Blockhains and Distributed Ledgers Lecture 08

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Lecture 08

- Permissionless vs. Permissioned Ledgers.
- BFT and PoS-based approaches for permissioned ledgers.
- Dynamic participation.

Permissionless Protocols

- Bitcoin and similar PoW-based blockchain protocols provide a permissionless setting:
  - Anyone can participate in the protocol and receive BTC as rewards by performing the PoW-based mining operation.
  - The mechanism of pouring currency in the system via proof of work, makes it feasible for anyone (possessing sufficient hashing power) to participate.
  - The ledger itself is public, readable and writeable by anyone (the latter assuming one possesses bitcoin)

Permissioned Protocols

- Participation is restricted:
  - Producing transactions and/or blocks can only be performed after being authorized by the other nodes.
- In their simplest form the set of nodes is **static**: the set of nodes implementing the protocol is fixed and determined at the onset of protocol execution.

Permissioning How-To

- Most straight approach: employ a PKI (=public-key infrastructure).
- Based on digital signatures / authentication protocols.
- **Certificate authorities** can authorize other entities.
    - authorization includes a signature from the CA on the entity's public-key, identity information etc.
- Sharing certificate authority information is necessary; (how, where?)

X.509 Certificates

- Internet standard since 1988.
- Hierarchical.
  - http://www.ietf.org/rfc/rfc3280.txt

Structure of X.509 Certificates

Version
Serial Number
Algorithm / Parameters
Issuer
Period of Validity: not before date not after date
Subject
Algorithm/ Parameters/ Key
x509v3 extensions
...
Signature

X.509
does not
specify
cryptographic
algorithms

Example, I

```
Certificate:
    Data:
        Version: 3 (0x2)
        Serial Number:
            13:86:35:4d:1d:3f:06:f2:c1:f9:65:05:d5:90:1c:62
        Signature Algorithm: sha1WithRSAEncryption
        Issuer: C=US, O=VISA, OU=Visa International Service Association, CN=Visa eCommerce Root
        Validity
            Not Before: Jun 26 02:18:36 2002 GMT
            Not After : Jun 24 00:16:12 2022 GMT
        Subject: C=US, O=VISA, OU=Visa International Service Association, CN=Visa eCommerce Root
        Subject Public Key Info:
            Public Key Algorithm: rsaEncryption
            RSA Public Key: (2048 bit)
                Modulus (2048 bit):
                    00:af:57:de:56:1e:6e:a1:da:60:b1:94:27:cb:17:
                    db:07:3f:80:85:4f:c8:9c:b6:d0:f4:6f:4f:cf:99:
                    d8:e1:db:c2:48:5c:3a:ac:39:33:c7:1f:6a:8b:26:
                    3d:2b:35:f5:48:b1:91:c1:02:4e:04:96:91:7b:b0:
                    33:f0:b1:14:4e:11:6f:b5:40:af:1b:45:a5:4a:ef:
                    7e:b6:ac:f2:a0:1f:58:3f:12:46:60:3c:8d:a1:e0:
                    7d:cf:57:3e:33:1e:fb:47:f1:aa:15:97:07:55:66:
                    a5:b5:2d:2e:d8:80:59:b2:a7:0d:b7:46:ec:21:63:
```

Hierarchical name spec

The RSA Algorithm is used; the DSA is also an option

This is a self-signed root certificate

Example, II

```
            4a:ea:db:df:72:38:8c:f3:96:bd:f1:17:bc:d2:ba:
            3b:45:5a:c6:a7:f6:c6:17:8b:01:9d:fc:19:a8:2a:
            83:16:b8:3a:48:fe:4e:3e:a0:ab:06:19:e9:53:f3:
            80:13:07:ed:2d:bf:3f:0a:3c:55:20:39:2c:2c:00:
            69:74:95:4a:bc:20:b2:a9:79:e5:18:89:91:a8:dc:
            1c:4d:ef:bb:7e:37:0b:5d:fe:39:a5:88:52:8c:00:
            6c:ec:18:7c:41:bd:f6:8b:75:77:ba:60:9d:84:e7:
            fe:2d
        Exponent: 65537 (0x10001)
    X509v3 extensions:
      X509v3 Basic Constraints: critical
        CA:TRUE
      X509v3 Key Usage: critical
        Certificate Sign, CRL Sign
      X509v3 Subject Key Identifier:
        15:38:83:0F:3F:2C:3F:70:33:1E:CD:46:FE:07:8C:20:E0:D7:C3:B7
  Signature Algorithm: sha1WithRSAEncryption
    5f:f1:41:7d:7c:5c:08:b9:2b:e0:d5:92:47:fa:67:5c:a5:13:
    c3:03:21:9b:2b:4c:89:46:cf:59:4d:c9:fe:a5:40:b6:63:cd:
    ..............
```

note:
public-exponent, corresponding to RSA function: the public-key is a large integer N that is a product of two primes and a small exponent.

