An Unstoppable Ideal Functionality for Signatures and a Modular Analysis of the Dolev-Strong Broadcast

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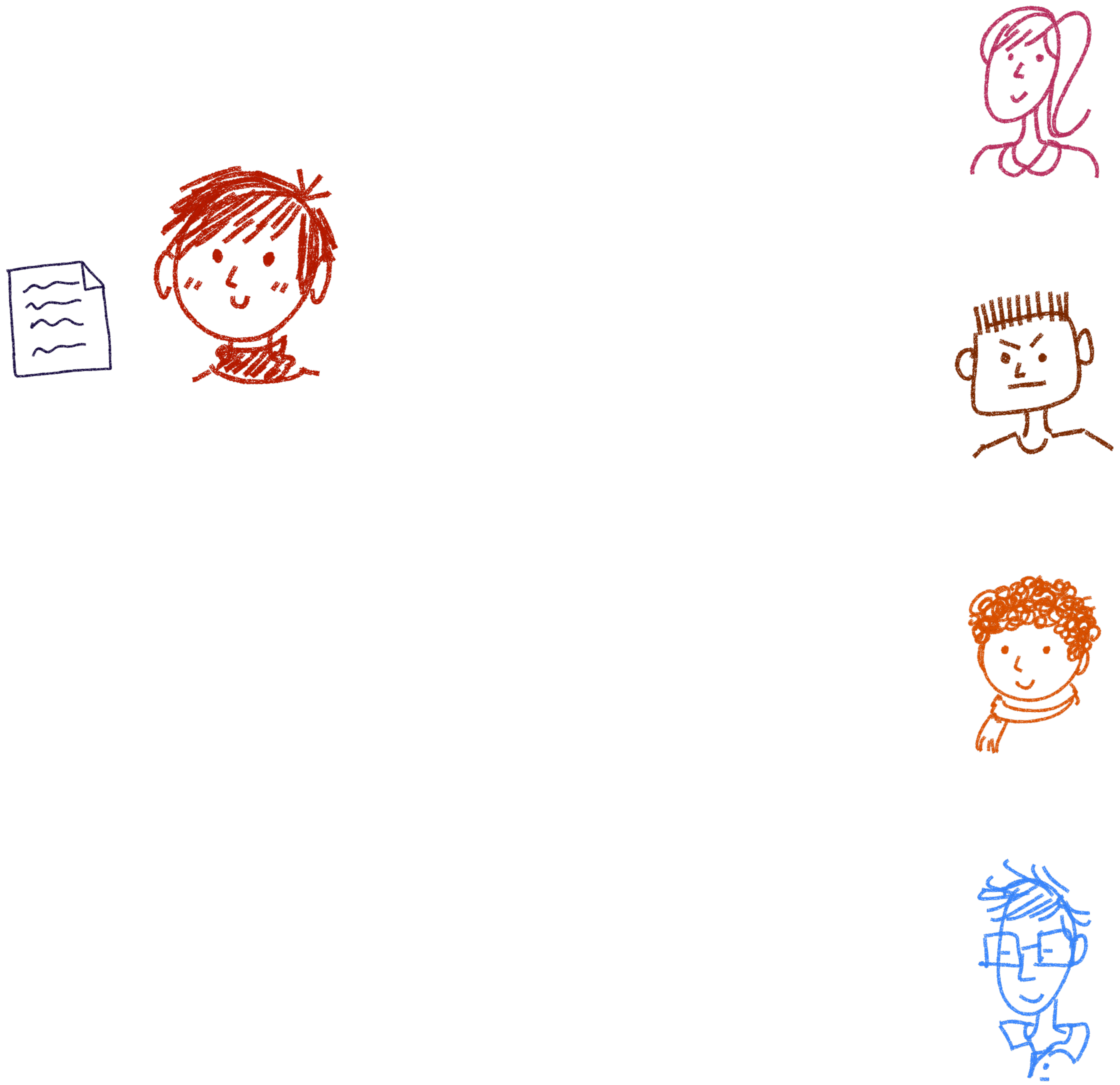
Motivating Example: Broadcast



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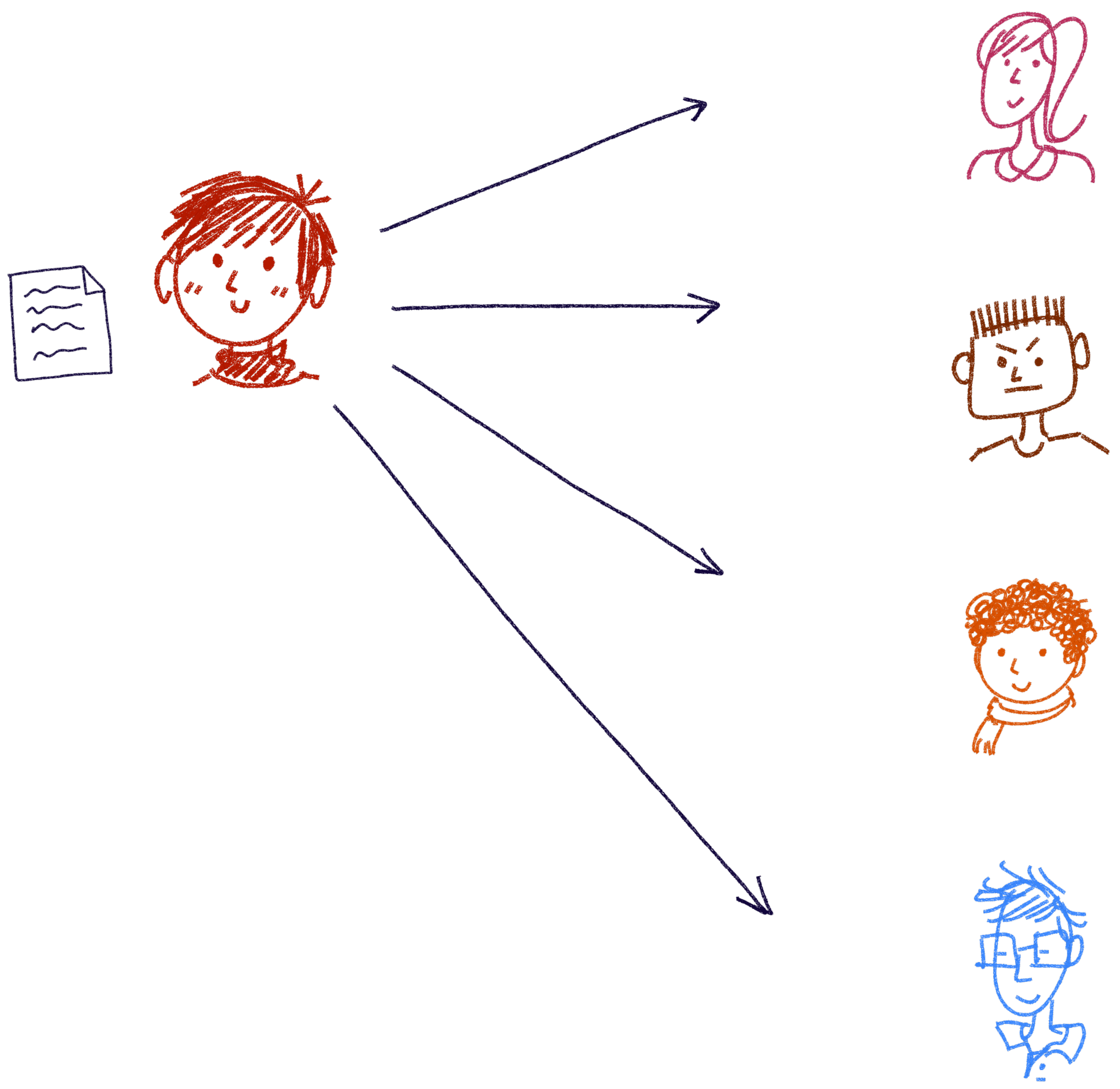

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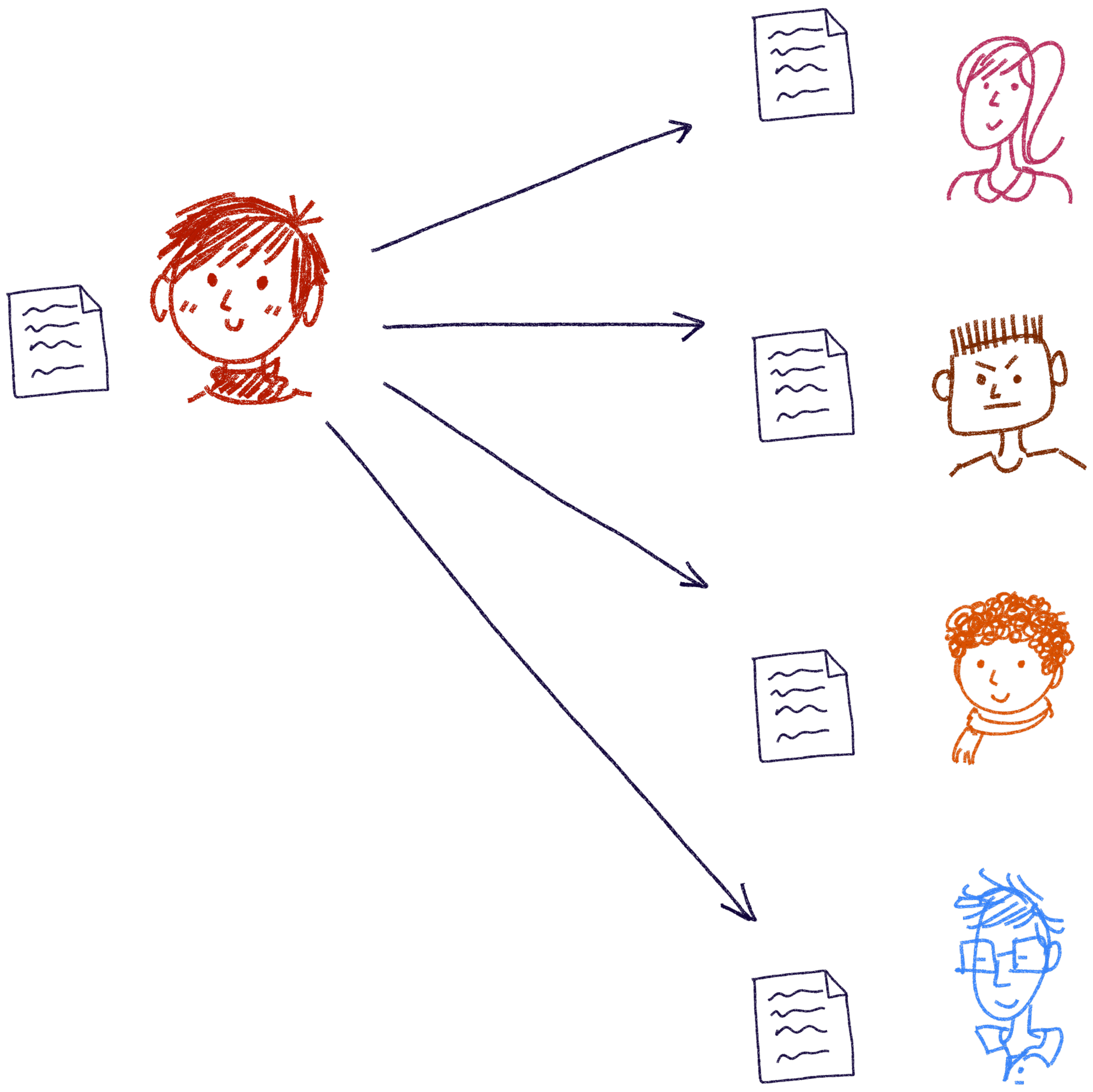
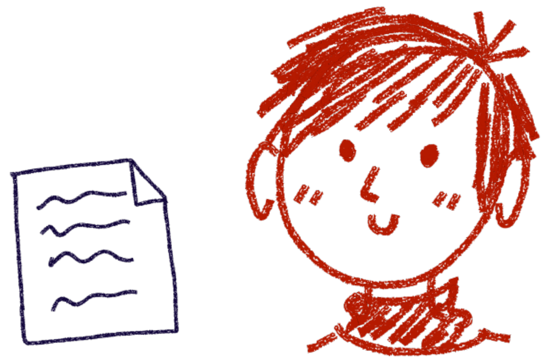
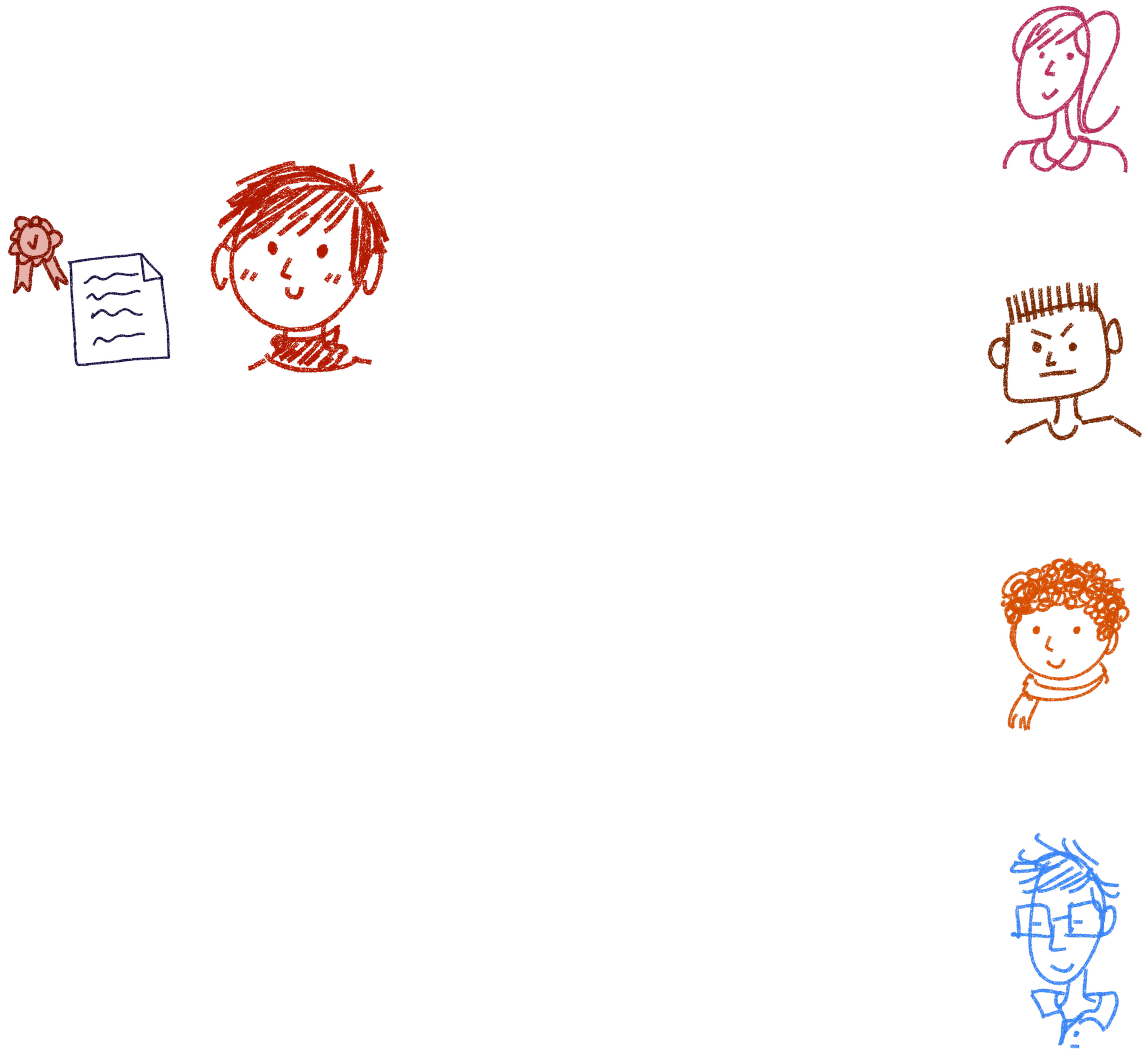


Dolev-Strong Broadcast [DS83]



Dolev-Strong Broadcast [DS83]

