprint arXiv:1402.2009*, 2014.



C. Grunspan and R. Perez-Marco, "Double spend race," *International Journal of Theoretical and Applied Finance*, vol. 21, p. 1850053, dec 2018.

# Refinements of the double spending problem

## Security of PoW blockchain

Let the length of honest and dishonest chain be driven by counting processes

- Honest chain  $\Rightarrow z + N_t$ ,  $t \geq 0$ , where  $z \geq 1$ .
- Malicious chain  $\Rightarrow M_t$ ,  $t \geq 0$
- Study the distribution of the first-*rendez-vous* time

$$\tau_z = \inf\{t \geq 0, M_t = z + N_t\}.$$

If  $N_t \sim \text{Pois}(\lambda t)$  and  $M_t \sim \text{Pois}(\mu t)$  such that  $\lambda > \mu$  then

$$\phi(z) = \left(\frac{\mu}{\lambda}\right)^z, \quad z \geq 0.$$



P.-O. Goffard, "Fraud risk assessment within blockchain transactions," *Advances in Applied Probability*, vol. 51, pp. 443–467, jun 2019.  
<https://hal.archives-ouvertes.fr/hal-01716687v2>.



R. Bowden, H. P. Keeler, A. E. Krzesinski, and P. G. Taylor, "Modeling and analysis of block arrival times in the bitcoin blockchain," *Stochastic Models*, vol. 36, pp. 602–637, jul 2020.

# Perspectives

## Security of PoW blockchain

- Distribution of  $\tau_z$  ? (To be discussed later)
- Distribution of  $Z$ 
  - ↳ Negative binomial when the length of the blockchain are driven by Poisson processes
  - ↳ if not ?

# Proof of Stake protocol

## Decentralization in PoS blockchain

PoS is the most popular alternative to PoW.

- A block validator is selected according to the number of native coins she owns
- Update the blockchain and receive a reward or do nothing

Two problems

- ⚠ Nothing at stake  $\Rightarrow$  Consensus postponed
- ⚠ Rich gets richer  $\Rightarrow$  Risk of centralization

# Nothing-at-Stake

## Decentralization in PoS blockchain

If given the opportunity a node will always append a new block

- Everlasting fork if any

Perpetuating disagreement prevent users to exchange which lower the coin value.

### Theorem

To get consensus faster and almost surely

- Set a minimum stake to outweigh the benefit of the reward
- Set up a modest reward schedule  $\sum_{t=1}^{\infty} r_t < \infty$



F. Saleh, "Blockchain without waste : Proof-of-stake," *The Review of Financial Studies*, vol. 34, pp. 1156–1190, jul 2020.

# Risk of centralization ?

## Decentralization in PoS blockchain

### Block appending process

- Draw a coin at random
- The owner of the coin append a block and collect the reward
- The block appender is more likely to get selected during the next round

Similar to Polya's urn



- Consider an urn of  $N$  balls of color in  $E = \{1, \dots, p\}$
- Draw a ball of color  $x \in E$
- Replace the ball together with  $r$  balls of color  $x$

$p$  is the number of peers and  $r$  is the size of the block reward.

### Theorem

The proportion of coins owned by each peer is stable on average over the long run



I. Roşu and F. Saleh, "Evolution of shares in a proof-of-stake cryptocurrency," *Management Science*, vol. 67, pp. 661–672, feb 2021.

# Proof

## Decentralization in PoS blockchain

Consider the balls of some color  $x \in E$ , and denote by

- $N_x$  the number of balls of color  $x$  initially in the urn
- $Y_n$  the number of balls of color  $x$  in the urn after  $n$  draws
- $Z_n$  the corresponding proportion of balls of color  $x$ .

We show that  $(Z_n)_{n \geq 0}$  is a  $\mathcal{F}_n$ -Martingale where  $\mathcal{F}_n = \sigma(Y_1, \dots, Y_n)$ . We have

$$\mathbb{E}(Z_{n+1} | \mathcal{F}_n) = Z_n \frac{Y_n + r}{N + r(n+1)} + (1 - Z_n) \frac{Y_n}{N + r(n+1)} = Z_n$$

It follows that

$$\mathbb{E}(Z_n) = \mathbb{E}(Z_0) = \frac{N_x}{N}, \text{ for } n \geq 0.$$

hence the stability. Furthermore, because  $|Z_n| < 1$ , then  $\lim_{n \rightarrow \infty} Z_n = Z_\infty$  exists and it holds that  $\mathbb{E}(Z_\infty) = \mathbb{E}(Z_0)$ .