Note that SHA-1 is broken now : https://shattered.io

Certificate Encoding

- Certificates are binary files.
- They can be Base64 encoded to be stored/tansported as text files.
- This encoding is called PEM from (privacy enhanced mail)


```
-----BEGIN CERTIFICATE-----
MIIFXzCCBEegAwIBAgIHK5Bmkq9qPzANBgkqhkiG9w0BAQUFADCByjELMAkGA1UE
BhMCVVMxEDAOBgNVBAgTB0FyaXpvbmExEzARBgNVBAcTClNjb3R0c2RhbGUxGjAY
BgNVBAoTEUdvRGFkZHkuY29tLCBJbmMuMTMwMQYDVQQLEypodHRwOi8vY2VydGlm
aWNhdGVzLmdvZGFkZHkuY29tL3JlcG9zaXRvcnkxMDAuBgNVBAMTJ0dvIERhZGR5
IFNlY3VyZSBDZXJ0aWZpY2F0aW9uIEF1dGhvcml0eTERMA8GA1UEBRMIMDc5Njky
ODcwHhcNMTEwMTEwMTkyMzIyWhcNMTIwMjI1MTMyMTEyWjBZMRkwFwYDVQQKDBAq
LmVuZ3IudWNvbm4uZWR1MSEwHwYDVQQLDBhEb21haW4gQ29udHJvbCBWYWxpZGF0
ZWQxGTAXBgNVBAMMECouZW5nci51Y29ubi5lZHUwggEiMA0GCSqGSIb3DQEBAQUA
A4IBDwAwggEKAoIBAQCOgAbFE4TOs2KA/WM9rZ5Q+3G6teSFdjmxZynMeCch+/e/
bSudinQ0oJShqXkyiwrGa1brr3pbQkGLn7AUdli+479IMOq2tFpvZ9SgCVsp2Jk1
/6MqBleBTKfVGfVEz6+YzkwcoiEe7cY+deOeIG1ZFVlnI3kw19V42gk+ZU25oVgL
uiJB2RRD3djpaV1txMVyCnzHa0u2eEHhmh87faIA6EckEW/cWRoVuBZF5Oojsr5c
iXgLIwImQn+Cmo7NQVGV4pKqJVnHPyFX8w+CcLJ8GonVxQeKlehO2DycpDoi2SpP
/hAZ1Vh9mEfftpCikXPwF1unoZAmaN9mWUtcpyMnAgMBAAGjggG4MIIBtDAPBgNV
HRMBAf8EBTADAQEAMB0GA1UdJQQWMBQGCCsGAQUFBwMBBggrBgEFBQcDAjAOBgNV
HQ8BAf8EBAMCBaAwMwYDVR0fBCwwKjAooCagJIYiaHR0cDovL2NybC5nb2RhZGR5
LmNvbS9nZHMxLTI4LmNybDBNBgNVHSAERjBEMEIGC2CGSAGG/W0BBxcBMDMwMQYI
KwYBBQUHAgEWJWh0dHBzOi8vY2VydHMuZ29kYWRkeS5jb20vcmVwb3NpdG9yeS8w
gYAGCCsGAQUFBwEBBHQwcjAkBggrBgEFBQcwAYYYaHR0cDovL29jc3AuZ29kYWRk
eS5jb20vMEoGCCsGAQUFBzAChj5odHRwOi8vY2VydGlmaWNhdGVzLmdvZGFkZHku
Y29tL3JlcG9zaXRvcnkvZ2RfaW50ZXJtZWRpYXRlLmNydDAfBgNVHSMEGDAWgBT9
rGEyk2xF1uLuhV+auud2mWjM5zArBgNVHREEJDAighAqLmVuZ3IudWNvbm4uZWR1
gg5lbmdyLnVjb25uLmVkdTAdBgNVHQ4EFgQU9Z+3hgNCeZLUiGGdUr4pyrMtS4cw
DQYJKoZIhvcNAQEFBQADggEBAGJzGVObEDODThT3di8+JC8hKde1DxOHNzmtv3I3
/eDGR5vO8squzmWh9fn5FZFbHd/UfFPddO6ykR7ffPLGTNCUYbviVjfA+hTpPnPA
3D5u791VfPUJBZf+ccAGr9E1BY+kYGaGqJgHmHcdG7XU0d7bU0XW82Q8wbHQj7H4
jvKSrir4bdGbmZ5VMAjsRL7xMwVypbh2KlOq/wU6AUDs3Rodawa6BnqyCHEpjn0I
i2NUiTzDRKL2OvRCPNs7aY1s4L0oN+HU6yeDkriOHR1NBt3lBGLW+bjZalT6GjPl
xz4fZtag71g7a9mgSAwDE9YlCP2e9WSdlf0THZQ5y3aV868=
-----END CERTIFICATE-----
```