Round 1: Sender signs a message and multicasts



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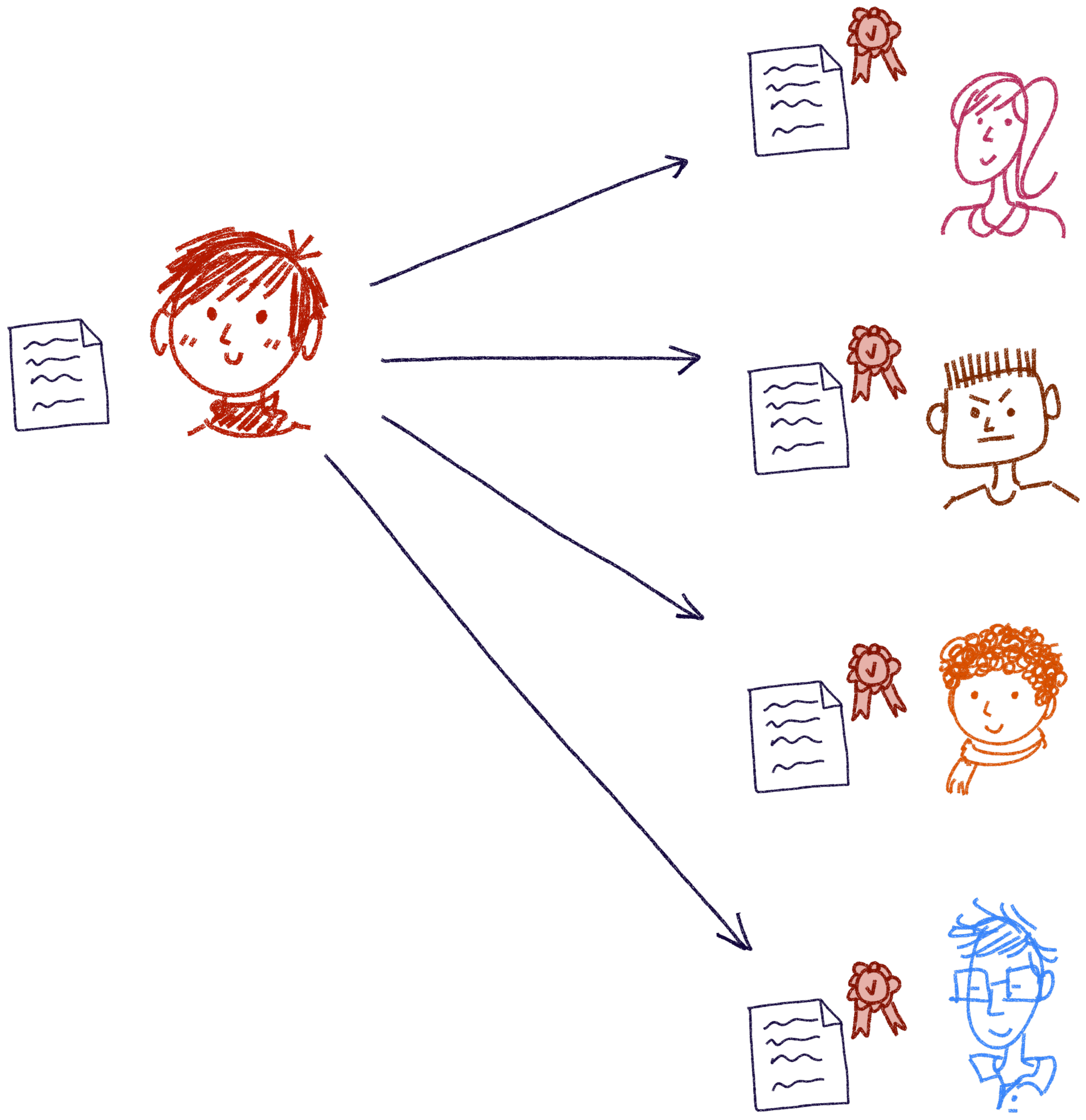
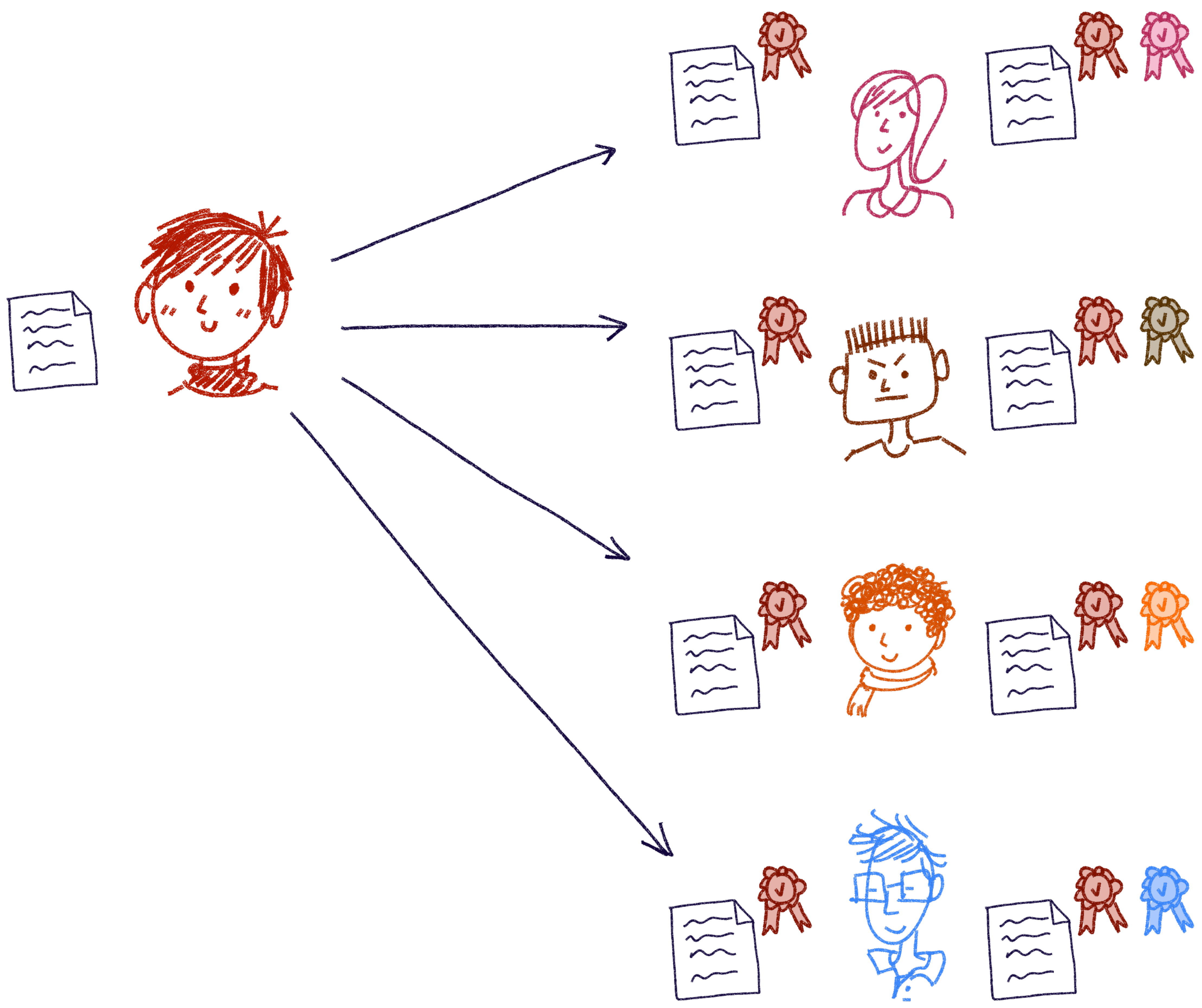


Dolev-Strong Broadcast [DS83]

Round 1: Sender signs a message and multicasts
Round r: If incoming message is “valid” and “new”, sign and multicast



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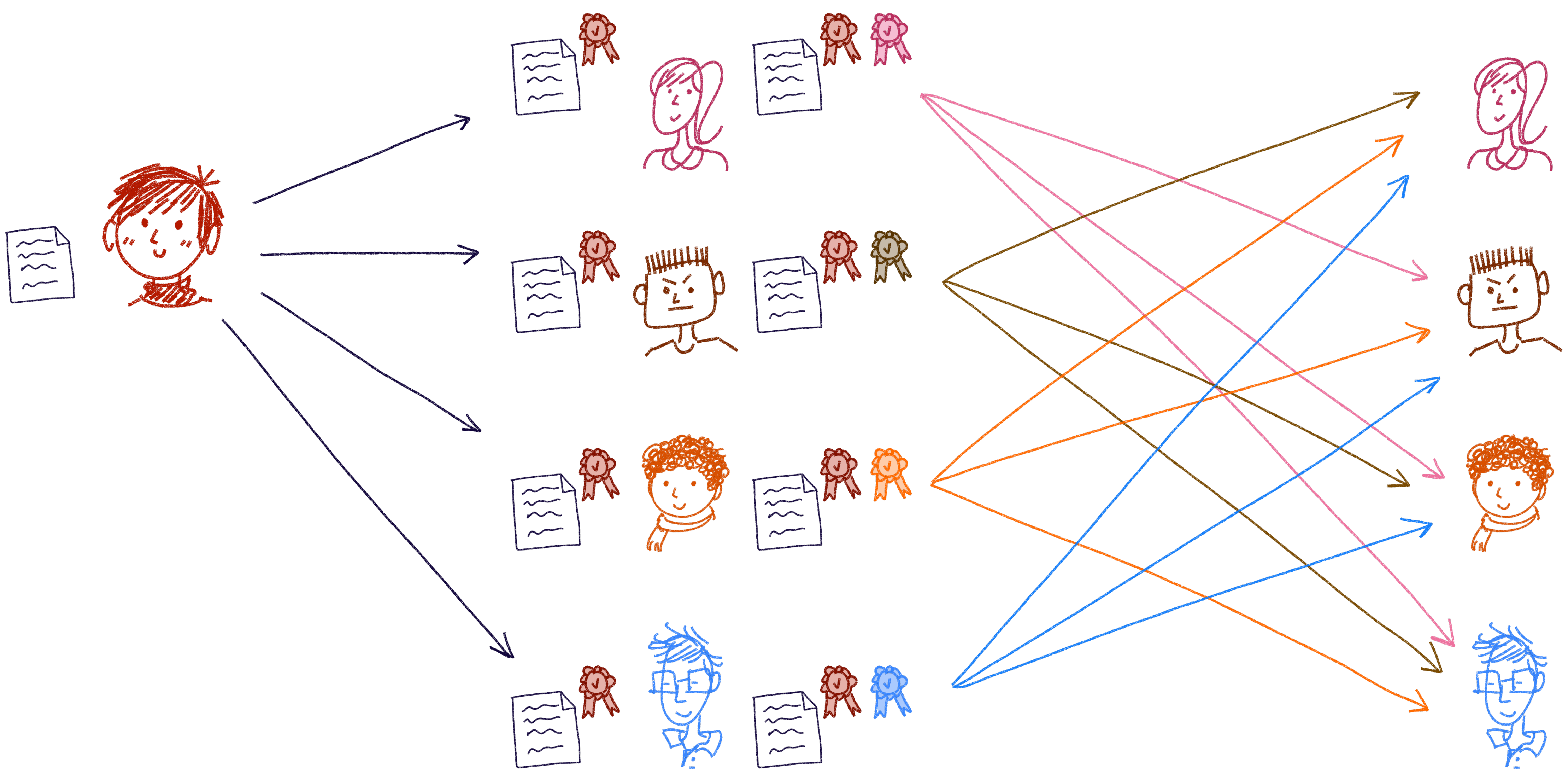
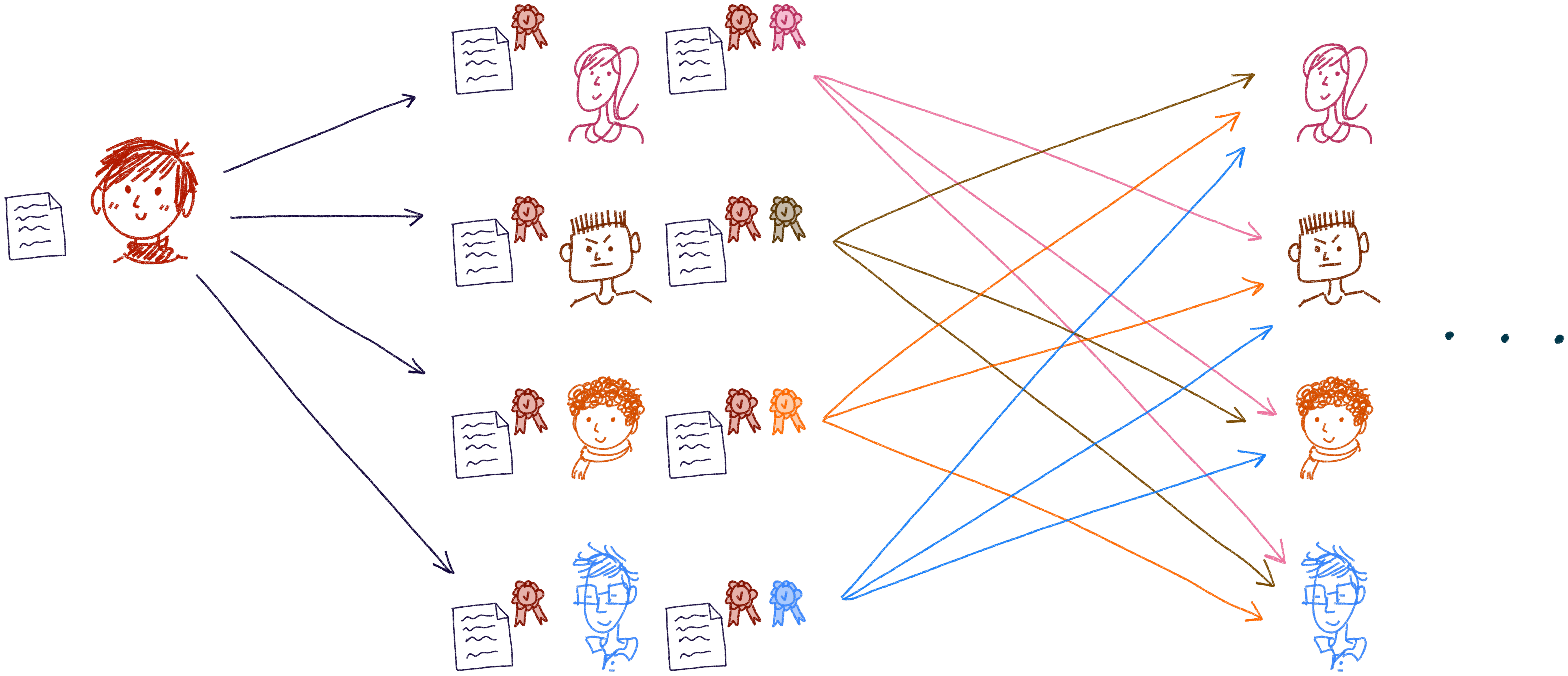


Dolev-Strong Broadcast [DS83]

Round 1: Sender signs a message and multicasts
Round r: If incoming message is "valid" and "new", sign and multicast
Round t+1: If you only received one "valid" message, output message.
Otherwise output bot



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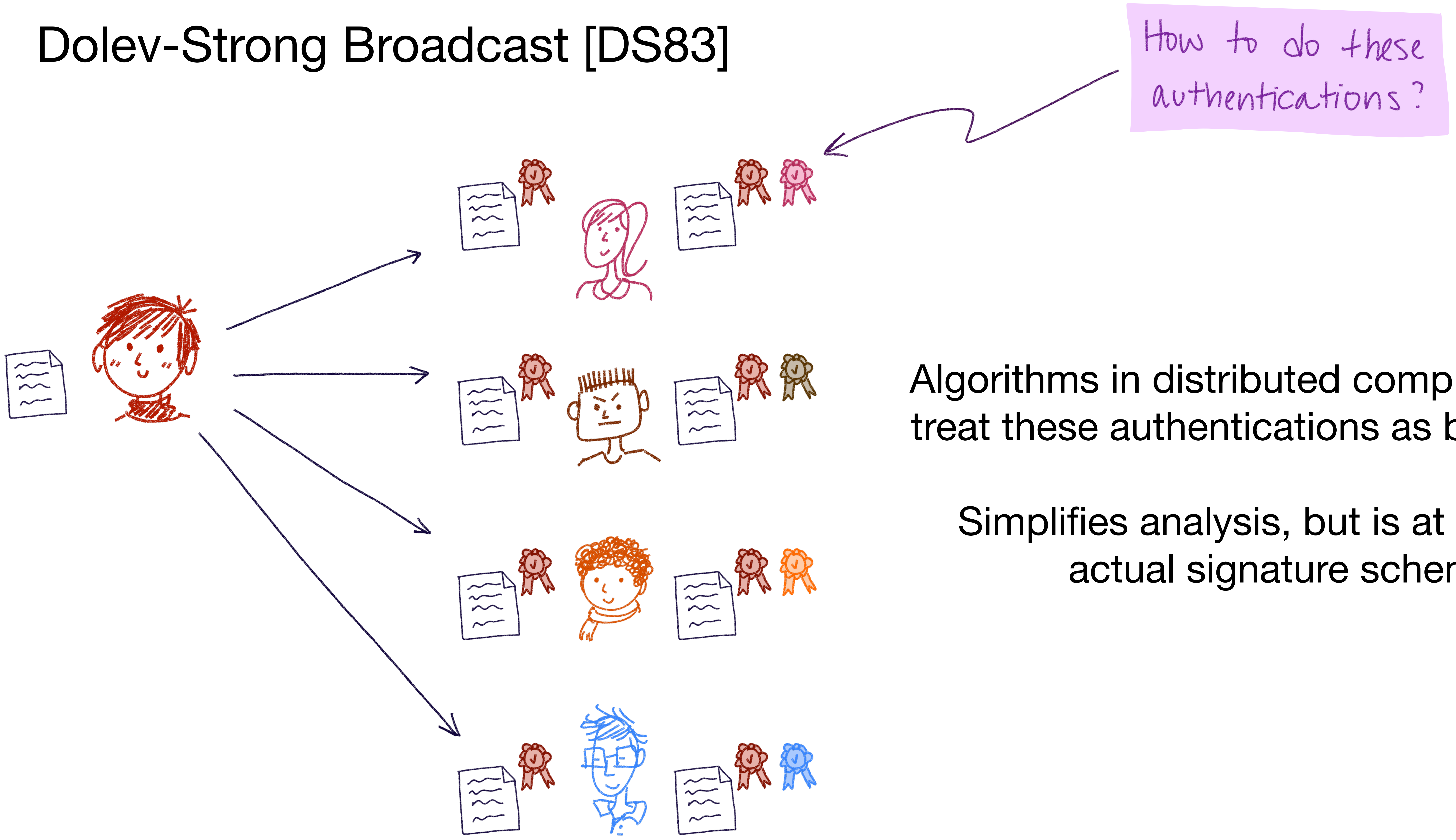
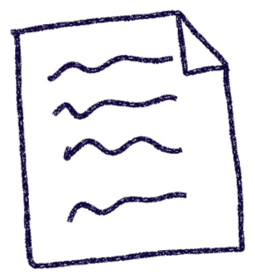


Algorithms in distributed computing tend to treat these authentications as being *perfect*

Simplifies analysis, but is at odds with actual signature schemes

Digital Signatures



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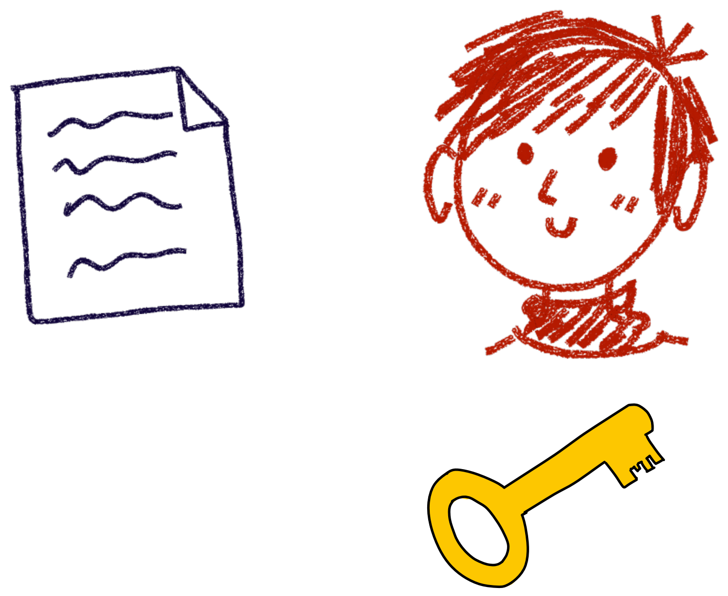
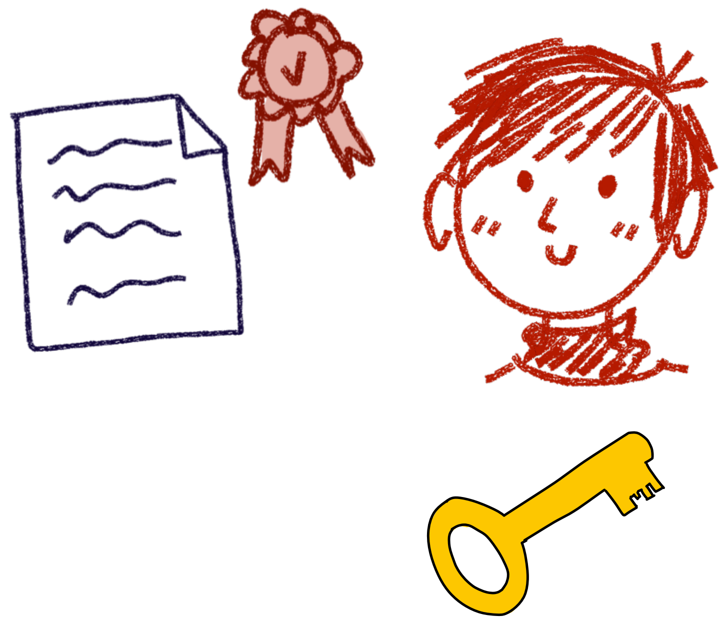


Signature Algorithms:

- KeyGen

Digital Signatures



Signature Algorithms:

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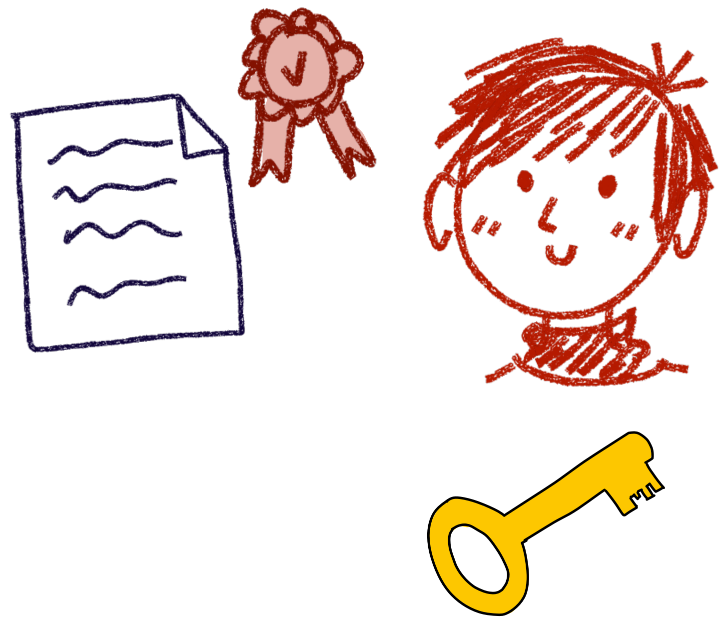