# What is the limiting distributions of the shares ?

Decentralization in PoS blockchain

## Dirichlet distribution

A random vector  $(Z_1, \dots, Z_p)$  has a Dirichlet distribution  $\text{Dir}(\alpha_1, \dots, \alpha_p)$  with **pdf**

$$f(z_1, \dots, z_p; \alpha_1, \dots, \alpha_p) = \frac{1}{B(\alpha)} \prod_{i=1}^p z_i^{\alpha_i - 1},$$

for  $\alpha_1, \dots, \alpha_p > 0$ ,  $0 < z_1, \dots, z_p < 1$  and  $\sum_{i=1}^p z_i = 1$ , where

$$B(\alpha) = \frac{\prod_{i=1}^p \Gamma(\alpha_i)}{\Gamma(\sum_{i=1}^p \alpha_i)}.$$

## Theorem (Convergence toward a Dirichlet distribution)

Suppose that  $r = 1$  and let  $X_n$  be the color of the ball drawn at the  $n^{\text{th}}$  round then

$$\{\mathbb{P}(X_\infty = x), x \in E\} \sim \text{Dir}(\{N_x, x \in E\}).$$



# Proof I

## Decentralization in PoS blockchain

We have that

$$\mathbb{P}(X_1 = x) = \frac{N_x}{N} \quad (3)$$

and

$$\mathbb{P}(X_{n+1} = x) = \frac{N_x + \sum_{i=1}^n \delta_{X_i}(x)}{N + n} = \frac{N_x + \lambda_n(x)}{N + n} = m_n(x) \quad (4)$$

where  $\delta_{X_i}$  denotes the Dirac measure at  $X_i$ .

A sequence that satisfies (3) and (4) is said to be a Polya sequence with parameter  $N_x, x \in E$ .

## Lemma

*There is an equivalence between the two following statements*

- (i)  $X_1, X_2, \dots$ , is a Polya sequence
- (ii)  $\mu^* \sim \text{Dir}(N_x, x \in E)$  and  $X_1, X_2, \dots$  given  $\mu^*$  are iid as  $\mu^*$

Consider the event  $A_n = \{X_1 = x_1, \dots, X_n = x_n\}$ . Induction on  $n$  allows us to show that (i) is equivalent to

$$\mathbb{P}(A_n) = \frac{\prod_{x \in E} N_x^{[\lambda_n(x)]}}{N[n]}, \quad (5)$$

# Proof II

## Decentralization in PoS blockchain

where  $\lambda_n(x)$  is the number of  $i$ 's in  $1, \dots, n$  for which  $x_i = x$  and  $a^{[k]} = a(a+1)\dots(a+k-1)$ . Now assume that (ii) holds true, then

$$\mathbb{P}(A_n | \mu^*) = \prod_{x \in E} \mu^*(x)^{\lambda_n(x)},$$

recall that  $\mu^*$  is a random vector, indexed on  $E$ . We denote by  $\mu^*(x)$  the component associated with  $x \in E$ . The law of total probability then yields

$$\mathbb{P}(A_n) = \mathbb{E} \left[ \prod_{x \in E} \mu^*(x)^{\lambda_n(x)} \right], \quad (6)$$

which is the same as (5). Applying the lemma together with the law of large number yields

$$n^{-1} \sum_{i=1}^n \delta_{X_i}(x) \rightarrow \mu^*(x) \text{ as } n \rightarrow \infty.$$

and then  $m_n(x) \rightarrow \mu^*(x)$ .



D. Blackwell and J. B. MacQueen, "Ferguson distributions via poly urn schemes," *The Annals of Statistics*, vol. 1, mar 1973.

# Measuring decentrality

## Decentralization in PoS blockchain

### Fact

The most desirable situation corresponds to all the peers being equally likely to be selected.

Decentrality maybe measure by Shannon's entropy

$$H(\mu^*) = -\mathbb{E}\left\{\sum_x \mu^*(x) \ln[\mu^*(x)]\right\} = -\sum_x \frac{N}{N_x} [\psi(N_x + 1) - \psi(N + 1)],$$

where  $\psi(x) = \frac{d}{dx} \ln[\Gamma(x)]$  is the digamma function, to be compared to  $\ln(p)$



S. P. Gochhayat, S. Shetty, R. Mukkamala, P. Foytik, G. A. Kamhoua, and L. Njilla, "Measuring decentrality in blockchain based systems," *IEEE Access*, vol. 8, pp. 178372–178390, 2020.