Binary Encoding

- The elements of certificate are encoded using DER (distinguished encoding rules)

Items are stored in TLV format : triplets <Type,Length,Value>

```
1.    30 23             ; SEQUENCE (23 Bytes)
2.    | |  31 0f             ; SET (f Bytes)
3.    | | |  30 0d             ; SEQUENCE (d Bytes)
4.    | | |     06 03          ; OBJECT_ID (3 Bytes)
5.    | | |     |  55 04 03
6.    | | |     |     ; 2.5.4.3 Common Name (CN)
7.    | | |     13 06          ; PRINTABLE_STRING (6 Bytes)
8.    | | |        54 65 73 74 43 4e                    ; TestCN
9.    | | |           ; "TestCN"
10.   | |  31 10             ; SET (10 Bytes)
11.   | |     30 0e             ; SEQUENCE (e Bytes)
12.   | |        06 03          ; OBJECT_ID (3 Bytes)
13.   | |        |  55 04 0a
14.   | |        |     ; 2.5.4.10 Organization (O)
15.   | |        13 07          ; PRINTABLE_STRING (7 Bytes)
16.   | |           54 65 73 74 4f 72 67                ; TestOrg
17.   | |              ; "TestOrg"
```

Digital Signatures and Certificates

- A certificate contains a digital signature.
- Recall that cryptographic design of digital signatures involves typically:
  - A cryptographic signing operation that acts on a fixed input of a specific type and has a public-verifiability feature.
  - A cryptographic hash function that takes arbitrary strings and maps them to the data type suitable for the signing operation.
- Common setting today: SHA2 with RSA/DSA.

Certificate Considerations

- All computer systems come with preloaded certificates from certificate authorities. This provide a **setup assumption**.

- Certificates need to be revoked in case the corresponding secret keys become exposed or the algorithms used are not safe anymore.

- In a blockchain system, certificate information can be provided as part of the genesis block.

Secure Channels and Certificates

- Possession of mutually acceptable certificates not only permits authenticated communication (exchanging signed mechanism between two entities) but also allows building a secure channel

  - Protocol **TLS 1.2** is used to build such secure channel.

  - It relies on cryptographic protocols such as the Diffie Hellman key exchange. It can ensure the confidentiality of the data exchanged.

Static Permissioned Blockchain

- All participants are identified by self-signed certificates in the genesis block.
- The set of participants remains the same throughout the execution.
- This is the simplest form of a PKI / public-key directory.

Recall: Robust Transaction Ledger

- persistence: Transactions are organized in a “log” and honest nodes agree on it.

- liveness: New transactions are included in the log nodes, after a suitable period of time.

In more detail

- Common prefix / persistence / consistency of the LOG:
  - For each two nodes that maintains a log, and at any two times t1 <= t2, it holds that LOG1 is a prefix of LOG2
    (where LOG2 includes pending transactions)
- Liveness of the log:
  - An honestly generated transaction will become part of all honest parties' LOGs after a specified time window *u.*

Permissioning

- Prior to system operation the nodes register their certificates that are included in the genesis block.
- Using such certificates, all the nodes are capable of authenticating each participant and allowing interaction with the LOG in a way that is prescribed by the participants’ credentials.

Centralized Permissioned Ledger

- One of participants acts as a server and maintains the LOG.
- Readers and writers to the LOG authenticate with the server and can perform read and write operations.
  - Consistency of the LOG is guaranteed assuming the server is trusted.
  - Liveness of the LOG is guaranteed assuming the server is trusted and functional.