Signature Algorithms:

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- Verify

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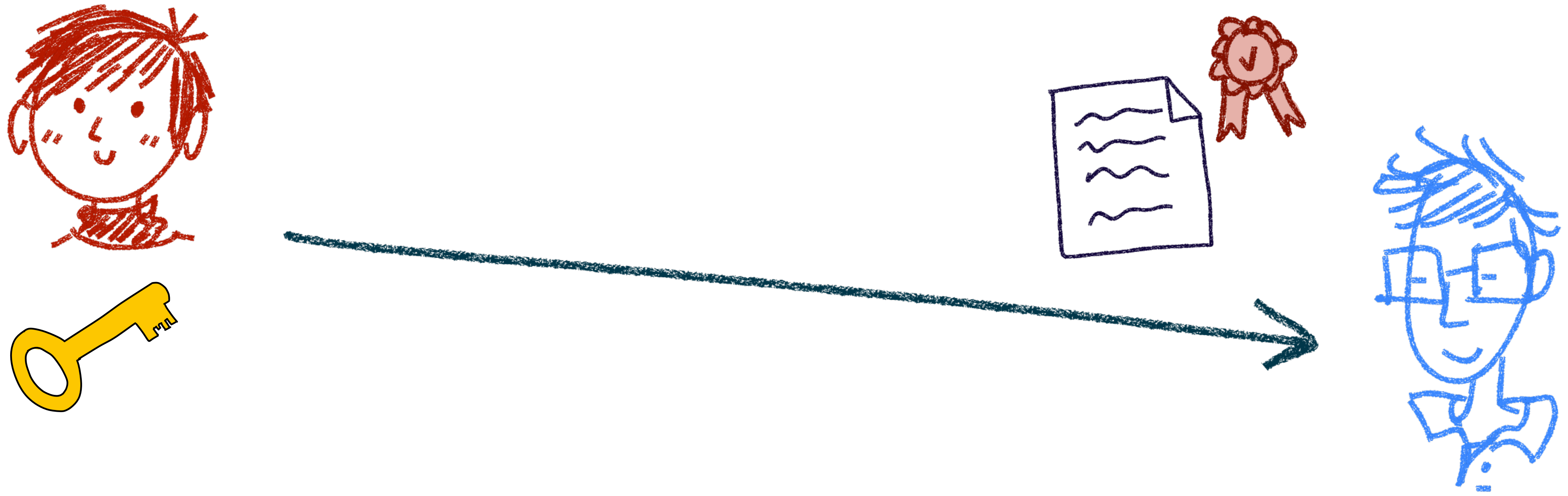

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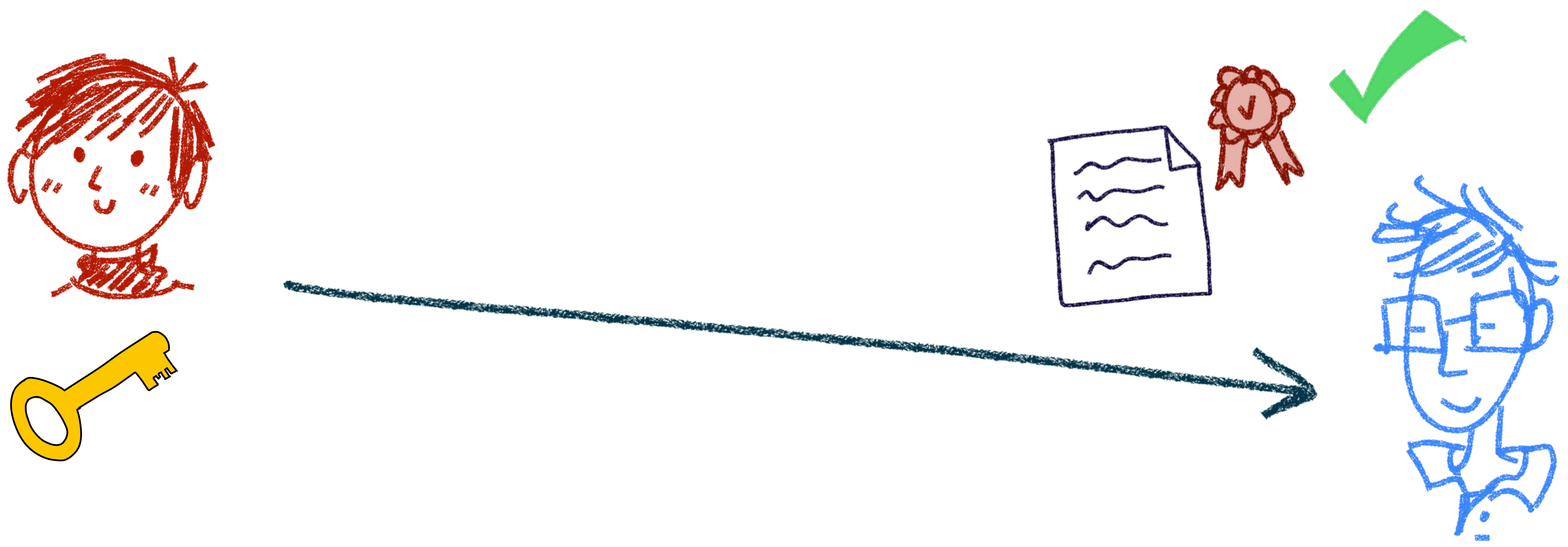

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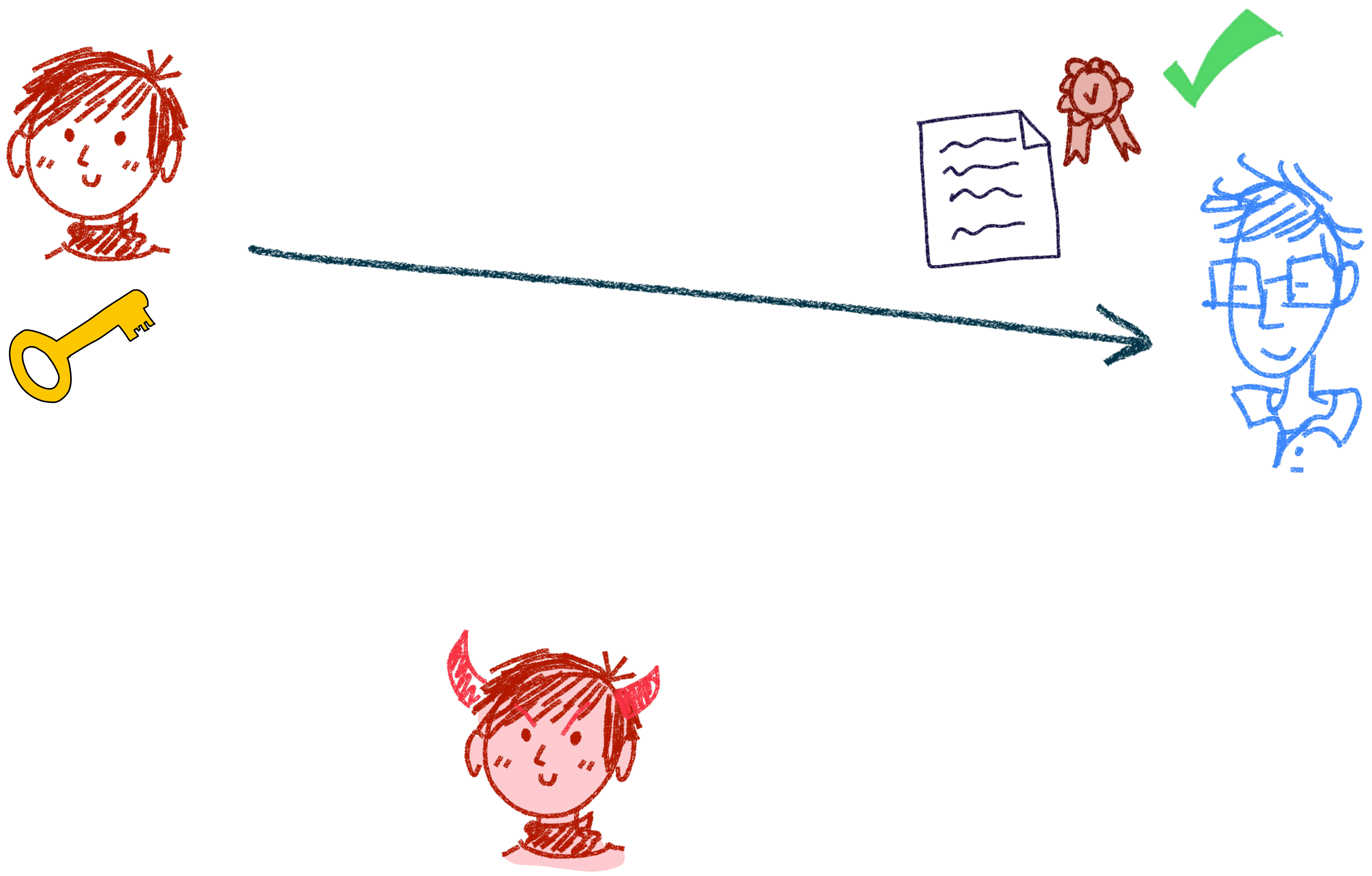

Signature Algorithms:

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Properties:

- Correctness
- Existential Unforgeability (EUF-CMA)

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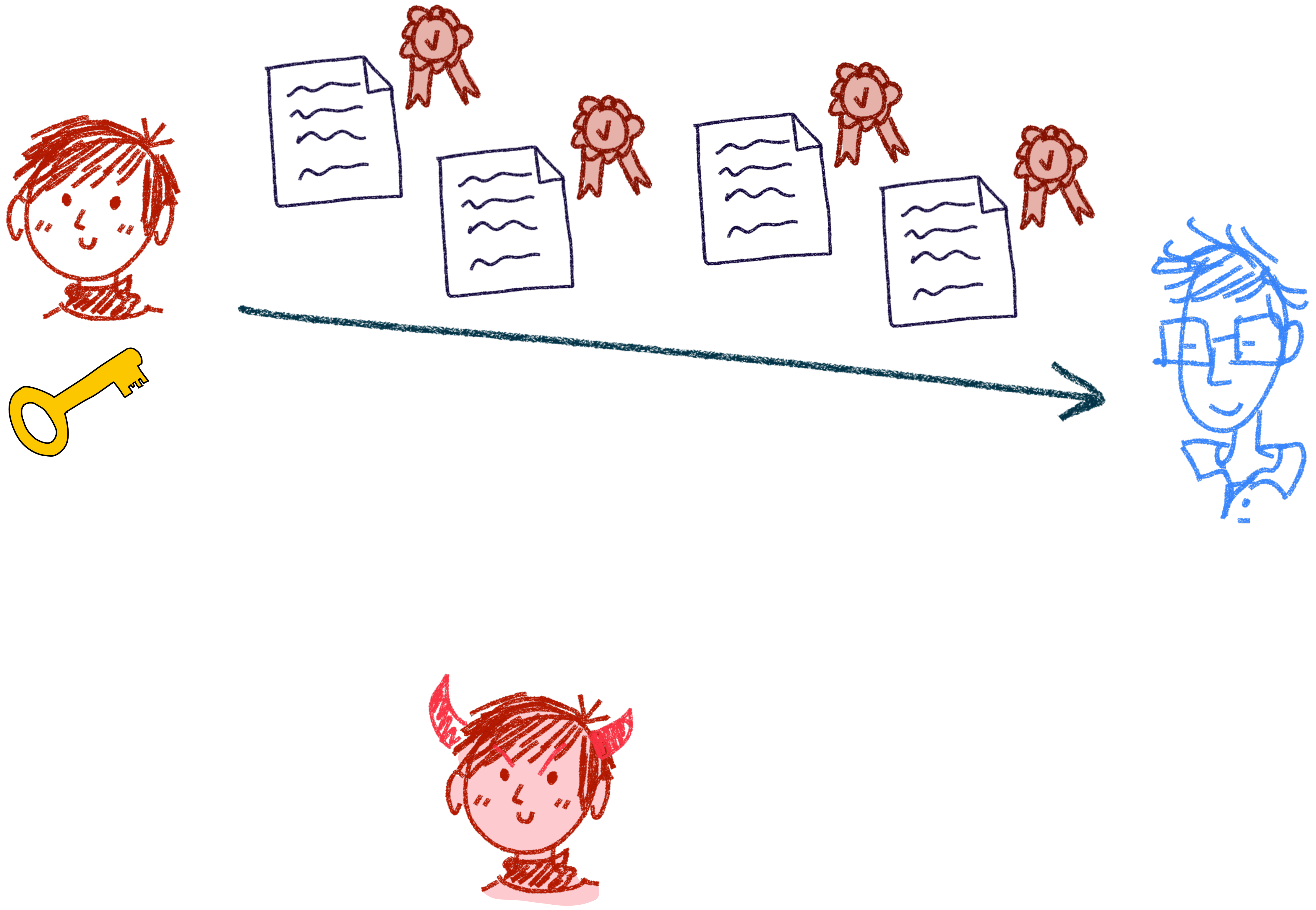

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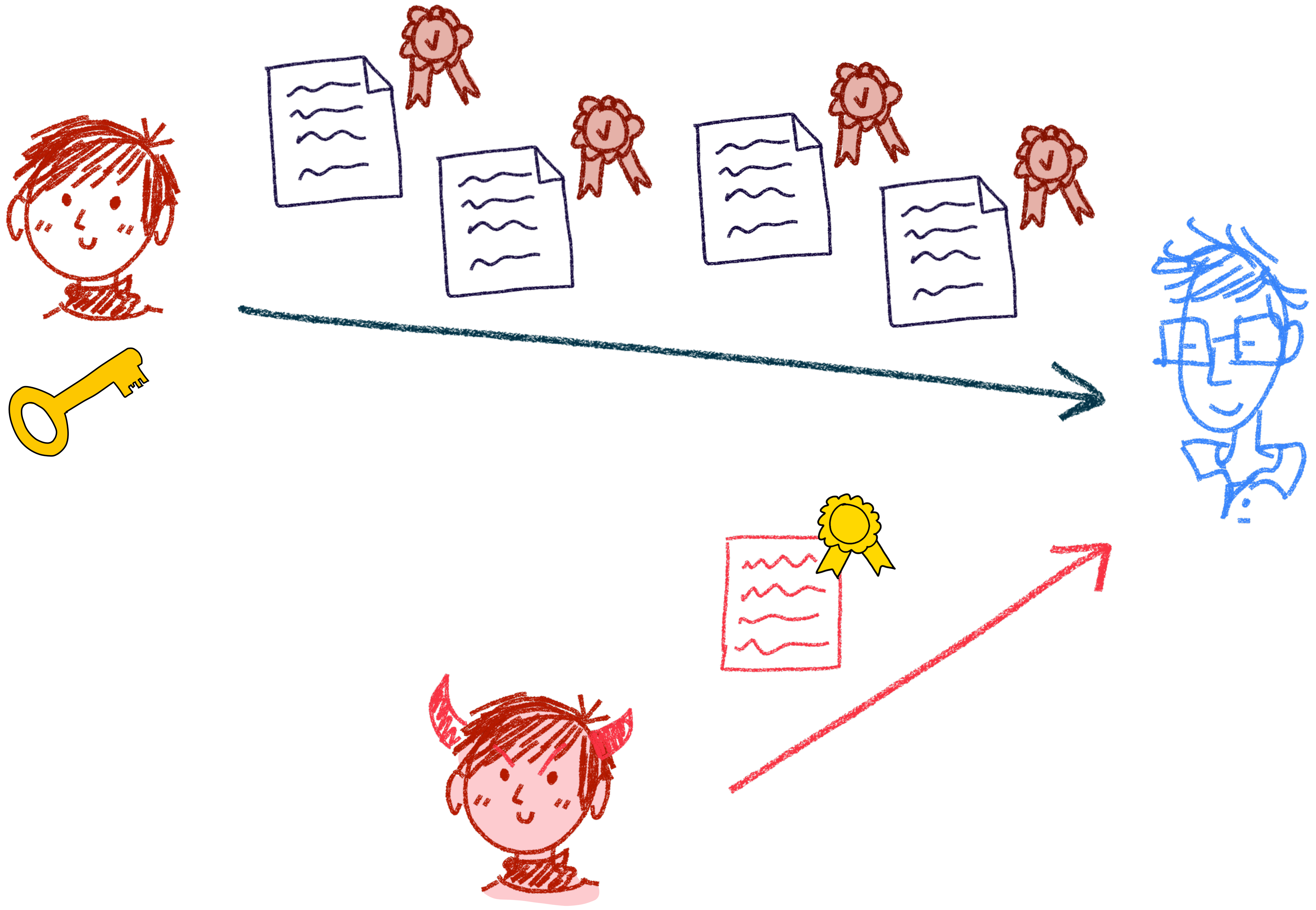

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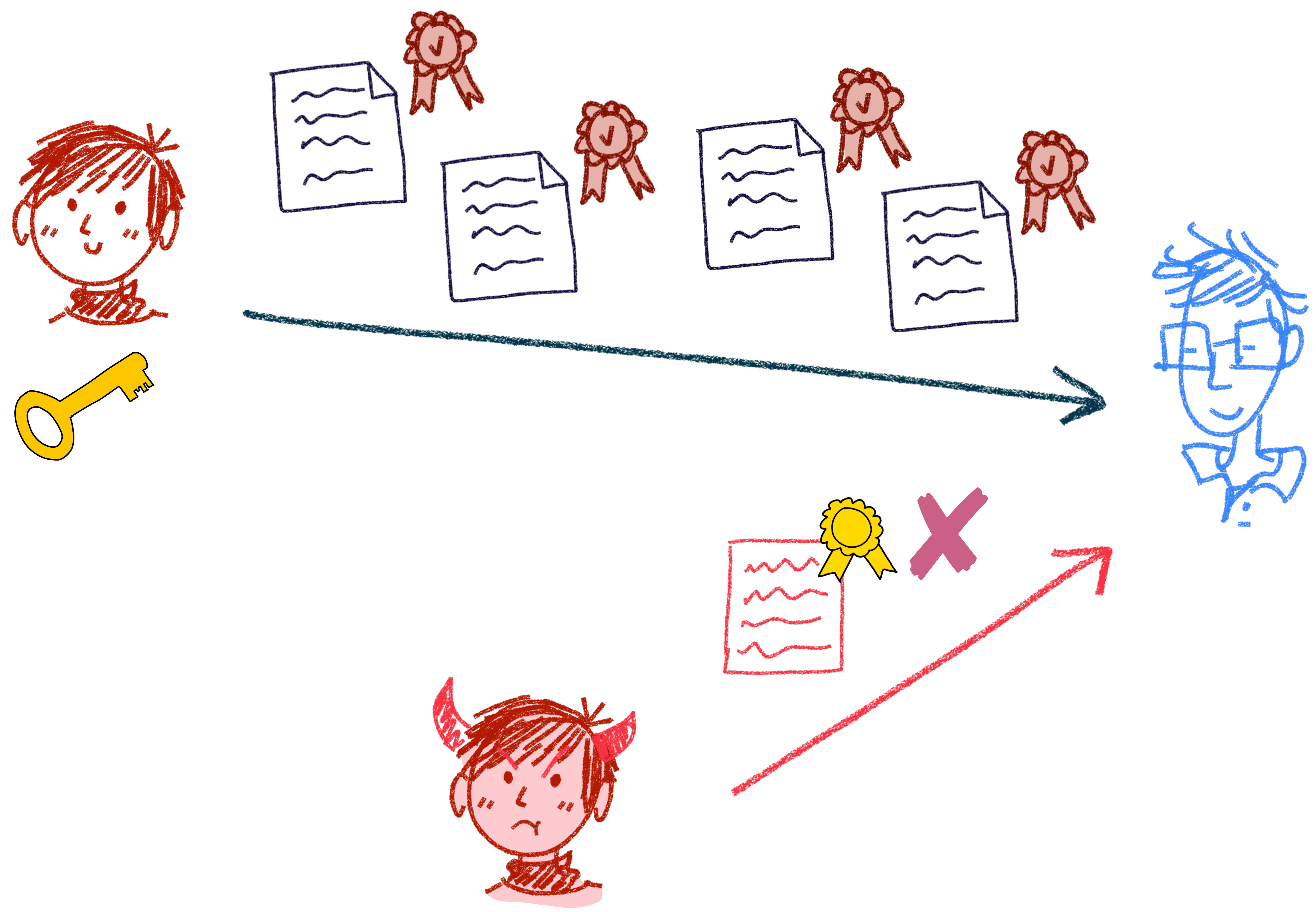