# Extensions and perspectives

## Decentralization in PoS blockchain

- How to include more peers along the way ?
- What if the peers are not simply buy and hold investors ?
- Find ways to monitor decentralization and take action if necessary



I. Roşu and F. Saleh, “Evolution of shares in a proof-of-stake cryptocurrency,” *Management Science*, vol. 67, pp. 661–672, feb 2021.

# Efficiency

## Blockchain efficiency

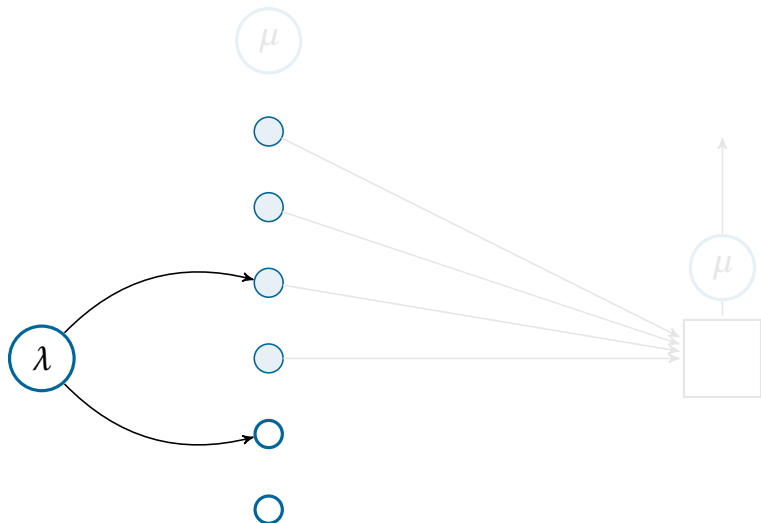
Efficiency is characterized by

- Throughputs : Number of transaction being processed per time unit
- Latency : Average transaction confirmation time

We focus on a PoW equipped blockchain and study the above quantities using a queueing model.