Bitcoin’s Permissionless Setting

- The genesis block contains no certificate information.
- Reading from the LOG is open (anyone can do it without credentials).
- Writing to the LOG can only be done in specific ways (issuing transactions).
    - Nodes can obtain valid credentials (accounts) by generating a public and secret-key and either mining a block (which will reward their account with BTC) or buy BTC from another node.
    - Once the LOG records their account credit, they can issue transactions.
    - In essence: crediting a bitcoin account is creating a certificate that imparts the account holder with certain permissions w.r.t. the ledger.

Distributed Permissioned Ledger, I

- A number of servers maintain the ledger LOG individually.
- Each share the same genesis block that identifies all participants.
- Assuming a synchronous operation, at each round, Readers and Writers authenticate with the servers and interact with the LOG in a prescribed fashion.

Distributed Permissioned Ledger, II

- Readers authenticate to each server and obtain Read access.
- Writers authenticate to each server and provide their inputs.
- Servers run a **consensus protocol** to agree what inputs should be included in the LOG.

Reader/Writer Management

- Readers and Writers can authenticate to each server referring to the information in the genesis block.
- It is possible to introduce additional readers and writers by suitably issuing certificates to other users.
- Note that each participant would then need to show a valid certificate chain that establishes her privileges for the specific read or write access that is requested.

Read requests

- Is it possible to restrict read requests as in the centralized setting?
    - Nodes can maintain blocks of transactions private and issue them only to users that are authenticated.
    - The TLS protocol can be used to build a secure channel between the reader and the responding node.
- Note that the above would require that all servers remain honest (as they all share the LOG).

A classical BFT-based approach for permissioned ledgers

- Focus on write requests next. We want to ensure LOG liveness and consistency.
- We will apply a “byzantine fault tolerant” (BFT) agreement protocol that uses two important tools:
    - a graded broadcast.
    - and a common coin binary consensus protocol.

Graded Broadcast

- Parties involved : a single sender and several receivers.
  - The i-th receiver outputs (M_i, G_i).
  - The value G_i is in {0,1,2}.
    - If the sender is honest then $M_i = M_j$ for all i,j and $G_i = 2$.
    - If the sender is malicious and one receiver outputs $G_i = 2$ then other honest receivers output $G_i >= 1$.

Graded Broadcast Construction, I

- **Round 1.** The sender sends the message *M* to all receivers.
- **Round 2.** The *i*-th receiver obtains *M1i* from round 1 and sends it to all receivers.
- **Round 3.** The *i*-th receiver obtains *M2ji* from the *j*-th receiver in round 2 and performs the following:
  if there is a single message that was sent by *2n/3* receivers then send it to all receivers. Else send nothing.

Graded Broadcast Construction, II

- The *i*-th receiver obtains *M3ji* from the *j*-th receiver in round 3.
  - If there is a single message that was sent by more than *2n/3* receivers output that message as *Mi* and set *Gi*=2.
  - If there is a single message that was sent by more than n/3 receivers output that message as *Mi* and set *Gi*=1.
  - In any other case output *fail* and *Gi*=0.

Graded Broadcast Construction, III

- Analysis. Assume that malicious parties are $t < n/3$.
  - If the sender is honest, then each receiver will receive the same message $>=2n/3$ times in round 2 and 3. All honest receivers will output *Gi=2* and that message.

Graded Broadcast IV

- **Lemma.** If two honest receivers send a message in round 3 it **must be** the *same.*
  - Indeed, if they send messages $M \neq M'$, they both have received them by at least 2n/3 receivers from round 2.
  - Given the above, observe that $2n/3-t>n/3$ honest parties have sent *M* in round 2.
  - Thus $<n-n/3 = 2n/3$ parties are capable of sending M' (which is different than *M*), leading to contradiction.

Graded Broadcast, V

- Suppose the *i*-th receiver returns *Gi=2* and let *Mi* be the message it chooses. Consider the output (*Mj*, *Gj*)
  - The *i*-th receiver has received the message from at least *2n/3* receivers in round 3.
  - => More than *n/3* honest receivers have sent *M* in round 3. Thus the *j*-th receiver should produce a grade *Gj*>=1.
  - If there is another message *M'* sent by more n/3 receivers in round 3, at least one of them is honest; this leads to a contradiction of the **lemma**. Thus *Mj*=*Mi.*

From Graded Broadcast to a BFT-based ledger

- Execute n/3 phases:
  - In each phase perform:
    - A designated sender organizes all valid transactions it collected as **M** and performs a graded broadcast.
    - A binary consensus protocol that determines whether everyone's grade is 2. If that is true each node signs the output to generate a public endorsement and appends **M** on their LOG (together with the signatures). Otherwise LOG remains the same.