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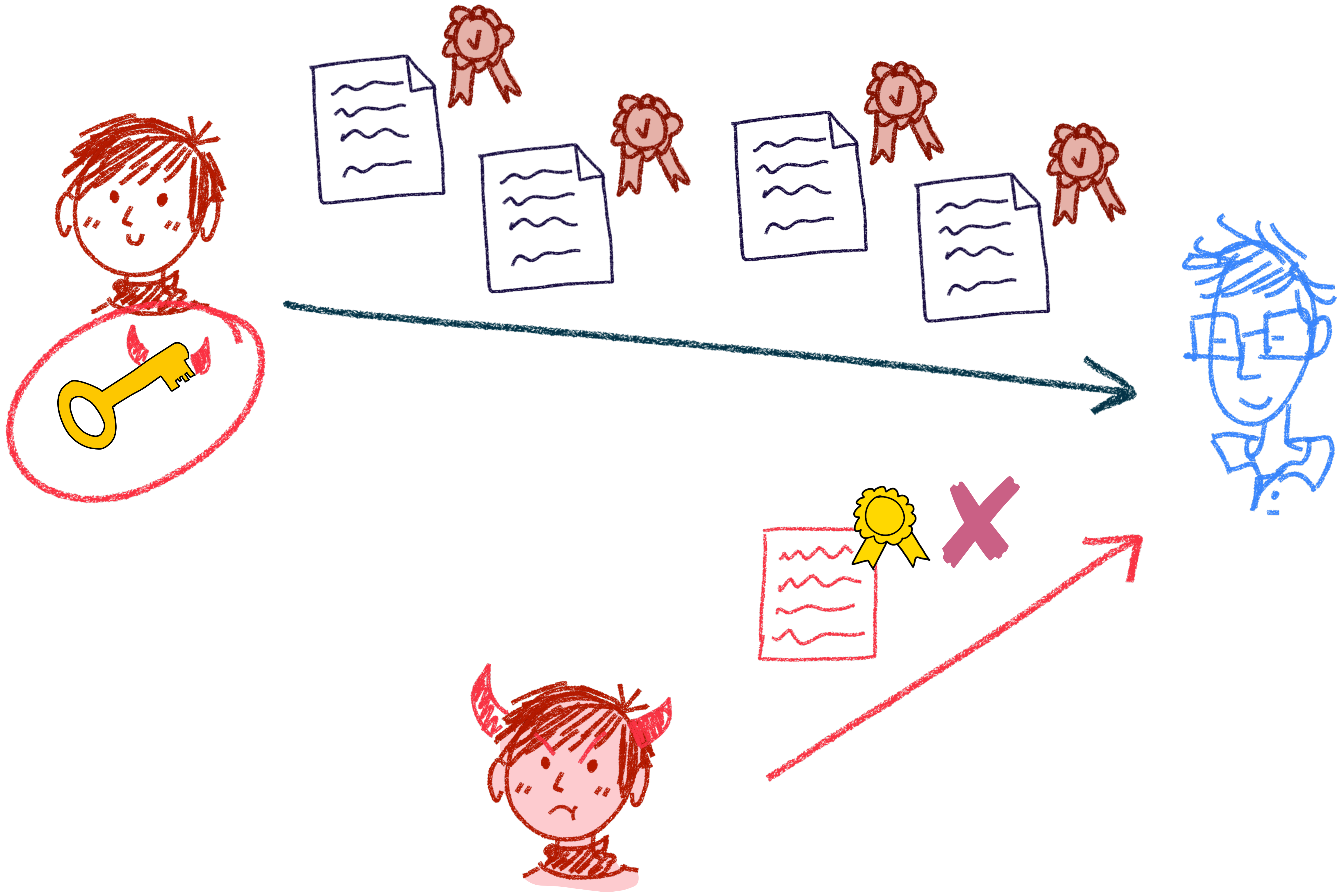
Properties not addressed by EUF-CMA



- Maliciously generated keys

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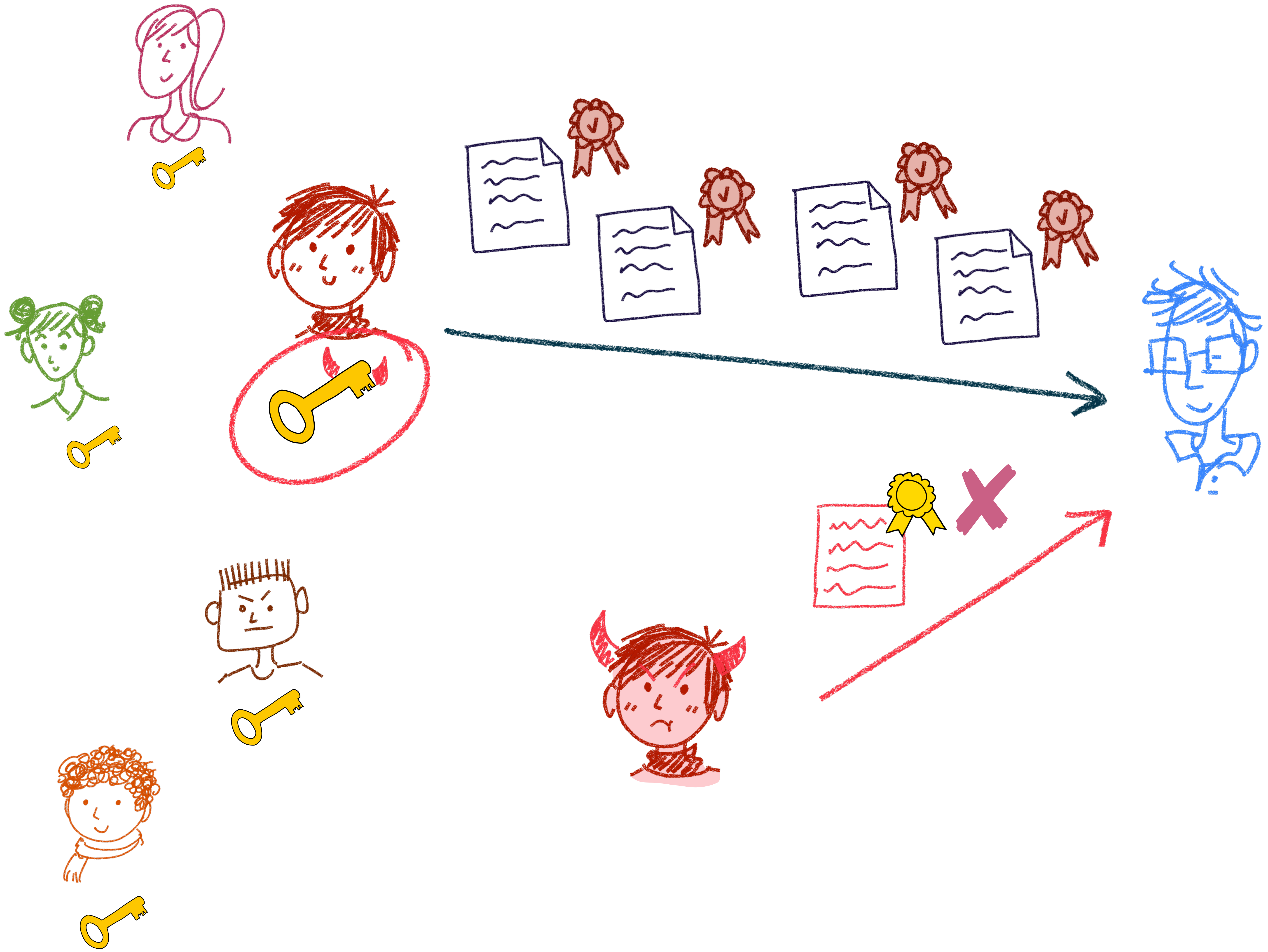

- Maliciously generated keys
- Concurrency

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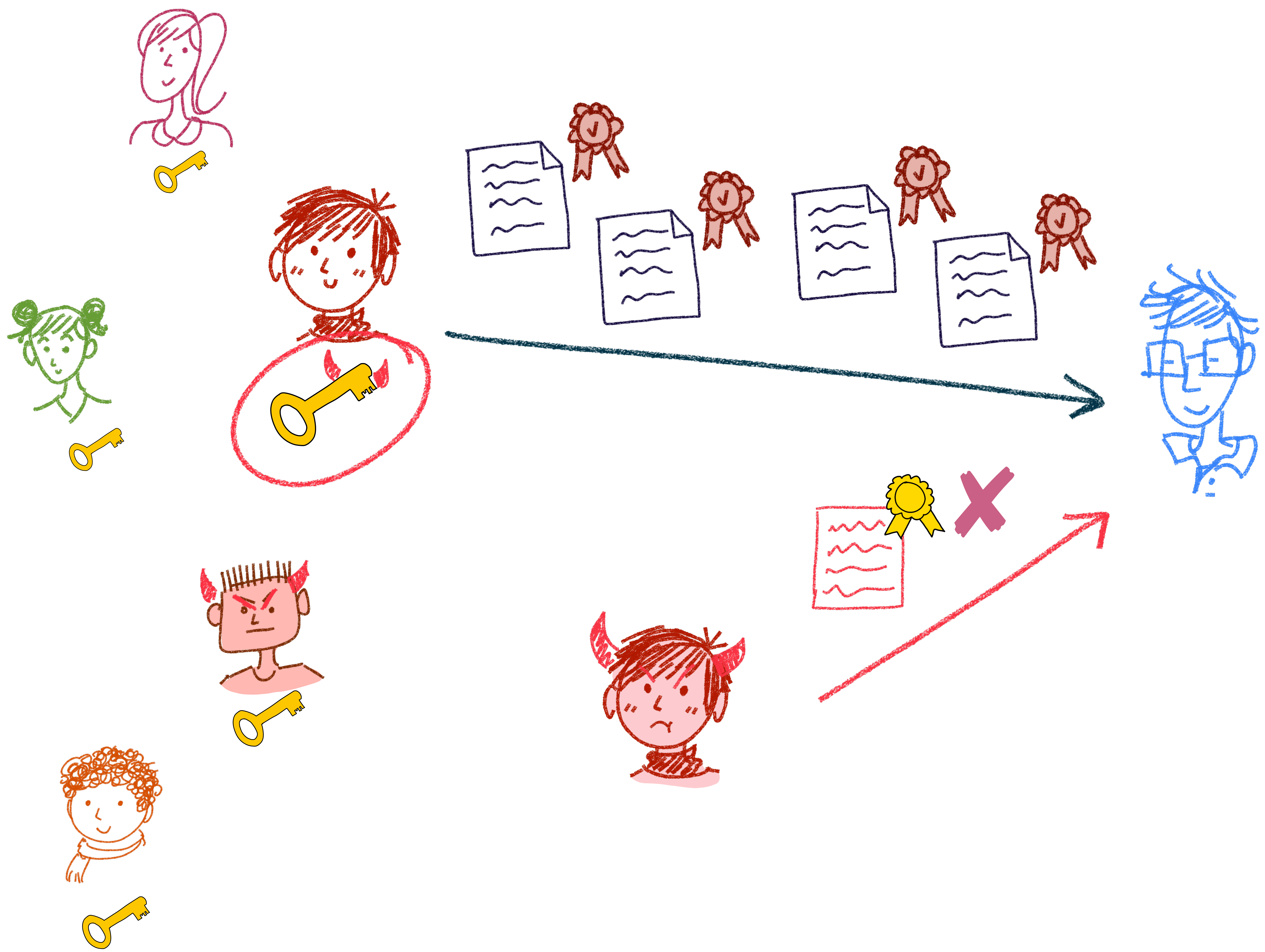

- Maliciously generated keys
- Concurrency
- Adaptive corruptions

Digital Signatures

Signature Functionality

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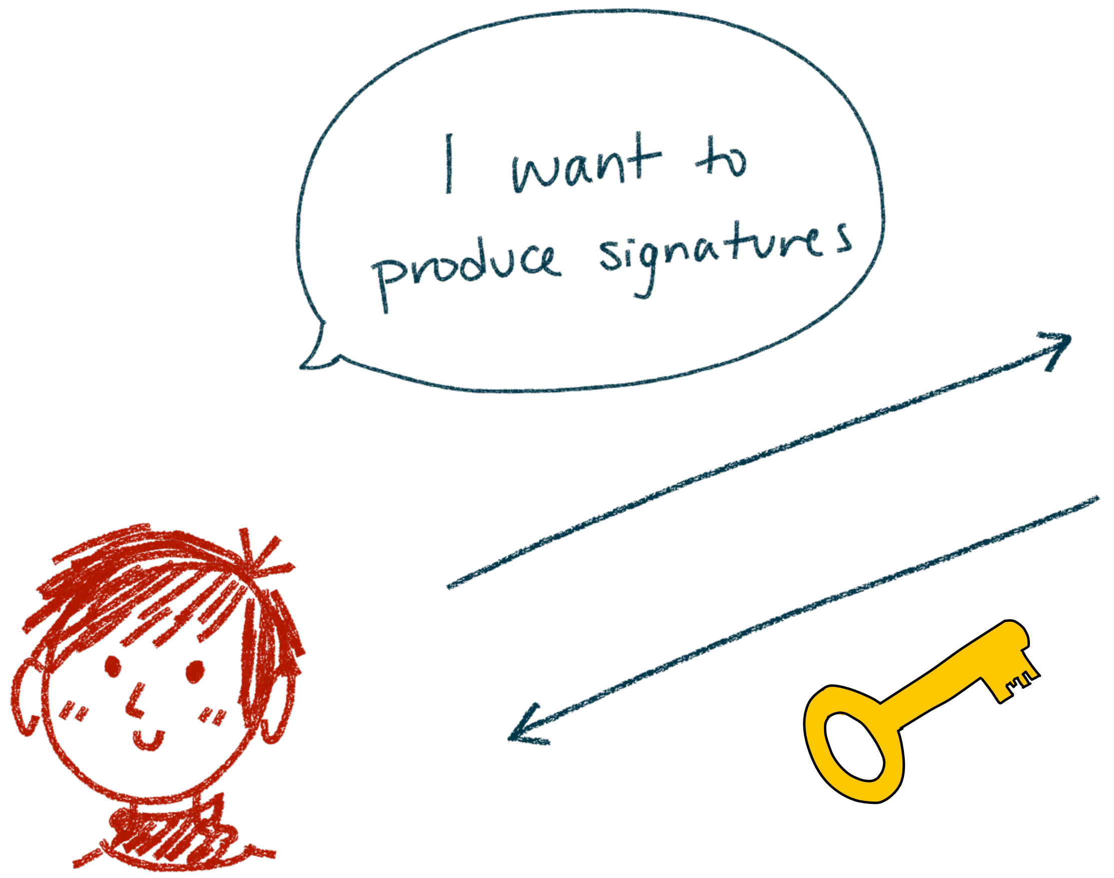

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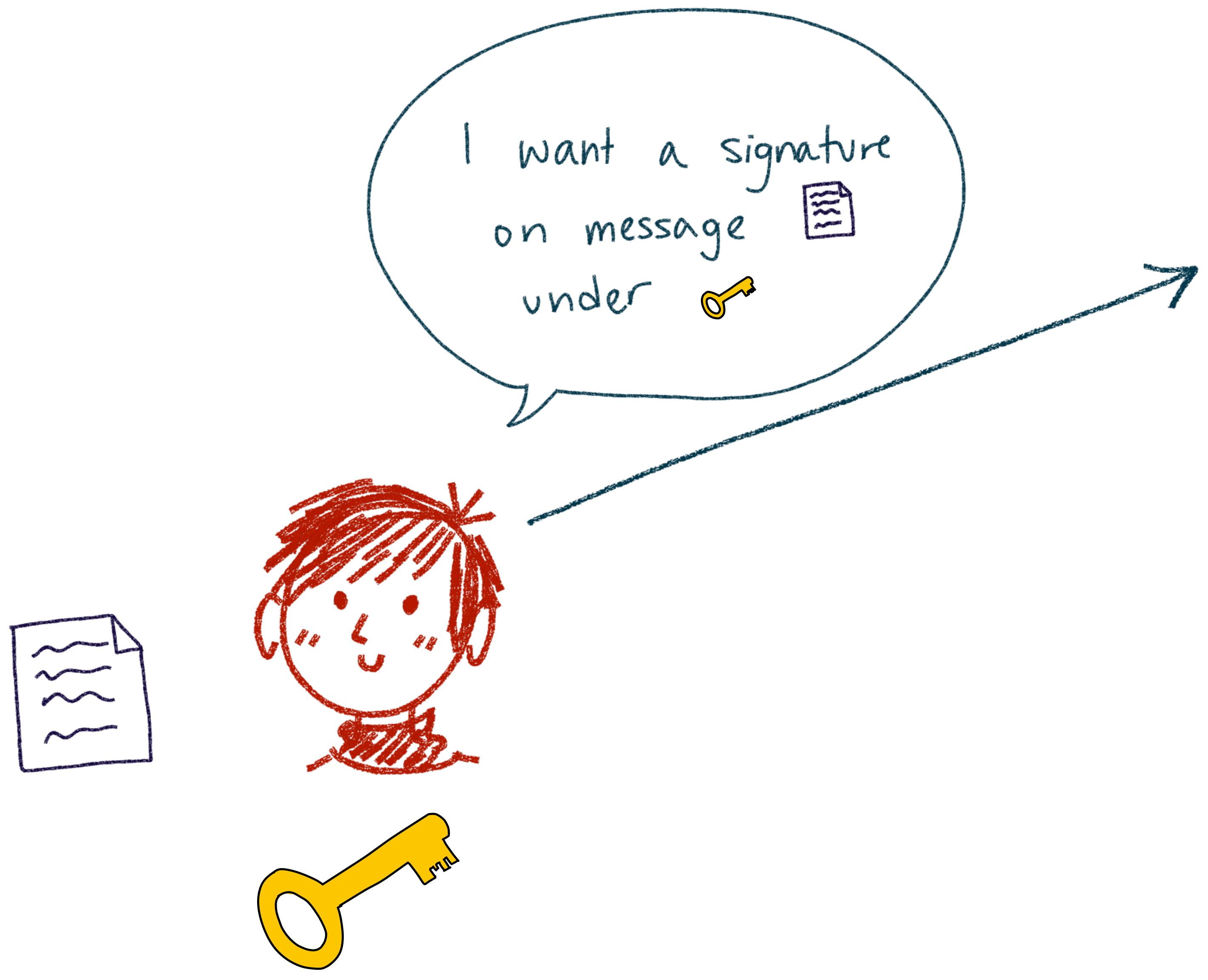