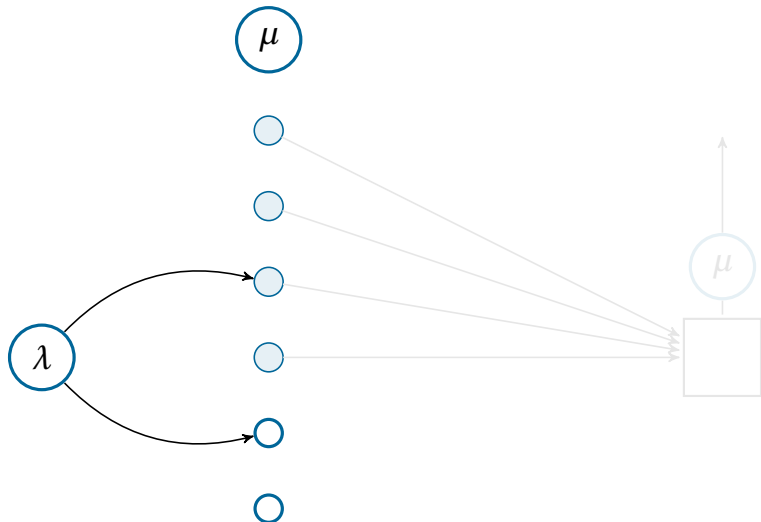
# Queue settings

Blockchain efficiency



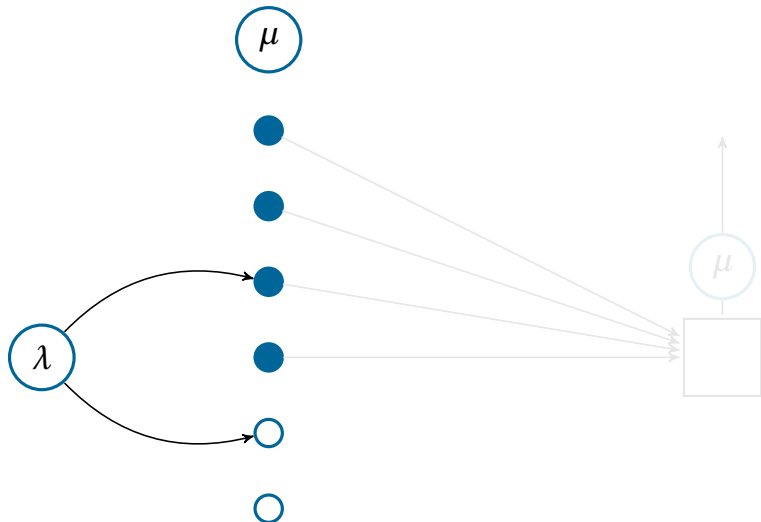
# Queue settings

Blockchain efficiency



# Queue settings

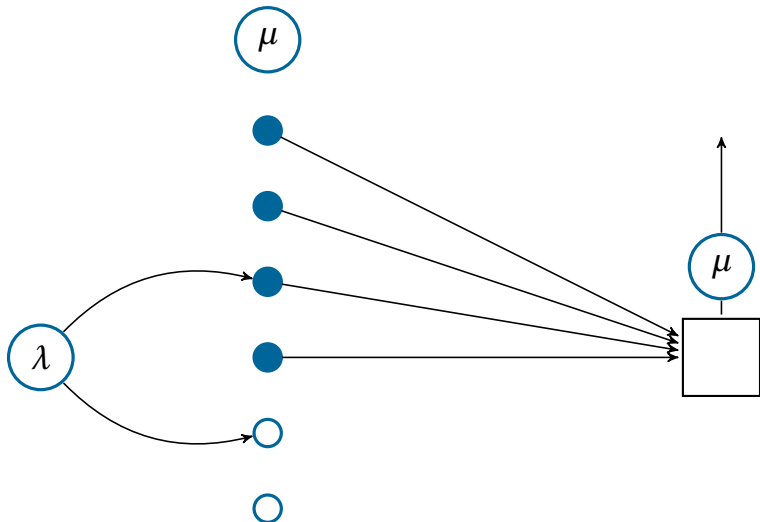
Blockchain efficiency





# Queue settings

Blockchain efficiency



# Queueing setting

## Blockchain efficiency

- Poisson arrival with rate  $\lambda > 0$  for the transactions
- Poisson arrival with rate  $\mu > 0$  for the blocks
- Block size  $b \in \mathbb{N}^* \Rightarrow$  Batch service

⚠ The server is always busy

This is somekind of  $M/M^b/1$  queue.



Y. Kawase and S. Kasahara, "Transaction-confirmation time for bitcoin : A queueing analytical approach to blockchain mechanism," in *Queueing Theory and Network Applications*, pp. 75–88, Springer International Publishing, 2017.



N. T. J. Bailey, "On queueing processes with bulk service," *Journal of the Royal Statistical Society : Series B (Methodological)*, vol. 16, pp. 80–87, jan 1954.



D. R. Cox, "The analysis of non-markovian stochastic processes by the inclusion of supplementary variables," *Mathematical Proceedings of the Cambridge Philosophical Society*, vol. 51, pp. 433–441, jul 1955.

# Queue length distribution

## Blockchain efficiency

The queueing process eventually reaches stationarity if

$$\mu \cdot b > \lambda. \quad (7)$$

We denote by  $N^q$  the length of the queue upon stationarity.

### The blockchain efficiency theorem

Assume that (7) holds then  $N^q$  is geometrically distributed

$$\mathbb{P}(N^q = n) = (1 - p) \cdot p^n,$$

where  $p = 1/z^*$  and  $z^*$  is the only root of

$$-\frac{\lambda}{\mu} z^{b+1} + z^b \left( \frac{\lambda}{\mu} + 1 \right) - 1,$$

such that  $|z^*| > 1$ .