Recall Consensus Properties

- Termination $\forall i \in \mathsf{H}(u_i \text{ is defined})$
- Agreement $\forall i, j \in \mathsf{H}\,(u_i = u_j)$
- Validity $\exists v(\forall i \in \mathsf{H}\,(v_i = v)) \implies (\forall i \in \mathsf{H}\,(u_i = v))$

Common Coin Consensus, I

- *Bi is the input of party i in {0,1}*

- **Round 1.** The *i*-th party sends *Bi* to all parties.
- **Round 2.** A randomly selected common coin *c* is made available.
- **Round 3.** The *i*-th party obtains *B1i* from round 0 and performs the following:
  if 0 was sent by *2n/3* parties set *Bi=0.*
  if 1 was sent by *2n/3* parties set *Bi=1.*
  else set *Bi=c.*

Common Coin Consensus, II

- **Validity.** Suppose all honest parties agree on their input initially; i.e., for all *i*,*j*, $B_i = B_j$.
    - Then, given that $t<n/3$, they will set *B* to that bit in round 3.

- **Agreement.** Suppose that an honest party outputs 0 because *2n/3* sent 0 in round 1. It follows that $> n/3$ honest parties had 0 as input prior to the protocol. As a result any other honest party will also output 0 with probability 1/2. Similar argument can be made for 1.

- **Termination.** it will always happen in 3 rounds.

Common Coin Consensus, III

- Repeat protocol for *k* times.
- After *k* repetitions, it is guaranteed that honest parties will reach agreement with probability 1-2^(-k) (original input is only used in first rep)
  - (note that they will not know they did).
  - [more involved techniques exist that bring the number of repetitions to expected constant with detection of agreement].

Producing a common coin

- Suppose that the common coin protocol is imperfect and serves a proper coin with probability ε and no other assumptions otherwise. E.g., with probability $1-\varepsilon$, the parties may produce a different adversarially selected value.

- Then, agreement in the consensus protocol will only hold with probability $\varepsilon/2$.

- Same analysis as before works but need to repeat protocol for $k\varepsilon^{-1}$ times.

    - It is easy to implement common coin for small ε: have each party simply flip a coin. it holds that $\varepsilon = 2^{-n+t+1}$. [More involved techniques provide a large constant $\varepsilon<1$]