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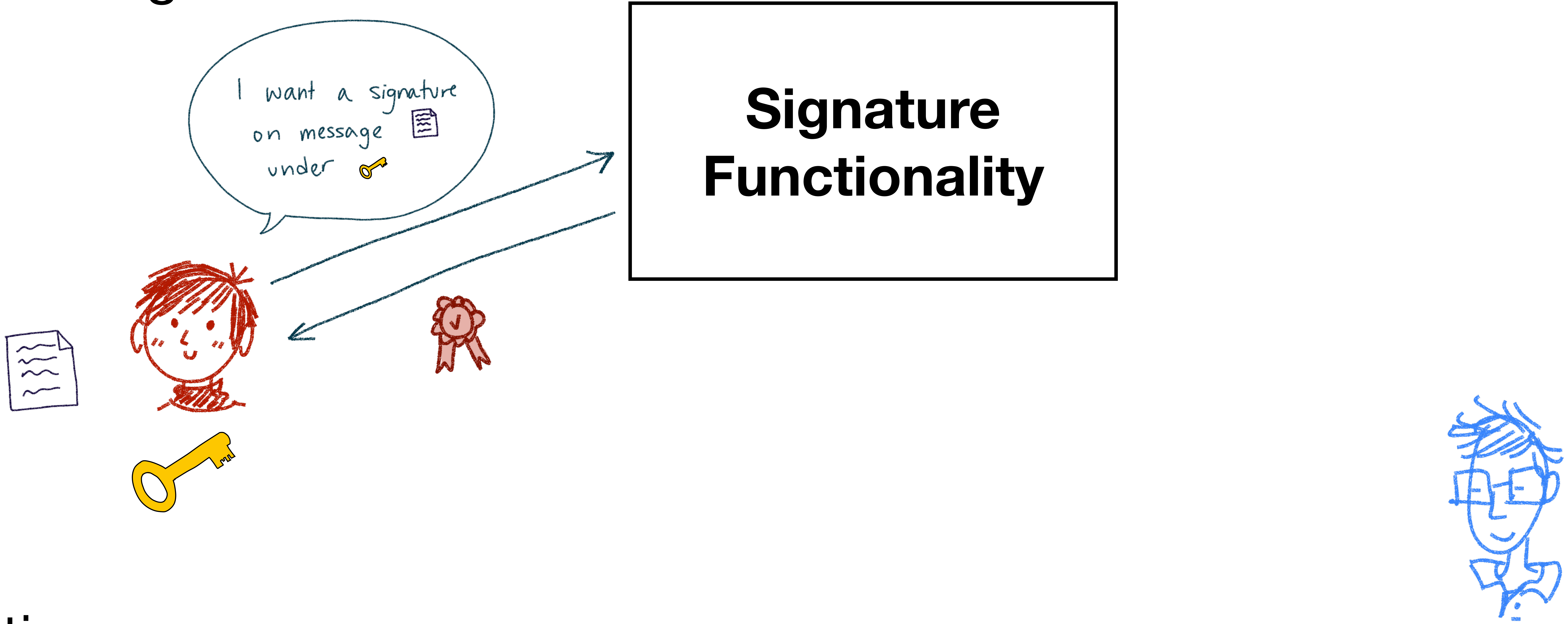

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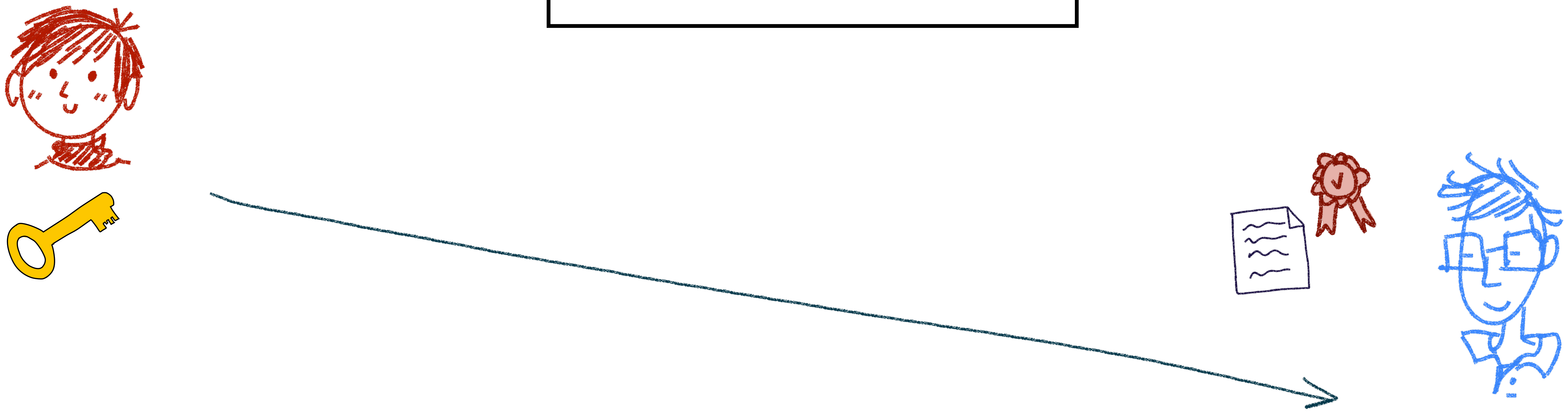

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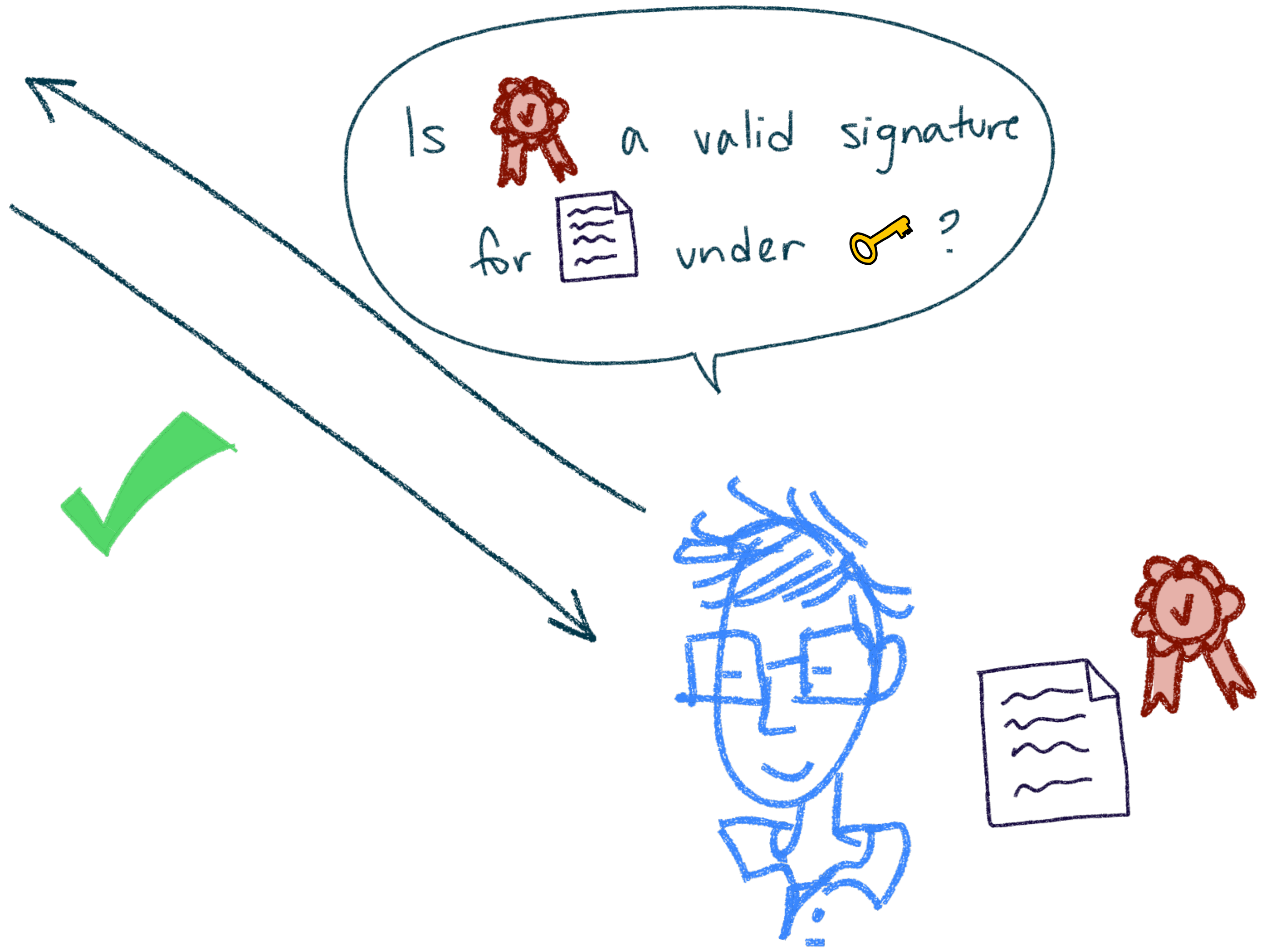

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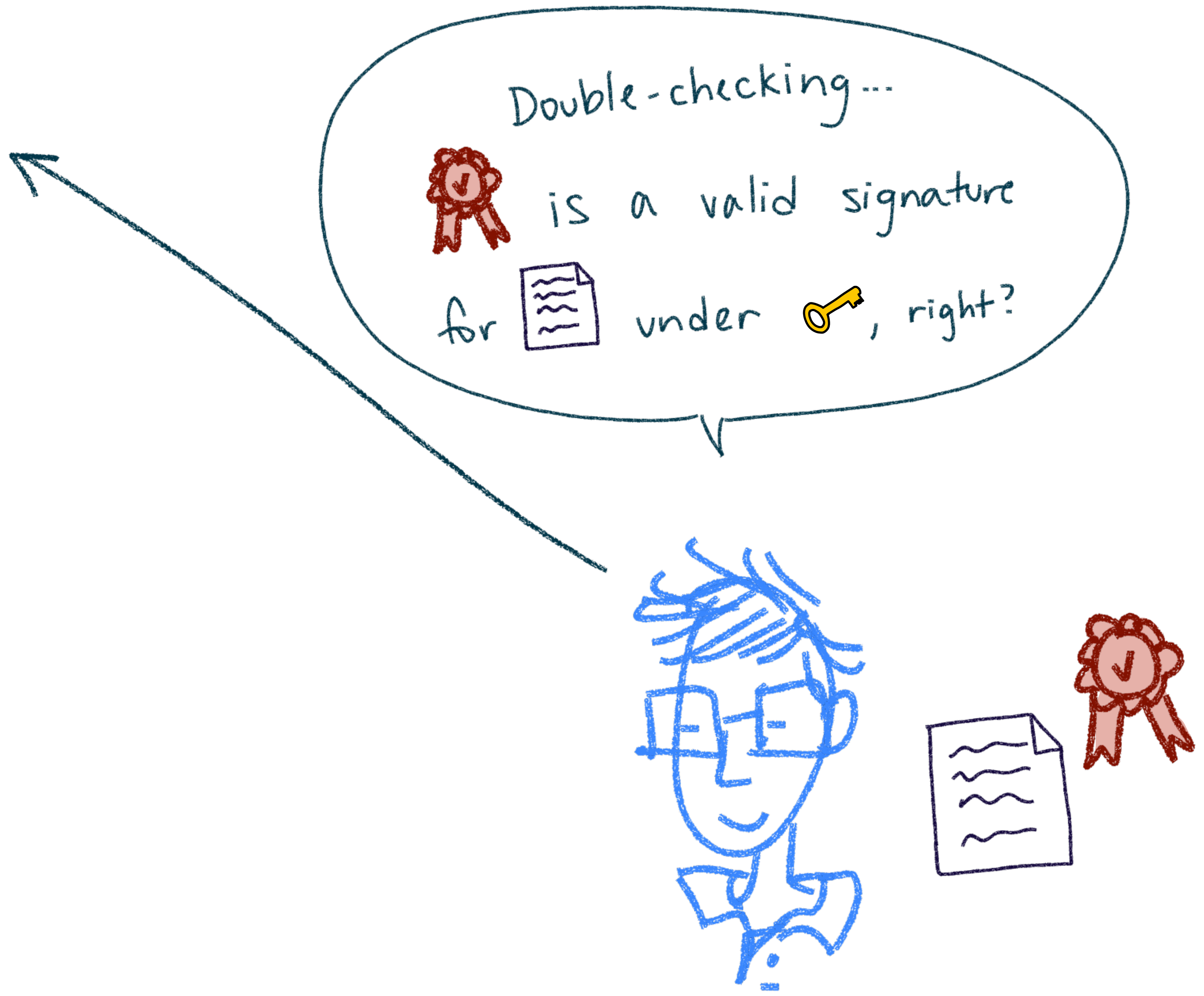

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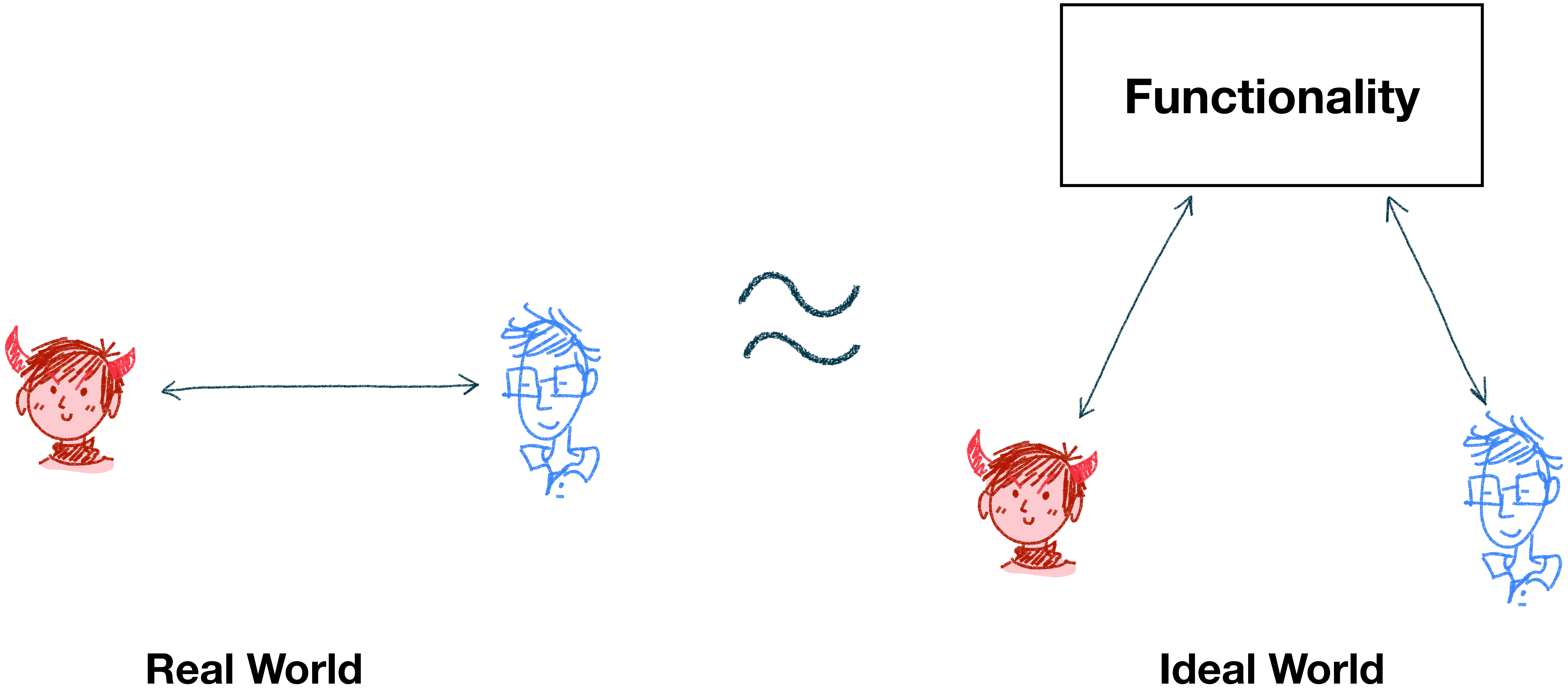
Real/Ideal Paradigm



Universal Composition (UC)

- Framework for describing protocols and analyzing security
- Functionalities can be used as building blocks in larger protocols
- Composition theorem
  - If a scheme realizes a functionality, then that scheme can replace where the functionality is used as a sub-protocol
- Security maintained even with adversarially-controlled arbitrary concurrent sessions

Existing UC Signature Functionalities

- Many existing UC signature functionalities in the literature [C01,C04,CR03,BH04,GKZ10,CSV16,BCH+20,…]
    - Proven equivalent to EUF-CMA secure signatures
- However, issues arises when you plug it into a larger protocol
    - Adversary can force functionality into scenarios that don’t happen with secure signature schemes
    - Prior functionalities output an error and halt
        - Proofs don’t go through for protocols like Dolev-Strong broadcast!

Goal of this work (aka a sneak peek at the results)

- Can we define a signature functionality that works even when used in a larger protocol?
  - An *unstoppable* functionality that the adversary can't disable
- Can we show its usefulness by plugging it into Dolev-Strong broadcast and prove security?

Generations of Ideal Signatures

Pictured: Different generations of Pokemon that I don't expect anyone over the age of 30 to recognize

First generation: Pass control to the adversary

- Ask the adversary for responses to key generation and signing
  - Gives a lot of power to the adversary!
  - Adversary can choose to just never respond
  - Worse, adversary can force an error message

Functionality A.1. $\mathcal{F}_{\text{sig-1st}}$ (Example First-Generation Signature Functionality)

Key Generation. Upon receiving $(\texttt{keygen}, \mathsf{sid})$ from some party S, verify that $\mathsf{sid} = (S, \mathsf{sid}')$ for some sid'. If not, then ignore this request. Else, hand $(\texttt{keygen}, \mathsf{sid})$ to the adversary. Upon receiving $(\texttt{VerificationKey}, \mathsf{sid}, v)$ from the adversary, output $(\texttt{VerificationKey}, \mathsf{sid}, v)$ to the caller S, and record the pair (S, v).