# Proof of the efficiency theorem I

## Blockchain efficiency

Let  $N_t^q$  be the number of transactions in the queue at time  $t \geq 0$  and  $X_t$  the time elapsed since the last block was found. Further define

$$P_n(x, t) dx = \mathbb{P}[N_t^q = n, X_t \in (x, x + dx)]$$

If  $\lambda < \mu \cdot b$  holds then the process admits a limiting distribution given by

$$\lim_{t \rightarrow \infty} P_n(x, t) = P_n(x).$$

We aim at finding the distribution of the queue length upon stationarity

$$\mathbb{P}(N^q = n) := \alpha_n = \int_0^\infty P_n(x) dx. \quad (8)$$

Consider the possible transitions over a small time lapse  $h$  during which no block is being generated. Over this time interval, either

- no transactions arrives
- one transaction arrives

# Proof of the efficiency theorem II

## Blockchain efficiency

We have for  $n \geq 1$

$$P_n(x+h) = e^{-\mu h} \left[ e^{-\lambda h} P_n(x) + \lambda h e^{-\lambda h} P_{n-1}(x) \right]$$

Differentiating with respect to  $h$  and letting  $h \rightarrow 0$  leads to

$$P'_n(x) = -(\lambda + \mu)P_n(x) + \lambda P_{n-1}(x), \quad n \geq 1. \quad (9)$$

Similarly for  $n=0$ , we have

$$P'_0(x) = -(\lambda + \mu)P_0(x). \quad (10)$$

We denote by

$$\xi(x)dx = \mathbb{P}(x \leq X < x+dx | X \geq x) = \mu dx$$

the hazard function of the block arrival time (constant as it is exponentially distributed). The system of differential equations (9), (10) admits boundary conditions at  $x=0$  with

$$\begin{cases} P_n(0) = \int_0^{+\infty} P_{n+b}(x)\xi(x)dx = \mu\alpha_{n+b}, & n \geq 1, \\ P_0(0) = \mu \sum_{n=0}^b \alpha_n, & n = 0, \dots, b \end{cases} \quad (11)$$

# Proof of the efficiency theorem III

## Blockchain efficiency

Define the probability generating function of  $N^q$  at some elapsed service time  $x \geq 0$  as

$$G(z; x) = \sum_{n=0}^{\infty} P_n(x) z^n.$$

By differentiating with respect to  $x$ , we get (using (9) and (10))

$$\frac{\partial}{\partial x} G(z; x) = -[\lambda(1-z) + \mu] G(z; x)$$

and therefore

$$G(z; x) = G(z; 0) \exp\{-[\lambda(1-z) + \mu]x\}$$

We get the probability generating function of  $N^q$  by integrating over  $x$  as

$$G(z) = \frac{G(z; 0)}{\lambda(1-z) + \mu} \tag{12}$$

# Proof of the efficiency theorem IV

## Blockchain efficiency

Using the boundary conditions (11), we write

$$\begin{aligned} G(z; 0) &= \sum_{n=0}^{\infty} P_n(0) z^n \\ &= P_0(0) + \sum_{n=1}^{+\infty} P_n(0) z^n \\ &= \mu \sum_{n=0}^b \alpha_n + \mu \sum_{n=1}^{+\infty} \alpha_{n+b} z^n \\ &= \mu \sum_{n=0}^b \alpha_n + \mu z^{-b} \left[ G(z) - \sum_{n=0}^b \alpha_n z^n \right] \end{aligned} \tag{13}$$

Replacing the left hand side of (13) by (12), multiplying on both side by  $z^b$  and rearranging yields

$$\frac{G(z)}{M(z)} [z^b - M(z)] = \sum_{n=0}^{b-1} \alpha_n (z^b - z^n), \tag{14}$$

where  $M(z) = \mu / (\lambda(1-z) + \mu)$ . Using Rouché's theorem, we find that both side of the equation shares  $b$  zeros inside the circle  $\mathcal{C} = \{z \in \mathbb{C} ; |z| < 1 + \epsilon\}$  for some epsilon.

# Proof of the efficiency theorem V

## Blockchain efficiency

### Rouche's theorem

Let  $\mathcal{C} \in \mathbb{C}$  and  $f$  and  $g$  two holomorphic functions on  $\mathcal{C}$ . Let  $\partial\mathcal{C}$  be the contour of  $\partial\mathcal{C}$ . If

$$|f(z) - g(z)| < |g(z)|, \quad \forall z \in \partial\mathcal{C}$$

then  $Z_f - P_f = Z_g - P_g$ , where  $Z_f$ ,  $P_f$ ,  $Z_g$ , and  $P_g$  are the number of zeros and poles of  $f$  and  $g$  respectively.