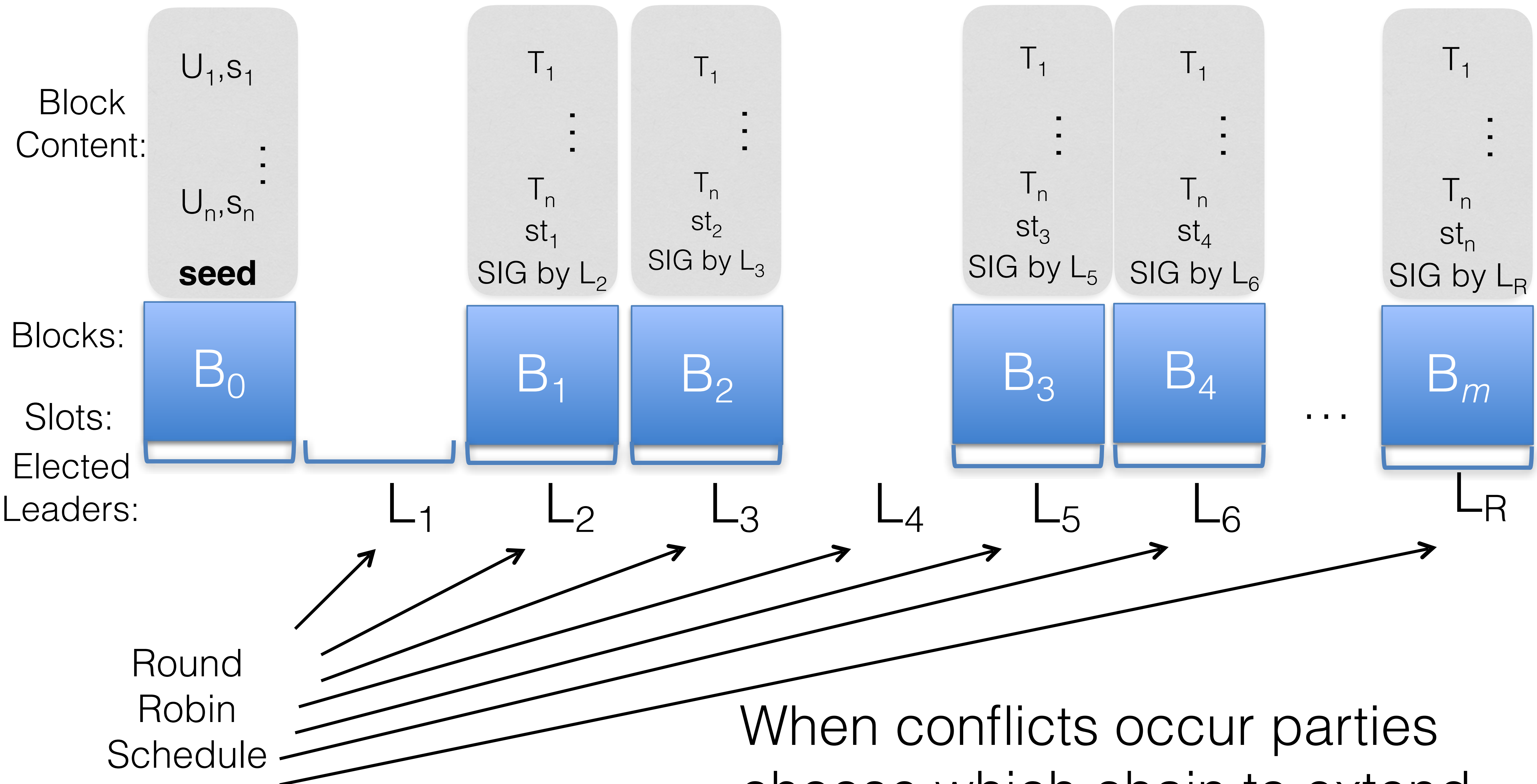
Distributed Ledger

- Using the above protocol it is guaranteed that:
  - The LOG will grow by a new set of transactions.
  - The transactions are contributed by an honest server and thus include all new transactions received by that node.
  - The waiting time *u*, for a transaction to be included is proportional to the termination of the protocol that agrees on the next LOG entry; (exponential in our example but can be improved to constant).

PoS-based Approach for Permissioned Ledgers

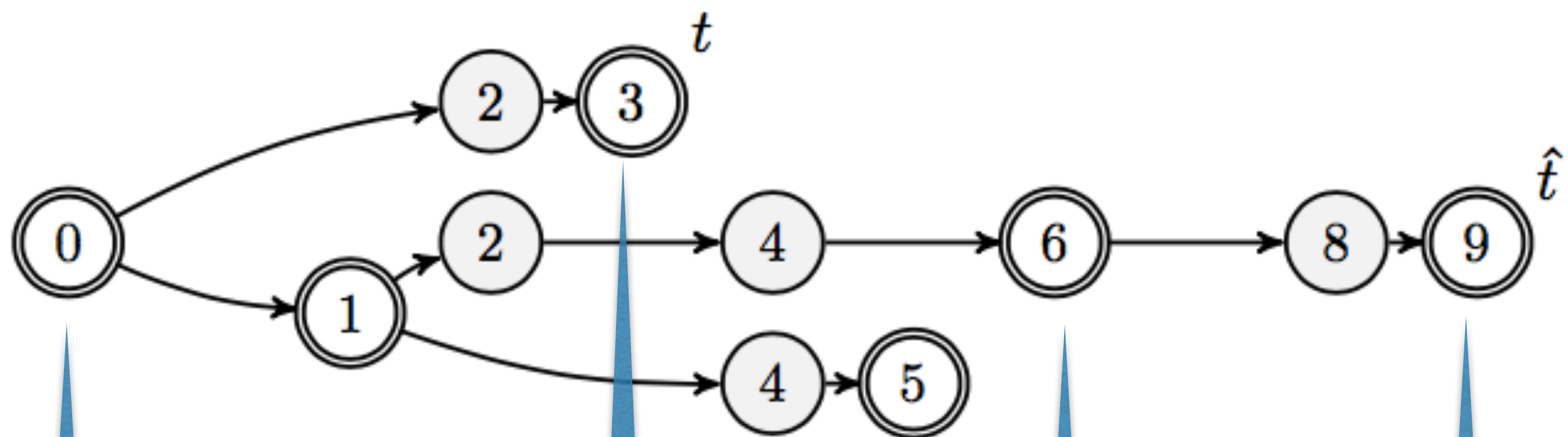
- Recall Proof of stake (PoS) protocols generalize the bitcoin blockchain protocol. Substitute PoW for PoS.
- Resulting protocol resembles blockchain operation (as opposed to the BFT approach).
  - Example: the Ouroboros protocol.