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Verify. On receiving the value $(\texttt{verify}, \mathsf{sid}, m, \sigma, v')$ from some party P, hand $(\texttt{verify}, \mathsf{sid}, m, \sigma, v')$ to the adversary. Upon receiving $(\texttt{verified}, \mathsf{sid}, m, \phi)$ from the adversary, do:

1. If $v' = v$ and the entry $(m, \sigma, v, 1)$ is recorded, then set $b = 1$.
   (This condition guarantees completeness: If the verification key v' is the registered one and σ is a legitimately generated signature for m, then the verification succeeds)
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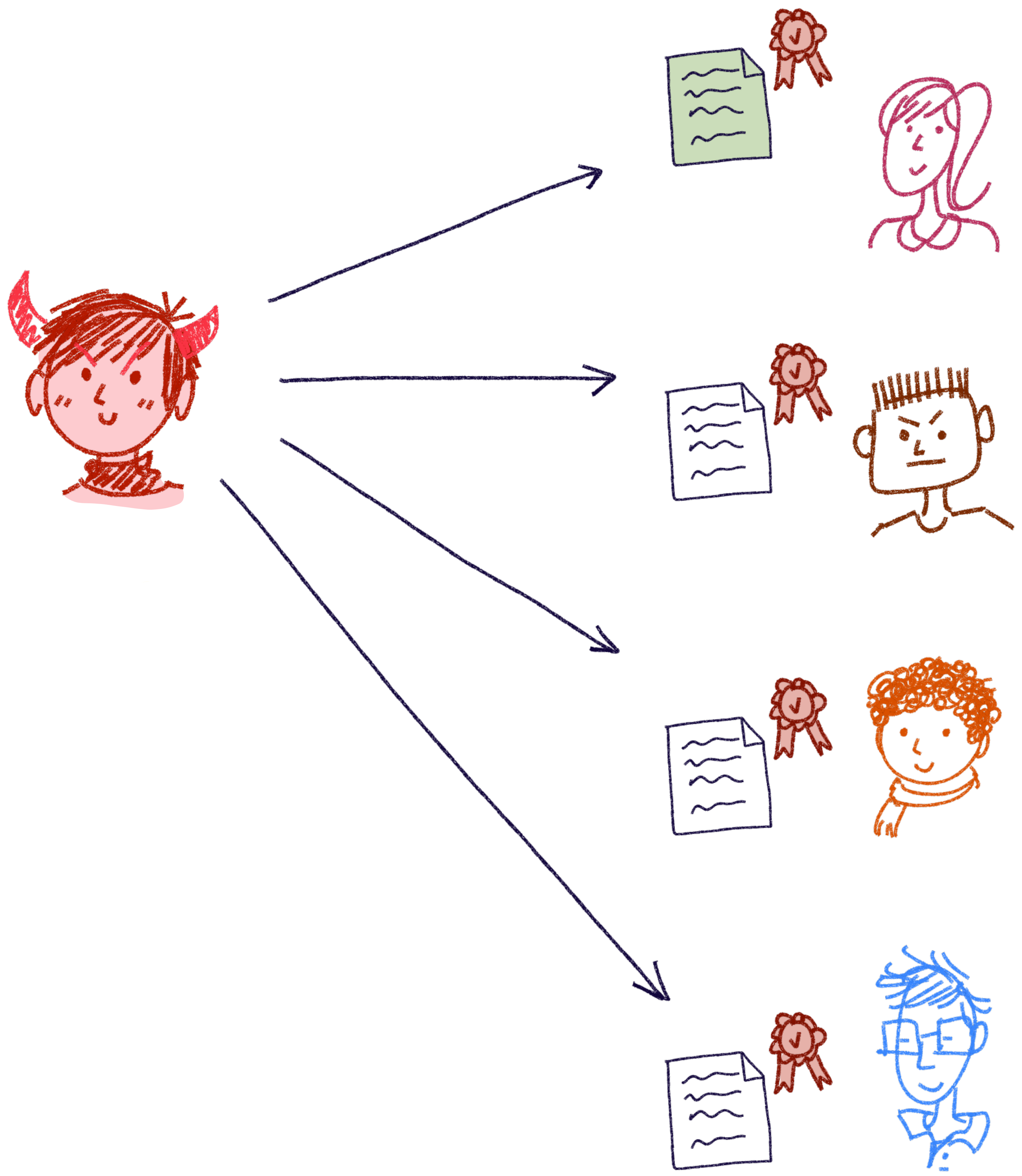

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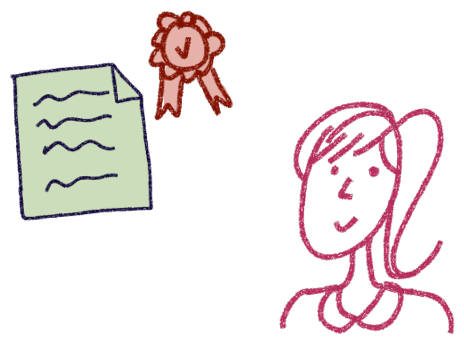

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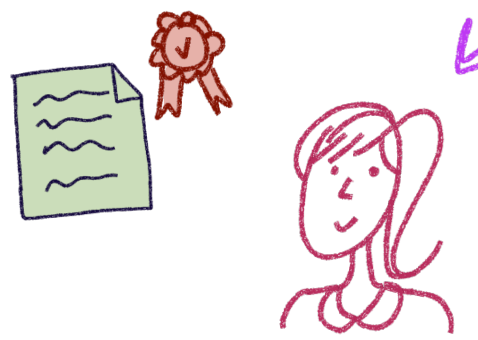
Alice wants a signature on what she received



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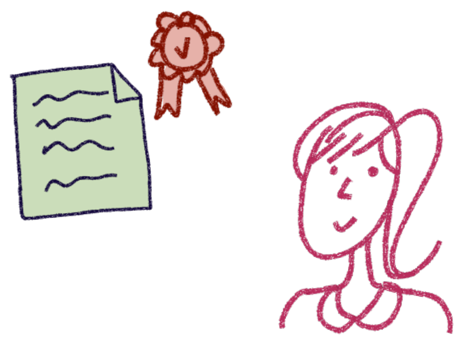

$(\texttt{sign}, \mathsf{sid}, m)$

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Sign. Upon receiving $(\texttt{sign}, \mathsf{sid}, m)$ from S, verify that $\mathsf{sid} = (S, \mathsf{sid}')$ for some sid'. If not, then ignore this request. Else, send $(\texttt{sign}, \mathsf{sid}, m)$ to the adversary. Upon receiving $(\texttt{signature}, \mathsf{sid}, m, \sigma)$ from the adversary, verify that no entry $(m, \sigma, v, 0)$ is recorded. If it is, then output an error message to S and halt. Else, output $(\texttt{signature}, \mathsf{sid}, m, \sigma)$ to S, and record the entry $(m, \sigma, v, 1)$.

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Verify. On receiving the value $(\texttt{verify}, \mathsf{sid}, m, \sigma, v')$ from some party P, hand $(\texttt{verify}, \mathsf{sid}, m, \sigma, v')$ to the adversary. Upon receiving $(\texttt{verified}, \mathsf{sid}, m, \phi)$ from the adversary, do:

1. If $v' = v$ and the entry $(m, \sigma, v, 1)$ is recorded, then set $b = 1$.
   (This condition guarantees completeness: If the verification key v' is the registered one and σ is a legitimately generated signature for m, then the verification succeeds)
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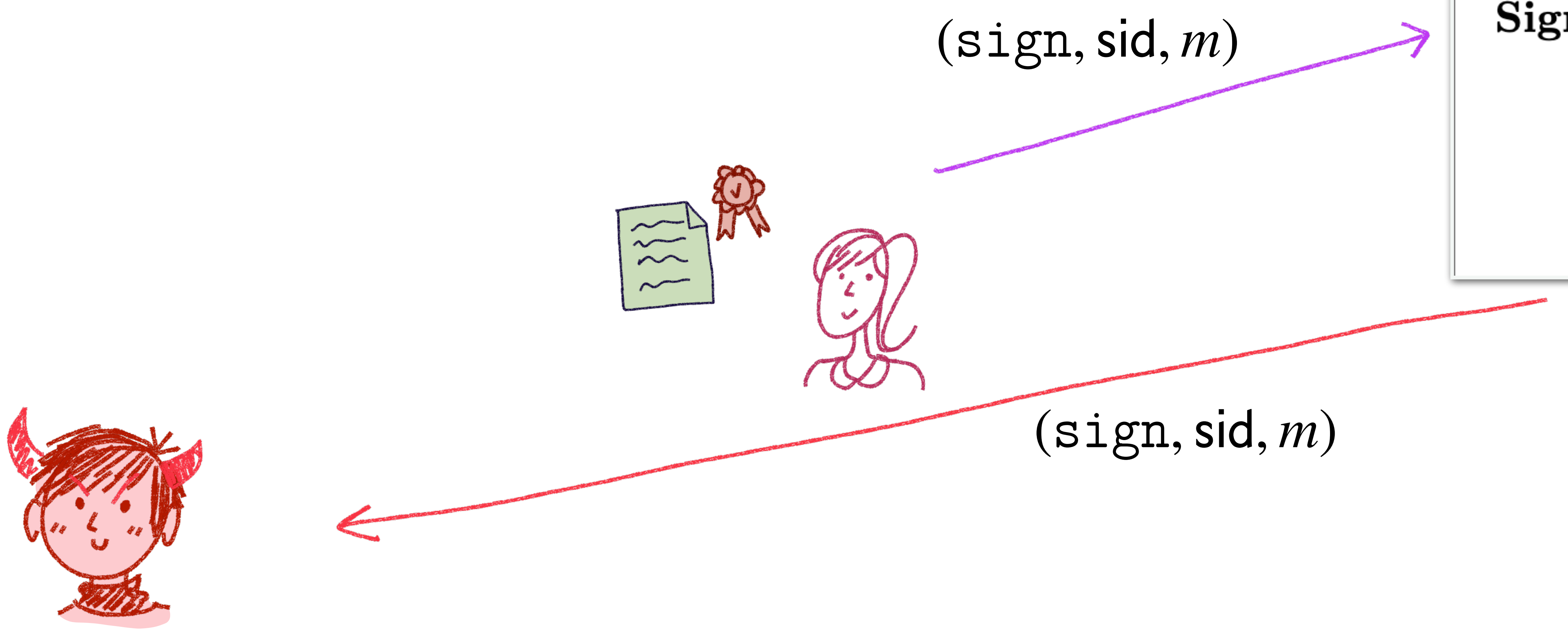
Return $(\texttt{verified}, \mathsf{sid}, m, b)$ to P.

What can go wrong with first generation?



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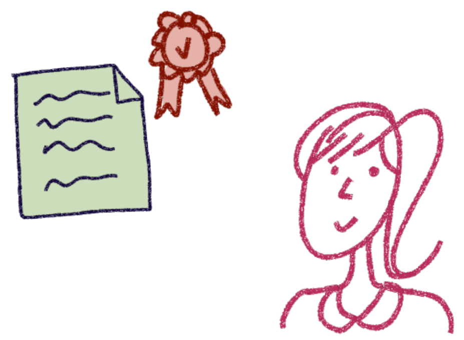

$(\texttt{sign}, \mathsf{sid}, m)$

$(\texttt{verify}, \mathsf{sid}, m, \sigma, v)$

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Adv uses verify interface to get (m, σ) registered as a bad signature pair

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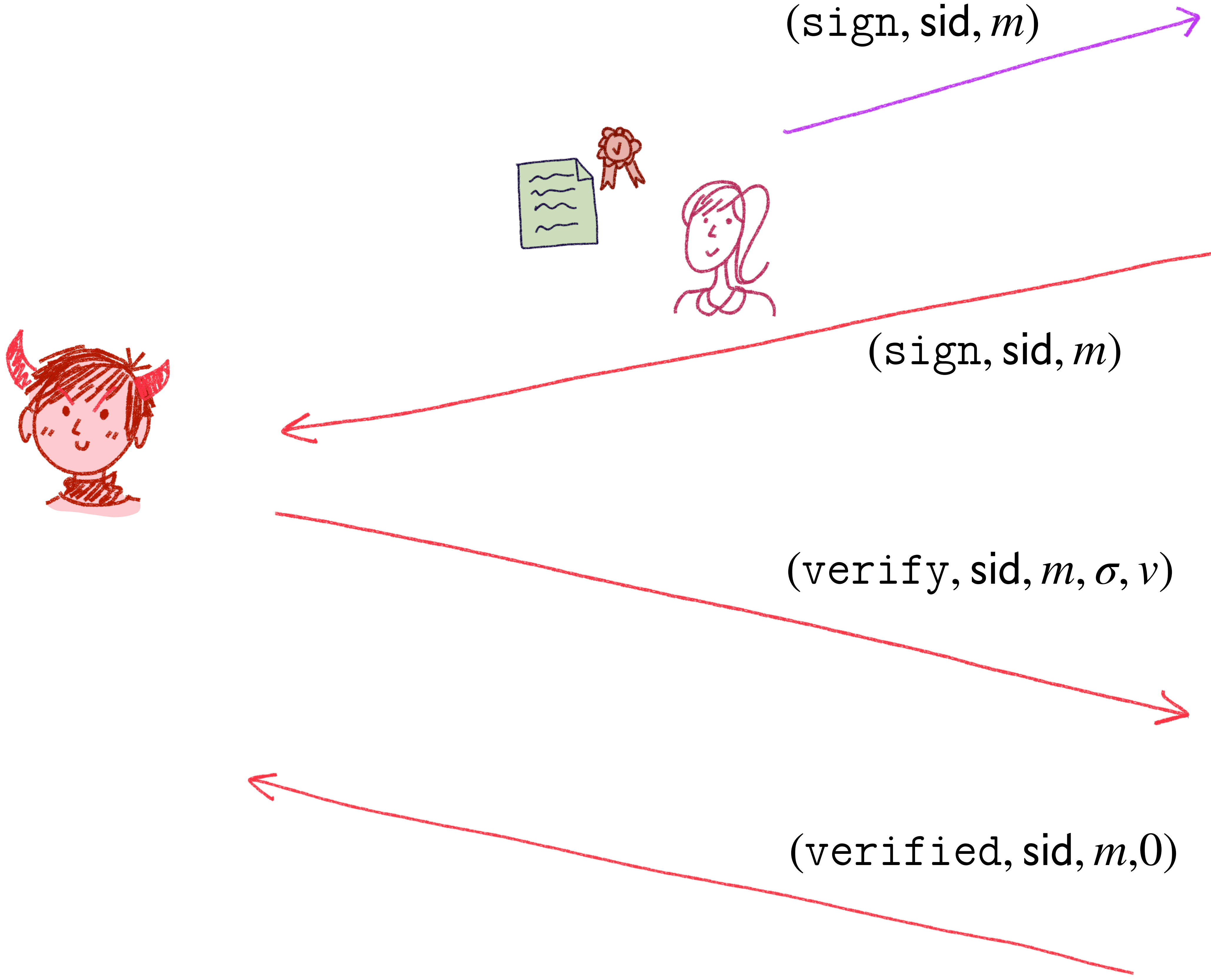

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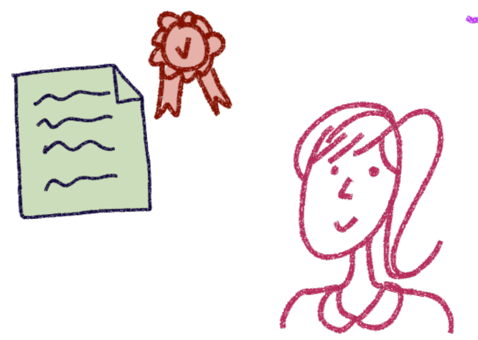

$(\texttt{sign}, \mathsf{sid}, m)$

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Functionality asks Adv for the signature

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Verify. hand (v m the ad

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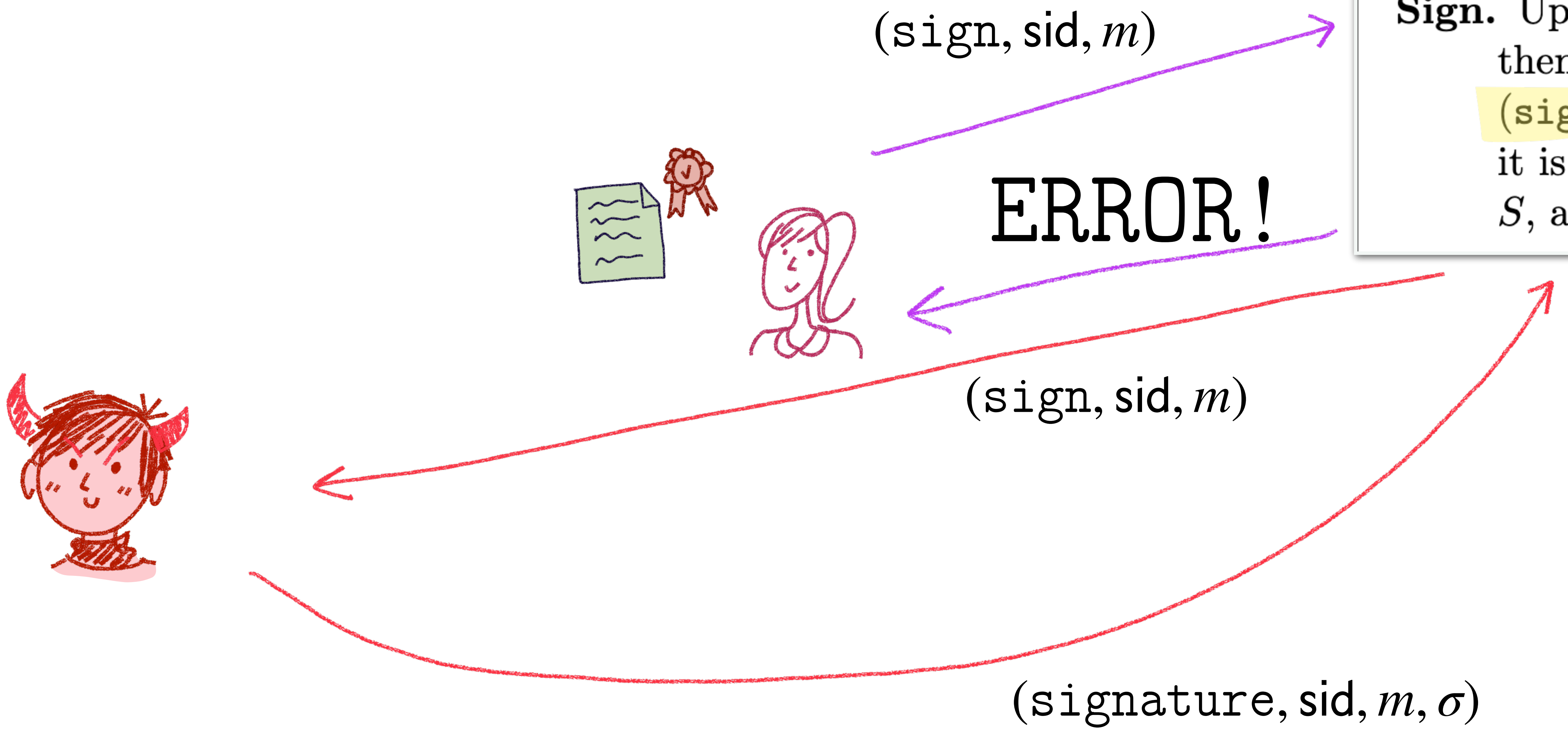

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Return $(\texttt{verified}, \mathsf{sid}, m, b)$ to P.

Second generation: Adversary supplies algorithms

- Use algorithms given by the Adversary
  - Works when supplied with honest algorithms
  - What if the adversary supplies bad algorithms?

Functionality A.2. $\mathcal{F}_{\text{sig-2nd}}$ (Example Second-Generation Signature Functionality)

Key Generation. Upon receiving $(\texttt{keygen}, \mathsf{sid})$ from some party S, verify that $\mathsf{sid} = (S, \mathsf{sid}')$ for some sid'. If not, then ignore this request. Else, hand $(\texttt{keygen}, \mathsf{sid})$ to the adversary. Upon receiving $(\texttt{algs}, \mathsf{sid}, s, v)$ from the adversary, where s is a description of a PPT ITM, and v is a description of a *deterministic* polytime ITM, output $(\texttt{VerificationAlgorithm}, \mathsf{sid}, v)$ to S.

Sign. Upon receiving $(\texttt{sign}, \mathsf{sid}, m)$ from S, let $\sigma = s(m)$, and verify that $v(m, \sigma) = 1$. If so, then output $(\texttt{signature}, \mathsf{sid}, m, \sigma)$ to the caller P_i and record the entry (m, σ). Else, output an error message to S and halt.

Verify. On receiving the value $(\texttt{verify}, \mathsf{sid}, m, \sigma, v')$ from some party V do: If $v' = v$, the signer is not corrupted, $v(m, \sigma) = 1$, and no entry (m, σ') for any σ' is recorded, then output an error message to S and halt. Else, output $(\texttt{verified}, \mathsf{sid}, m, v'(m, \sigma))$ to V.

What can go wrong with second generation?

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What can go wrong with second generation?