We have  $\partial\mathcal{C} = \{z \in \mathbb{C}; |z| = 1 + \epsilon\}$ . The left hand side can be rewritten as

$$G(z) \left[ -\frac{\lambda}{\mu} z^{b+1} + \left(1 + \frac{\lambda}{\mu}\right) z^b - 1 \right].$$

Define  $f(z) = -\frac{\lambda}{\mu} z^{b+1} + \left(1 + \frac{\lambda}{\mu}\right) z^b - 1$  and  $g(z) = \left(1 + \frac{\lambda}{\mu}\right) z^b$ . We have

$$|f(z) - g(z)| = \left| -\frac{\lambda}{\mu} z^{b+1} - 1 \right| < \frac{\lambda}{\mu} (1 + \epsilon)^{b+1} + 1 \rightarrow \frac{\lambda}{\mu} + 1, \text{ as } \epsilon \rightarrow 0.$$



# Proof of the efficiency theorem VI

## Blockchain efficiency

and

$$|g(z)| = \left(1 + \frac{\lambda}{\mu}\right)(1+\epsilon)^b \rightarrow \frac{\lambda}{\mu} + 1, \text{ as } \epsilon \rightarrow 0.$$

Regarding the right hand side, define  $f(z) = \sum_{n=0}^{b-1} \alpha_n (z^b - z^n)$  and  $g(z) = \sum_{n=0}^{b-1} \alpha_n z^b$ . We have

$$|f(z) - g(z)| < \left| \sum_{n=0}^{b-1} \alpha_n z^n \right| < \sum_{n=0}^{b-1} \alpha_n (1+\epsilon)^n \rightarrow \sum_{n=0}^{b-1} \alpha_n, \text{ as } \epsilon \rightarrow 0.$$

and

$$|g(z)| = (1+\epsilon)^b \sum_{n=0}^{b-1} \alpha_n \rightarrow \sum_{n=0}^{b-1} \alpha_n, \text{ as } \epsilon \rightarrow 0.$$

One of them is 1, and we denote by  $z_k$ ,  $k=1, \dots, b-1$  the remaining  $b-1$  zeros. Given the polynomial form of the right hand side of (14), the fundamental theorem of algebra indicates that the number of zero is  $b$ . Given the left hand side

$$G(z) \left[ -\frac{\lambda}{\mu} z^{b+1} + \left(1 + \frac{\lambda}{\mu}\right) z^b - 1 \right].$$

# Proof of the efficiency theorem VII

## Blockchain efficiency

we deduce that there is one zero outside  $\mathcal{C}$ , we can further show that it is a real number  $z^*$ .  
Multiplying both side of (14) by  $(z-1)\prod_{k=1}^{b-1}(z-z_k)$ , and using  $G(1)=1$  yields

$$G(z) = \frac{1-z^*}{z-z^*}.$$

$N^q$  is then a geometric random variable with parameter  $p = \frac{1}{z^*}$ .

# Latency and throughputs

## Blockchain efficiency

### Little's law

Consider a stationary queueing system and denote by

- $1/\lambda$  the mean of the unit inter-arrival times
- $L$  be the mean number of units in the system
- $W$  be the mean time spent by units in the system

We have

$$L = \lambda \cdot W$$



J. D. C. Little, "A proof for the queueing formula  $L = \lambda W$ ," *Operations Research*, vol. 9, pp. 383–387, jun 1961.

- Latency is the confirmation time of a transaction

$$\text{Latency} = \frac{p}{(1-p)\lambda} + \frac{1}{\mu}$$

- Throughput is the number of transaction confirmed per time unit

$$\text{Throughput} = \mu \mathbb{E}(N^q \mathbb{I}_{N^q \leq b} + b \mathbb{I}_{N^q > b}) = \mu \sum_{n=0}^b n(1-p)p^n + bp^{b+1}.$$

### 1 Include some priority consideration to account for the transaction fees



Y. Kawase, , and S. Kasahara, "Priority queueing analysis of transaction-confirmation time for bitcoin," *Journal of Industrial & Management Optimization*, vol. 16, no. 3, pp. 1077–1098, 2020.

### 2 Go beyond the Poisson process framework



Q.-L. Li, J.-Y. Ma, and Y.-X. Chang, "Blockchain queue theory," in *Computational Data and Social Networks*, pp. 25–40, Springer International Publishing, 2018.



Q.-L. Li, J.-Y. Ma, Y.-X. Chang, F.-Q. Ma, and H.-B. Yu, "Markov processes in blockchain systems," *Computational Social Networks*, vol. 6, jul 2019.

# A fourth dimension to analyse

Blockchain efficiency

The energy consumption dimension



<https://cbeci.org/>