Ouroboros-BFT



When conflicts occur parties choose which chain to extend based on **longest chain rule**

Forks and Protocol Executions



Characteristic string $w = 0 \quad 1 \quad 0 \quad 1 \quad 0 \quad 0 \quad 1 \quad 1 \quad 0$

Genesis

honest party produce block 1

adversary serves block 2 to honest party

adversary serves block 4 to honest party

adversary serves block 2,4 to honest party

adversary serves block 8 to honest party

$$w_i = \begin{cases} 0 & i\text{-th slot belongs to an honest party} \\ 1 & i\text{-th slot belongs to a malicious coalition} \end{cases}$$

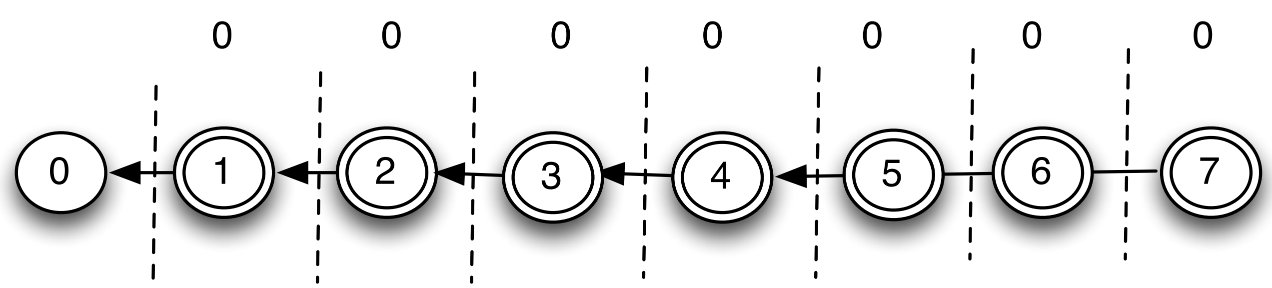
PoW vs. PoS Proof

- The adversary is at a **much better position** in this protocol execution compared to Bitcoin's PoW-based execution.
  - it can **see** ahead of time how stakeholders are activated.
  - it can **generate multiple** different blocks for the **same slot** at any time **without cost**.
  - it can **wait** and act just before an honest party comes online.

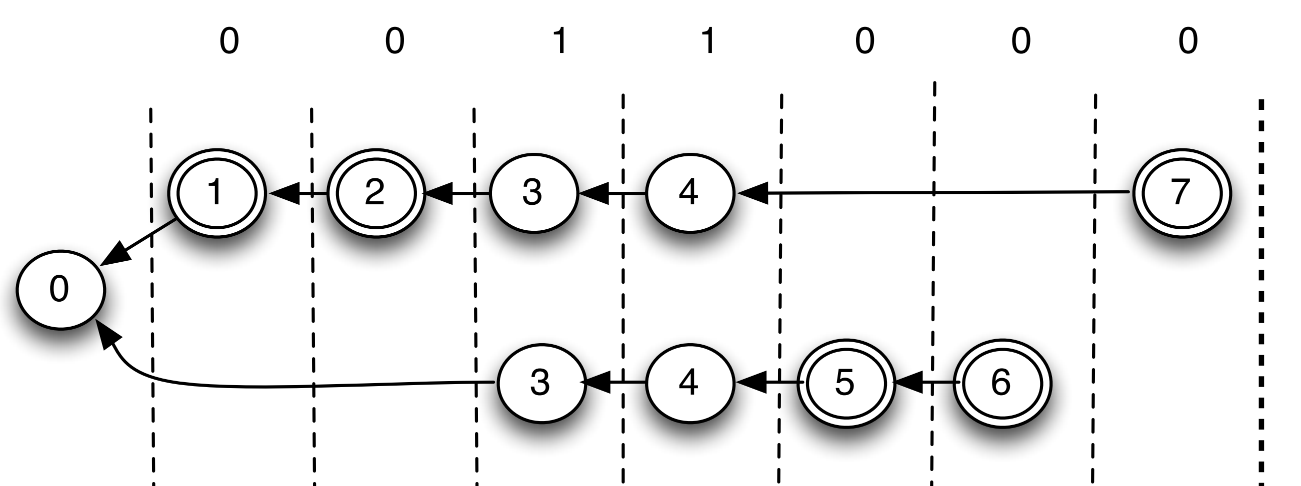
Forkable Strings

The characteristic strings the adversary prefers!