Functionality asks Adv for signing and verification algs

Functionality A.2. $\mathcal{F}_{\text{sig-2nd}}$ (Example

Adv can hard-code verify to always fail on strings of a specific form (e.g., fail if message contains Alice's ID)

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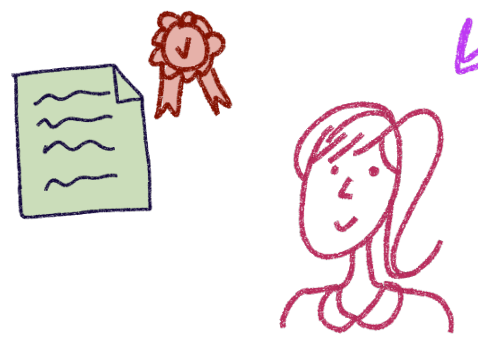
What can go wrong with second generation?

Alice wants a signature on what she received



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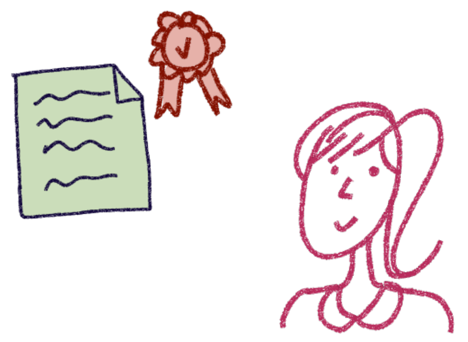

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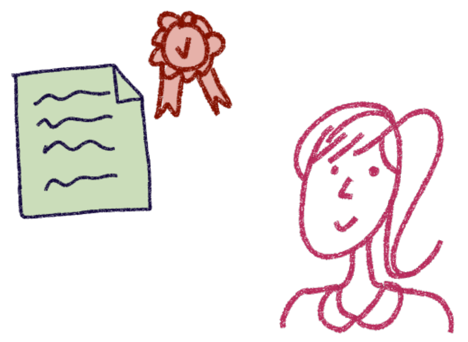

$(\texttt{sign}, \mathsf{sid}, m)$

ERROR!

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Third generation: Pre-determined Signature Algorithms

- Specify the signature scheme (e.g., ECDSA) and internally run the algorithms of the scheme
  - Side-steps the challenges with adversarial algorithms
  - Used mostly for threshold signatures
- Does not try to capture all signature schemes

What do we want from a fourth generation?

- Be compatible with as many existing signature schemes as possible
- Functionality should always provide perfect signatures to honest parties regardless of the behavior of the adversary
  - Adversary should never be able to violate security or render functionality useless (even with negligible probability)

Fourth generation Pokemon
my friend told me is unstoppable

This Work

- Introduce a new ideal functionality for signatures that can be realized by EUF-CMA* signatures and can't be disabled by an adversary
    - Prove equivalence to EUF-CMA*
- Compatible with how signatures are treated in consensus literature
    - Give the first modular analysis of Dolev-Strong
- Generalize our functionality to threshold signatures

*with the extra requirement that they're "consistent"

Our Approach

- Use the “second generation” as a starting point (adversary supplies algs)
- If the supplied algorithms are bad, have a fallback to continue working
  - Instead of throwing an error, act in a way that maintains how signatures are “supposed to” act
- Consider how signatures are “supposed to act” as invariants
  - When used in a larger protocol, can reason about in terms of invariants

Disclaimer: We don’t try (or claim) to do everything

- Although we want to be general, we focus on core, minimal properties
- Forgo inessential but possibly desirable properties
  - No notion of who “owns” a public key
  - No way of transferring signing powers to another party

Fallback: "Random Mode"

- Functionality guarantees certain invariants you'd expect from signatures
    - If these are about to be violated, functionality disregards algorithms and randomly samples future keys and signatures
- When used with a EUF-CMA signature against a poly-time adversary random mode doesn't activate
- Unfortunately adds a layer of complexity to the functionality itself to maintain bookkeeping

(Standard) Signature invariants

- **Correctness**
- **Unforgeability**
- **Consistency**

(Standard) Signature invariants

- **Correctness** → Signature pairs issued by the functionality should always verify
- **Unforgeability**
- **Consistency**

(Standard) Signature invariants

- **Correctness**
- **Unforgeability**
- **Consistency**

Signature pairs issued by the functionality should always verify

Verify should never pass for messages that have never been signed

(Standard) Signature invariants

- **Correctness** → Signature pairs issued by the functionality should always verify
- **Unforgeability** → Verify should never pass for messages that have never been signed
- **Consistency** → Identical verification queries give the same response

(Standard) Signature invariants

- **Correctness**
- **Unforgeability**
- **Consistency**

Signature pairs issued by the functionality should always verify

Verify should never pass for messages that have never been signed

Identical verification queries give the same response

Do not issue a signature σ on message m if verification has previously failed on (m, σ) under the same public key

(Non-Standard) Signature Functionality Invariants

- Functionality should never emit the same signature in response to signing queries on two different messages under the same public key

- Functionality should never emit the same public key twice in response to honest key-generation queries

Starting point: second generation functionality

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Starting point: second generation functionality

Receive algorithms from the adversary

Functionality A.2. $\mathcal{F}_{\text{sig-2nd}}$ (Example Second-Generation Signature Functionality)

Key Generation. Upon receiving ($\texttt{keygen}, \mathsf{sid}$) from some party S, verify that $\mathsf{sid} = (S, \mathsf{sid}')$ for some sid'. If not, then ignore this request. Else, hand ($\texttt{keygen}, \mathsf{sid}$) to the adversary. Upon receiving ($\texttt{algs}, \mathsf{sid}, s, v$) from the adversary, where s is a description of a PPT ITM, and v is a description of a *deterministic* polytime ITM, output ($\texttt{VerificationAlgorithm}, \mathsf{sid}, v$) to S.

Sign. Upon receiving ($\texttt{sign}, \mathsf{sid}, m$) from S, let $\sigma = s(m)$, and verify that $v(m, \sigma) = 1$. If so, then output ($\texttt{signature}, \mathsf{sid}, m, \sigma$) to the caller P_i and record the entry (m, σ). Else, output an error message to S and halt.

Verify. On receiving the value ($\texttt{verify}, \mathsf{sid}, m, \sigma, v'$) from some party V do: If $v' = v$, the signer is not corrupted, $v(m, \sigma) = 1$, and no entry (m, σ') for any σ' is recorded, then output an error message to S and halt. Else, output ($\texttt{verified}, \mathsf{sid}, m, v'(m, \sigma)$) to V.

Starting point: second generation functionality

Receive algorithms from the adversary

Functionality A.2. $\mathcal{F}_{\text{sig-2nd}}$ (Example Second-Generation Signature Functionality)

Key Generation. Upon receiving $(\texttt{keygen}, \mathsf{sid})$ from some party S, verify that $\mathsf{sid} = (S, \mathsf{sid}')$ for some sid'. If not, then ignore this request. Else, hand $(\texttt{keygen}, \mathsf{sid})$ to the adversary. Upon receiving $(\texttt{algs}, \mathsf{sid}, s, v)$ from the adversary, where s is a description of a PPT ITM, and v is a description of a *deterministic* polytime ITM, output $(\texttt{VerificationAlgorithm}, \mathsf{sid}, v)$ to S.

Sign. Upon receiving $(\texttt{sign}, \mathsf{sid}, m)$ from S, let $\sigma = s(m)$, and verify that $v(m, \sigma) = 1$. If so, then output $(\texttt{signature}, \mathsf{sid}, m, \sigma)$ to the caller P_i and record the entry (m, σ). Else, output an error message to S and halt.

Verify. On receiving the value $(\texttt{verify}, \mathsf{sid}, m, \sigma, v')$ from some party V do: If $v' = v$, the signer is not corrupted, $v(m, \sigma) = 1$, and no entry (m, σ') for any σ' is recorded, then output an error message to S and halt. Else, output $(\texttt{verified}, \mathsf{sid}, m, v'(m, \sigma))$ to V.

Enforce correctness and unforgeability

Starting point: second generation functionality

Receive algorithms from the adversary

Functionality A.2. $\mathcal{F}_{\text{sig-2nd}}$ (Example Second-Generation Signature Functionality)

Key Generation. Upon receiving $(\texttt{keygen}, \mathsf{sid})$ from some party S, verify that $\mathsf{sid} = (S, \mathsf{sid}')$ for some sid'. If not, then ignore this request. Else, hand $(\texttt{keygen}, \mathsf{sid})$ to the adversary. Upon receiving $(\texttt{algs}, \mathsf{sid}, s, v)$ from the adversary, where s is a description of a PPT ITM, and v is a description of a *deterministic* polytime ITM, output $(\texttt{VerificationAlgorithm}, \mathsf{sid}, v)$ to S.

Sign. Upon receiving $(\texttt{sign}, \mathsf{sid}, m)$ from S, let $\sigma = s(m)$, and verify that $v(m, \sigma) = 1$. If so, then output $(\texttt{signature}, \mathsf{sid}, m, \sigma)$ to the caller P_i and record the entry (m, σ). Else, output an error message to S and halt.

Verify. On receiving the value $(\texttt{verify}, \mathsf{sid}, m, \sigma, v')$ from some party V do: If $v' = v$, the signer is not corrupted, $v(m, \sigma) = 1$, and no entry (m, σ') for any σ' is recorded, then output an error message to S and halt. Else, output $(\texttt{verified}, \mathsf{sid}, m, v'(m, \sigma))$ to V.

Enforce correctness and unforgeability

Tasks:
- Handle asking adversary for algorithms
- Define new behavior on “error” to avoid halting

Our unstoppable signature functionality

Functionality 3.1. $\mathcal{F}_{\text{sig}}$ (An Unstoppable Signature Functionality)

This functionality interacts with an ideal adversary $\mathcal{S}$ and a number of real parties (all of them denoted P) that is not a-priori known. For simplicity of description, we assume this functionality has *per-session* memory. That is, all stored and recalled values are associated with the particular session ID sid of the query that generated them. Note that P may refer to a different party in every interaction.

Initialization.

1. Ignore any message from any party P that contains some session ID sid until *after* party P sends $(\texttt{init}, \mathsf{sid})$ to $\mathcal{F}_{\text{sig}}$.
2. Upon receiving $(\texttt{init}, \mathsf{sid})$ for the *first time* for some particular sid, send $(\texttt{init}, \mathsf{sid})$ to $\mathcal{S}$ and wait.
3. Upon receiving any second message that contains the session ID sid after the first $(\texttt{init}, \mathsf{sid})$ message (regardless of whether the same party transmitted the two messages):
   (a) If the message arrived from $\mathcal{S}$ and is of the form $(\texttt{algs}, \mathsf{sid}, \Sigma)$ where $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Verify}) := \Sigma$ is the description of three probabilistic Turing machines, store $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Verify})$ and $s := |\Sigma|$ in memory and set the flag $\mathsf{rmode} := 0$.
   (b) Otherwise, set the flag $\mathsf{rmode} := 1$.

   Regardless, set the integers $\ell_{\mathsf{pk}} := 1$ and $\ell_{\mathsf{sig}} := 1$, and initialize the set of assigned public keys $\mathcal{K} := \emptyset$ and the set of assigned signatures $\mathcal{Q} := \emptyset$. If $\mathsf{rmode} = 1$, process the second message for sid using the interfaces below.

Key Generation.

4. Upon receiving $(\texttt{keygen}, \mathsf{sid})$ from a party P,
   (a) If $\mathsf{rmode} = 0$, then sample a uniformly random bit-string r_k of appropriate length,[a] and compute $(\mathsf{sk}, \mathsf{pk}) := \mathsf{Gen}(r_k)$. If $\mathsf{pk} \in \mathcal{K}$ or Gen does not terminate in s computational steps, then switch to random mode by setting $\mathsf{rmode} := 1$ and following the instruction below for the case that $\mathsf{rmode} = 1$.
   (b) If $\mathsf{rmode} = 1$, then sample $\mathsf{pk} \leftarrow \{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K}$ uniformly and set $\mathsf{sk} := \bot$ and $r_k := \bot$.

   Regardless, update $\mathcal{K} := \mathcal{K} \cup \{\mathsf{pk}\}$ in memory and increment ℓ_{pk} until $\{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K} \neq \emptyset$. Store $(\texttt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$ in memory and send $(\texttt{public-key}, \mathsf{sid}, \mathsf{pk})$ to the caller P.

Signing.

5. Upon receiving $(\texttt{sign}, \mathsf{sid}, \mathsf{pk}, m)$ from a party P, update $\mathcal{K} := \mathcal{K} \cup \{\mathsf{pk}\}$, and increment ℓ_{pk} until $\{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K} \neq \emptyset$. Check if a record of the form $(\texttt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$ exists in memory for any $\mathsf{sk} \in \{0,1\}^* \cup \{\bot\}$ and any r_k. If not, return $\bot$ to P. Otherwise:
   (a) If $\mathsf{rmode} = 0$, then sample a uniformly random bit-string r_σ of appropriate length,[a] compute $\sigma := \mathsf{Sign}(\mathsf{sk}, m; r_\sigma)$ and check the following conditions:
   - $(\texttt{sig}, \mathsf{sid}, \mathsf{pk}, m', \sigma, r_\sigma)$ exists in memory such that $m \neq m'$.
   - $(\texttt{bad-sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ exists in memory.
   - Sign does not terminate in $(|m|+1) \cdot s$ computational steps.

   If any of the above conditions holds, then switch to random mode by setting $\mathsf{rmode} := 1$ and following the instruction below for the case that $\mathsf{rmode} = 1$.
   (b) If $\mathsf{rmode} = 1$, then sample $\sigma \leftarrow \{0,1\}^{\ell_{\mathsf{sig}}} \setminus \mathcal{Q}$ and set $r_\sigma := \bot$.

   Regardless, update $\mathcal{Q} := \mathcal{Q} \cup \{\sigma\}$ and increment ℓ_{sig} until $\{0,1\}^{\ell_{\mathsf{sig}}} \setminus \mathcal{Q} \neq \emptyset$. Store $(\texttt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, r_\sigma)$ in memory and return $(\texttt{signature}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ to the caller P.

Verification.

6. Upon receiving $(\texttt{verify}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ from some party P, update $\mathcal{K} := \mathcal{K} \cup \{\mathsf{pk}\}$, and increment ℓ_{pk} until $\{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K} \neq \emptyset$. Next, scan the memory for records of the form $(\texttt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, *)$ or $(\texttt{bad-sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$, for any σ, and for a record of the form $(\texttt{key}, \mathsf{sid}, P', \mathsf{pk}, *, *)$ for any P'.[b]
   (a) If the sig record exists, then set $b := 1$.
   (b) If there is no sig record, but there is a key record and P' is an honest party, then set $b := 0$.
   (c) If there is no sig record, but the bad-sig record exists, then set $b := 0$.
   (d) If Steps 6a through 6c do not apply, and $\mathsf{rmode} = 1$, then set $b := 0$.
   (e) If Steps 6a through 6c do not apply, and $\mathsf{rmode} = 0$, then set $b \leftarrow \mathsf{Verify}(\mathsf{pk}, m, \sigma)$. If Verify does not produce output before $(|m|+1) \cdot s$ computational steps have elapsed, then terminate its execution, set $b := 0$, and switch to random mode by setting $\mathsf{rmode} := 1$ in memory.

   If, after evaluating the above conditions, $b = 0$ but the record $(\texttt{bad-sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ is not stored in memory, then store it.

   If, after evaluating the above conditions, $b = 1$ but no record of the form $(\texttt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, *)$ exists in memory, then store $(\texttt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, \bot)$.

   Regardless, update $\mathcal{Q} := \mathcal{Q} \cup \{\sigma\}$ in memory and increment ℓ_{sig} until $\{0,1\}^{\ell_{\mathsf{sig}}} \setminus \mathcal{Q} \neq \emptyset$. Finally, return $(\texttt{verified}, \mathsf{sid}, \mathsf{pk}, m, \sigma, b)$ to P.

Corruption.

7. Upon receiving $(\texttt{corrupt}, \mathsf{sid}, P)$ from $\mathcal{S}$, search the memory for all records of the form $(\texttt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$, and for each such record compute the set $\mathcal{C}_{\mathsf{pk}}$ of all (m, σ, r_σ) such that there exists a record of the form $(\texttt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, r_\sigma)$ in memory. Return $(\texttt{corrupt}, \mathsf{sid}, P, \mathcal{C})$ to $\mathcal{S}$, where $\mathcal{C}$ is a set containing $(\mathsf{pk}, \mathsf{sk}, r_k, \mathcal{C}_{\mathsf{pk}})$ for every $(\texttt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$ that was found.

[a] We assume that the amount of randomness that Gen, Sign, and Verify need is part of their description.
[b] P' may or may not be the same as P.

Our unstoppable signature functionality

I do *not* expect you to read all of this!

We are going to walk through the main points

Functionality 3.1. $\mathcal{F}_{\mathsf{sig}}$ (An Unstoppable Signature Functionality)

This functionality interacts with an ideal adversary $\mathcal{S}$ and a number of real parties (all of them denoted P) that is not a-priori known. For simplicity of description, we assume this functionality has *per-session* memory. That is, all stored and recalled values are associated with the particular session ID sid of the query that generated them. Note that P may refer to a different party in every interaction.

Initialization.

1. Ignore any message from any party P that contains some session

signatures $\mathcal{Q} := \emptyset$. If $\mathsf{rmode} = 1$, process the second message for sid using the interfaces below.

Key Generation.

4. Upon receiving $(\mathtt{keygen}, \mathsf{sid})$ from a party P,
   (a) If $\mathsf{rmode} = 0$, then sample a uniformly random bit-string r_k of appropriate length,[a] and compute $(\mathsf{sk}, \mathsf{pk}) := \mathsf{Gen}(r_k)$. If $\mathsf{pk} \in \mathcal{K}$ or Gen does not terminate in s computational steps, then switch to random mode by setting $\mathsf{rmode} := 1$ and following the instruction below for the case that $\mathsf{rmode} = 1$.
   (b) If $\mathsf{rmode} = 1$, then sample $\mathsf{pk} \leftarrow \{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K}$ uniformly and set $\mathsf{sk} := \perp$ and $r_k := \perp$.

   Regardless, update $\mathcal{K} := \mathcal{K} \cup \{\mathsf{pk}\}$ in memory and increment ℓ_{pk} until $\{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K} \neq \emptyset$. Store $(\mathtt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$ in memory and send $(\mathtt{public\text{-}key}, \mathsf{sid}, \mathsf{pk})$ to the caller P.

Signing.

5. Upon receiving $(\mathtt{sign}, \mathsf{sid}, \mathsf{pk}, m)$ from a party P, update $\mathcal{K} := \mathcal{K} \cup \{\mathsf{pk}\}$, and increment ℓ_{pk} until $\{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K} \neq \emptyset$. Check if a record of the form $(\mathtt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$ exists in memory for any $\mathsf{sk} \in \{0,1\}^* \cup \{\perp\}$ and any r_k. If not, return $\perp$ to P. Otherwise:
   (a) If $\mathsf{rmode} = 0$, then sample a uniformly random bit-string r_σ of appropriate length,[a] compute $\sigma := \mathsf{Sign}(\mathsf{sk}, m; r_\sigma)$ and check the following conditions:
      - $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m', \sigma, r_\sigma)$ exists in memory such that $m \neq m'$.
      - $(\mathtt{bad\text{-}sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ exists in memory.
      - Sign does not terminate in $(|m|+1) \cdot s$ computational steps.

      If any of the above conditions holds, then switch to random mode by setting $\mathsf{rmode} := 1$ and following the instruction below for the case that $\mathsf{rmode} = 1$.
   (b) If $\mathsf{rmode} = 1$, then sample $\sigma \leftarrow \{0,1\}^{\ell_{\mathsf{sig}}} \setminus \mathcal{Q}$ and set $r_\sigma := \perp$.