Not Forkable!



Forkable!



the $t<n/3$ setting

- Consider any string with Hamming weight less than $n/3$.

- **Lemma.** A slot controlled by the attacker can be used in at most two different locations to contribute blocks in the set of all admissible blockchains (those that correspond to protocol executions).

- If follows if $t<n/3$, there is not enough slots possessed by the adversary to match the blocks of the honest participants.

Permissioned Ledgers with Dynamic participation

- Participation is still restricted: Producing transactions and/or blocks can only be performed only after being authorized.
- But dynamic: set of nodes implementing the protocol is evolving over time.
- Consider that each participant has some stake in the system

Design Approach

- Iterate a basic recursive step:
  - Form a committee that will run a fixed term of ledger updates.
  - Update committee based on the outcome of the inputs posted on the ledger.

Forming a committee, I

- The elected committee to perform the permissioned protocol execution should respect the adversarial bound under which the underlying protocol execution operates.

- Example of the simplest possible case: the stakeholder distribution is flat; a bound of $t<n/3$ is required. The committee selected is the set of all stakeholders.

- A bound of $<1/3$ in terms of relative adversarial stake directly translates to a $t<n/3$ bound in the selected committee.

Forming a committee, II

- Consider a biased stakeholder distribution.
- Where the i-th stakeholder has stake s_i with total stake is S $\in \mathbb{N}$
- Execute the permissioned protocol with the i-th stakeholder maintaining s_i identities out of a total space of identities that has cardinality equal to S.

Forming a committee, III

- What if the size of the total stake S is prohibitively large?
  - Random sampling may be used to select a subset of stakeholders to form the committee.
  - Perform the sampling following “weighing by stake”: the probability that the i-th stakeholder is selected should be s_i / S.
  - Randomness should be refreshed in each permissioned execution.

Stake Shift

- The stake shift signifies the statistical distance between the random weighed by stake sampling of a stakeholder between two stakeholder distributions.
- E.g., if a stakeholder distribution has 3 members sharing equal stake and one of them is replaced, the stake shift is 1/3.
- The maximum stake shift is 1 (the set stakeholders have completely changed).

Refreshing Randomness

- Critical for security :
  - Possible via techniques from secure multiparty computation. Coin flipping protocols.
  - Or derivation from some aspect of the protocol execution (e.g., *hash* the previous block of transactions and use the output as coins to seed the sampling).
- Beware: **grinding attacks;** the attacker tries to impose a protocol history that favors adversarial parties.
  - *Hashing* a large sequence of previous values can be seen to minimise the impact of such attacks.

New Parties Joining

- When a new party joins the system what information should be made available?
  - necessary: the initial stakeholder distribution.
  - sufficient: the most recent block for which consensus has been reached (checkpointing).

Genesis Block Joining

- The setting when new parties joining have access only to the genesis block.
- One has to deal with a **"long range"** attack:
    - Attacker builds a LOG that is acceptable starting from the genesis block.
- New parties joining have the task to choose which is the correct version of the LOG.

An example of a long range attack

- Assume the adversary can break with probability ε the randomness generation and choose the outcome.

  - Then it is impossible to protect against a long range attack: over an expected period of ε^(-1) permissioned executions, the attacker will get the opportunity to transfer control to a "**sybil**" committee.

  - (A sybil attack is when an attacker creates multiple fake identities that make the attacker appear as multiple parties in the system).

Mitigating Long Range Attacks

- ensure good randomness generation (if random sampling is used).

- Identify characteristics in the LOG structure that signify that the LOG is not the correct one. For instance here are some ideas that have been proposed:

  - blocks are signed by too few of the stakeholders.

  - the sequence of blocks is too sparse in the time-domain in the PoS-based approach.

End of lecture 08

- Next lecture:
  - Pitfalls and security vulnerabilities in smart contracts.