   Regardless, update $\mathcal{Q} := \mathcal{Q} \cup \{\sigma\}$ and increment ℓ_{sig} until $\{0,1\}^{\ell_{\mathsf{sig}}} \setminus \mathcal{Q} \neq \emptyset$. Store $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, r_\sigma)$ in memory and return $(\mathtt{signature}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ to the caller P.

Verification.

6. Upon receiving $(\mathtt{verify}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ from some party P, update $\mathcal{K} := \mathcal{K} \cup \{\mathsf{pk}\}$, and increment ℓ_{pk} until $\{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K} \neq \emptyset$. Next,

   If, after evaluating the above conditions, $b = 0$ but the record $(\mathtt{bad\text{-}sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ is not stored in memory, then store it.

   If, after evaluating the above conditions, $b = 1$ but no record of the form $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, *)$ exists in memory, then store $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, \perp)$.

   Regardless, update $\mathcal{Q} := \mathcal{Q} \cup \{\sigma\}$ in memory and increment ℓ_{sig} until $\{0,1\}^{\ell_{\mathsf{sig}}} \setminus \mathcal{Q} \neq \emptyset$. Finally, return $(\mathtt{verified}, \mathsf{sid}, \mathsf{pk}, m, \sigma, b)$ to P.

Corruption.

7. Upon receiving $(\mathtt{corrupt}, \mathsf{sid}, P)$ from $\mathcal{S}$, search the memory for all records of the form $(\mathtt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$, and for each such record compute the set $\mathcal{C}_{\mathsf{pk}}$ of all (m, σ, r_σ) such that there exists a record of the form $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, r_\sigma)$ in memory. Return $(\mathtt{corrupt}, \mathsf{sid}, P, \mathcal{C})$ to $\mathcal{S}$, where $\mathcal{C}$ is a set containing $(\mathsf{pk}, \mathsf{sk}, r_k, \mathcal{C}_{\mathsf{pk}})$ for every $(\mathtt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$ that was found.

[a] We assume that the amount of randomness that Gen, Sign, and Verify need is part of their description.

[b] P' may or may not be the same as P.

Our unstoppable signature functionality

No guarantee the adversary will give algorithms in a timely fashion
Can either:

- Use library functionality of Canetti, Jain, Swanberg, Varia '22
- Initialization stage that has the parties activate the functionality without expecting a response

Functionality 3.1. $\mathcal{F}_{\mathsf{sig}}$ (An Unstoppable Signature Functionality)

This functionality interacts with an ideal adversary $\mathcal{S}$ and a number of real parties (all of them denoted P) that is not a-priori known. For simplicity of description, we assume this functionality has *per-session* memory. That is, all stored and recalled values are associated with the particular session ID sid of the query that generated them. Note that P may refer to a different party in every interaction.

Initialization.

1. Ignore any message from any party P that contains some session ID sid until *after* party P sends $(\mathtt{init}, \mathsf{sid})$ to $\mathcal{F}_{\mathsf{sig}}$.
2. Upon receiving $(\mathtt{init}, \mathsf{sid})$ for the *first time* for some particular sid, send $(\mathtt{init}, \mathsf{sid})$ to $\mathcal{S}$ and wait.
3. Upon receiving any second message that contains the session ID sid after the first $(\mathtt{init}, \mathsf{sid})$ message (regardless of whether the same party transmitted the two messages):
   (a) If the message arrived from $\mathcal{S}$ and is of the form $(\mathtt{algs}, \mathsf{sid}, \Sigma)$ where $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Verify}) := \Sigma$ is the description of three probabilistic Turing machines, store $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Verify})$ and $s := |\Sigma|$ in memory and set the flag $\mathsf{rmode} := 0$.
   (b) Otherwise, set the flag $\mathsf{rmode} := 1$.

   Regardless, set the integers $\ell_{\mathsf{pk}} := 1$ and $\ell_{\mathsf{sig}} := 1$, and initialize the set of assigned public keys $\mathcal{K} := \emptyset$ and the set of assigned signatures $\mathcal{Q} := \emptyset$. If $\mathsf{rmode} = 1$, process the second message for sid using the interfaces below.

Key Generation.

4. Upon receiving $(\mathtt{keygen}, \mathsf{sid})$ from a party P,
   (a) If $\mathsf{rmode} = 0$, then sample a uniformly random bit-string r_k of appropriate length,[a] and compute $(\mathsf{sk}, \mathsf{pk}) := \mathsf{Gen}(r_k)$. If $\mathsf{pk} \in \mathcal{K}$ or Gen does not terminate in s computational steps, then switch to random mode by setting $\mathsf{rmode} := 1$ and following the instruction below for the case that $\mathsf{rmode} = 1$.
   (b) If $\mathsf{rmode} = 1$, then sample $\mathsf{pk} \leftarrow \{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K}$ uniformly and set $\mathsf{sk} := \perp$ and $r_k := \perp$.

   Regardless, update $\mathcal{K} := \mathcal{K} \cup \{\mathsf{pk}\}$ in memory and increment ℓ_{pk} until $\{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K} \neq \emptyset$. Store $(\mathtt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$ in memory and send $(\mathtt{public\text{-}key}, \mathsf{sid}, \mathsf{pk})$ to the caller P.

Signing.

5. Upon receiving $(\mathtt{sign}, \mathsf{sid}, \mathsf{pk}, m)$ from a party P, update $\mathcal{K} := \mathcal{K} \cup \{\mathsf{pk}\}$, and increment ℓ_{pk} until $\{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K} \neq \emptyset$. Check if a record of the form $(\mathtt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$ exists in memory for any $\mathsf{sk} \in \{0,1\}^* \cup \{\perp\}$ and any r_k. If not, return $\perp$ to P. Otherwise:
   (a) If $\mathsf{rmode} = 0$, then sample a uniformly random bit-string r_σ of appropriate length,[a] compute $\sigma := \mathsf{Sign}(\mathsf{sk}, m; r_\sigma)$ and check the following conditions:
   - $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m', \sigma, r_\sigma)$ exists in memory such that $m \neq m'$.
   - $(\mathtt{bad\text{-}sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ exists in memory.
   - Sign does not terminate in $(|m|+1) \cdot s$ computational steps.

   If any of the above conditions holds, then switch to random mode by setting $\mathsf{rmode} := 1$ and following the instruction below for the case that $\mathsf{rmode} = 1$.
   (b) If $\mathsf{rmode} = 1$, then sample $\sigma \leftarrow \{0,1\}^{\ell_{\mathsf{sig}}} \setminus \mathcal{Q}$ and set $r_\sigma := \perp$.

   Regardless, update $\mathcal{Q} := \mathcal{Q} \cup \{\sigma\}$ and increment ℓ_{sig} until $\{0,1\}^{\ell_{\mathsf{sig}}} \setminus \mathcal{Q} \neq \emptyset$. Store $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, r_\sigma)$ in memory and return $(\mathtt{signature}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ to the caller P.

Verification.

6. Upon receiving $(\mathtt{verify}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ from some party P, update $\mathcal{K} := \mathcal{K} \cup \{\mathsf{pk}\}$, and increment ℓ_{pk} until $\{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K} \neq \emptyset$. Next, scan the memory for records of the form $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, *)$ or $(\mathtt{bad\text{-}sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$, for any σ, and for a record of the form $(\mathtt{key}, \mathsf{sid}, P', \mathsf{pk}, *, *)$ for any P'.[b]
   (a) If the $\mathtt{sig}$ record exists, then set $b := 1$.
   (b) If there is no $\mathtt{sig}$ record, but there is a $\mathtt{key}$ record and P' is an honest party, then set $b := 0$.
   (c) If there is no $\mathtt{sig}$ record, but the $\mathtt{bad\text{-}sig}$ record exists, then set $b := 0$.
   (d) If Steps 6a through 6c do not apply, and $\mathsf{rmode} = 1$, then set $b := 0$.
   (e) If Steps 6a through 6c do not apply, and $\mathsf{rmode} = 0$, then set $b \leftarrow \mathsf{Verify}(\mathsf{pk}, m, \sigma)$. If Verify does not produce output before $(|m|+1) \cdot s$ computational steps have elapsed, then terminate its execution, set $b := 0$, and switch to random mode by setting $\mathsf{rmode} := 1$ in memory.

   If, after evaluating the above conditions, $b = 0$ but the record $(\mathtt{bad\text{-}sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ is not stored in memory, then store it.

   If, after evaluating the above conditions, $b = 1$ but no record of the form $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, *)$ exists in memory, then store $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, \perp)$.

   Regardless, update $\mathcal{Q} := \mathcal{Q} \cup \{\sigma\}$ in memory and increment ℓ_{sig} until $\{0,1\}^{\ell_{\mathsf{sig}}} \setminus \mathcal{Q} \neq \emptyset$. Finally, return $(\mathtt{verified}, \mathsf{sid}, \mathsf{pk}, m, \sigma, b)$ to P.

Corruption.

7. Upon receiving $(\mathtt{corrupt}, \mathsf{sid}, P)$ from $\mathcal{S}$, search the memory for all records of the form $(\mathtt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$, and for each such record compute the set $\mathcal{C}_{\mathsf{pk}}$ of all (m, σ, r_σ) such that there exists a record of the form $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, r_\sigma)$ in memory. Return $(\mathtt{corrupt}, \mathsf{sid}, P, \mathcal{C})$ to $\mathcal{S}$, where $\mathcal{C}$ is a set containing $(\mathsf{pk}, \mathsf{sk}, r_k, \mathcal{C}_{\mathsf{pk}})$ for every $(\mathtt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$ that was found.

[a] We assume that the amount of randomness that Gen, Sign, and Verify need is part of their description.
[b] P' may or may not be the same as P.

Our unstoppable signature functionality

No guarantee the adversary will give algorithms in a timely fashion
Can either:
- Use library functionality of Canetti, Jain, Swanberg, Varia '22
- Initialization stage that has the parties activate the functionality without expecting a response

Checking the inputted algorithms are maintain the invariants

Switches to random mode if anything is wrong

Functionality 3.1. $\mathcal{F}_{\mathsf{sig}}$ (An Unstoppable Signature Functionality)

This functionality interacts with an ideal adversary $\mathcal{S}$ and a number of real parties (all of them denoted P) that is not a-priori known. For simplicity of description, we assume this functionality has *per-session* memory. That is, all stored and recalled values are associated with the particular session ID sid of the query that generated them. Note that P may refer to a different party in every interaction.

Initialization.

1. Ignore any message from any party P that contains some session ID sid until *after* party P sends $(\mathtt{init}, \mathsf{sid})$ to $\mathcal{F}_{\mathsf{sig}}$.
2. Upon receiving $(\mathtt{init}, \mathsf{sid})$ for the *first time* for some particular sid, send $(\mathtt{init}, \mathsf{sid})$ to $\mathcal{S}$ and wait.
3. Upon receiving any second message that contains the session ID sid after the first $(\mathtt{init}, \mathsf{sid})$ message (regardless of whether the same party transmitted the two messages):
   (a) If the message arrived from $\mathcal{S}$ and is of the form $(\mathtt{algs}, \mathsf{sid}, \Sigma)$ where $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Verify}) := \Sigma$ is the description of three probabilistic Turing machines, store $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Verify})$ and $s := |\Sigma|$ in memory and set the flag $\mathsf{rmode} := 0$.
   (b) Otherwise, set the flag $\mathsf{rmode} := 1$.

   Regardless, set the integers $\ell_{\mathsf{pk}} := 1$ and $\ell_{\mathsf{sig}} := 1$, and initialize the set of assigned public keys $\mathcal{K} := \emptyset$ and the set of assigned signatures $\mathcal{Q} := \emptyset$. If $\mathsf{rmode} = 1$, process the second message for sid using the interfaces below.

Key Generation.

4. Upon receiving $(\mathtt{keygen}, \mathsf{sid})$ from a party P:
   (a) If $\mathsf{rmode} = 0$, then sample a uniformly random bit-string r_k of appropriate length,[a] and compute $(\mathsf{sk}, \mathsf{pk}) := \mathsf{Gen}(r_k)$. If $\mathsf{pk} \in \mathcal{K}$ or Gen does not terminate in s computational steps, then switch to random mode by setting $\mathsf{rmode} := 1$ and following the instruction below for the case that $\mathsf{rmode} = 1$.
   (b) If $\mathsf{rmode} = 1$, then sample $\mathsf{pk} \leftarrow \{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K}$ uniformly and set $\mathsf{sk} := \bot$ and $r_k := \bot$.

   Regardless, update $\mathcal{K} := \mathcal{K} \cup \{\mathsf{pk}\}$ in memory and increment ℓ_{pk} until $\{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K} \neq \emptyset$. Store $(\mathtt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$ in memory and send $(\mathtt{public\text{-}key}, \mathsf{sid}, \mathsf{pk})$ to the caller P.

Signing.

5. Upon receiving $(\mathtt{sign}, \mathsf{sid}, \mathsf{pk}, m)$ from a party P, update $\mathcal{K} := \mathcal{K} \cup \{\mathsf{pk}\}$, and increment ℓ_{pk} until $\{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K} \neq \emptyset$. Check if a record of the form $(\mathtt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$ exists in memory for any $\mathsf{sk} \in \{0,1\}^* \cup \{\bot\}$ and any r_k. If not, return $\bot$ to P. Otherwise:
   (a) If $\mathsf{rmode} = 0$, then sample a uniformly random bit-string r_σ of appropriate length,[a] compute $\sigma := \mathsf{Sign}(\mathsf{sk}, m; r_\sigma)$ and check the following conditions:
   - $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m', \sigma, r_\sigma)$ exists in memory such that $m \neq m'$.
   - $(\mathtt{bad\text{-}sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ exists in memory.
   - Sign does not terminate in $(|m|+1) \cdot s$ computational steps.

   If any of the above conditions holds, then switch to random mode by setting $\mathsf{rmode} := 1$ and following the instruction below for the case that $\mathsf{rmode} = 1$.
   (b) If $\mathsf{rmode} = 1$, then sample $\sigma \leftarrow \{0,1\}^{\ell_{\mathsf{sig}}} \setminus \mathcal{Q}$ and set $r_\sigma := \bot$.

   Regardless, update $\mathcal{Q} := \mathcal{Q} \cup \{\sigma\}$ and increment ℓ_{sig} until $\{0,1\}^{\ell_{\mathsf{sig}}} \setminus \mathcal{Q} \neq \emptyset$. Store $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, r_\sigma)$ in memory and return $(\mathtt{signature}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ to the caller P.

Verification.

6. Upon receiving $(\mathtt{verify}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ from some party P, update $\mathcal{K} := \mathcal{K} \cup \{\mathsf{pk}\}$, and increment ℓ_{pk} until $\{0,1\}^{\ell_{\mathsf{pk}}} \setminus \mathcal{K} \neq \emptyset$. Next, scan the memory for records of the form $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, *)$ or $(\mathtt{bad\text{-}sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$, for any σ, and for a record of the form $(\mathtt{key}, \mathsf{sid}, P', \mathsf{pk}, *, *)$ for any P'.[b]
   (a) If the $\mathtt{sig}$ record exists, then set $b := 1$.
   (b) If there is no $\mathtt{sig}$ record, but there is a $\mathtt{key}$ record and P' is an honest party, then set $b := 0$.
   (c) If there is no $\mathtt{sig}$ record, but the $\mathtt{bad\text{-}sig}$ record exists, then set $b := 0$.
   (d) If Steps 6a through 6c do not apply, and $\mathsf{rmode} = 1$, then set $b := 0$.
   (e) If Steps 6a through 6c do not apply, and $\mathsf{rmode} = 0$, then set $b \leftarrow \mathsf{Verify}(\mathsf{pk}, m, \sigma)$. If Verify does not produce output before $(|m|+1) \cdot s$ computational steps have elapsed, then terminate its execution, set $b := 0$, and switch to random mode by setting $\mathsf{rmode} := 1$ in memory.

   If, after evaluating the above conditions, $b = 0$ but the record $(\mathtt{bad\text{-}sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma)$ is not stored in memory, then store it.

   If, after evaluating the above conditions, $b = 1$ but no record of the form $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, *)$ exists in memory, then store $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, \bot)$.

   Regardless, update $\mathcal{Q} := \mathcal{Q} \cup \{\sigma\}$ in memory and increment ℓ_{sig} until $\{0,1\}^{\ell_{\mathsf{sig}}} \setminus \mathcal{Q} \neq \emptyset$. Finally, return $(\mathtt{verified}, \mathsf{sid}, \mathsf{pk}, m, \sigma, b)$ to P.

Corruption.

7. Upon receiving $(\mathtt{corrupt}, \mathsf{sid}, P)$ from $\mathcal{S}$, search the memory for all records of the form $(\mathtt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$, and for each such record compute the set $\mathcal{C}_{\mathsf{pk}}$ of all (m, σ, r_σ) such that there exists a record of the form $(\mathtt{sig}, \mathsf{sid}, \mathsf{pk}, m, \sigma, r_\sigma)$ in memory. Return $(\mathtt{corrupt}, \mathsf{sid}, P, \mathcal{C})$ to $\mathcal{S}$, where $\mathcal{C}$ is a set containing $(\mathsf{pk}, \mathsf{sk}, r_k, \mathcal{C}_{\mathsf{pk}})$ for every $(\mathtt{key}, \mathsf{sid}, P, \mathsf{pk}, \mathsf{sk}, r_k)$ that was found.

[a] We assume that the amount of randomness that Gen, Sign, and Verify need is part of their description.
[b] P' may or may not be the same as P.

Our unstoppable signature functionality

No guarantee the adversary will give algorithms in a timely fashion
Can either:
- Use library functionality of Canetti, Jain, Swanberg, Varia ’22
- Initialization stage that has the parties activate the functionality without expecting a response

Checking the inputted algorithms are maintain the invariants

Switches to random mode if anything is wrong

Random mode and bookkeeping for random mode

Functionality 3.1. $\mathcal{F}_{\text{sig}}$ (An Unstoppable Signature Functionality)

This functionality interacts with an ideal adversary $\mathcal{S}$ and a number of real parties (all of them denoted P) that is not a-priori known. For simplicity of description, we assume this functionality has *per-session* memory. That is, all stored and recalled values are associated with the particular session ID sid of the query that generated them. Note that P may refer to a different party in every interaction.

Initialization.

1. Ignore any message from any party P that contains some session ID sid until *after* party P sends (init, sid) to $\mathcal{F}_{\text{sig}}$.
2. Upon receiving (init, sid) for the *first time* for some particular sid, send (init, sid) to $\mathcal{S}$ and wait.
3. Upon receiving any second message that contains the session ID sid after the first (init, sid) message (regardless of whether the same party transmitted the two messages):
   (a) If the message arrived from $\mathcal{S}$ and is of the form (algs, sid, Σ) where (Gen, Sign, Verify) $:= \Sigma$ is the description of three probabilistic Turing machines, store (Gen, Sign, Verify) and $s := |\Sigma|$ in memory and set the flag rmode $:= 0$.
   (b) Otherwise, set the flag rmode $:= 1$.

   Regardless, set the integers $\ell_{\text{pk}} := 1$ and $\ell_{\text{sig}} := 1$, and initialize the set of assigned public keys $\mathcal{K} := \emptyset$ and the set of assigned signatures $\mathcal{Q} := \emptyset$. If rmode $= 1$, process the second message for sid using the interfaces below.

Key Generation.

4. Upon receiving (keygen, sid) from a party P,
   (a) If rmode $= 0$, then sample a uniformly random bit-string r_k of appropriate length,[a] and compute (sk, pk) $:=$ Gen(r_k). If pk $\in \mathcal{K}$ or Gen does not terminate in s computational steps, then switch to random mode by setting rmode $:= 1$ and following the instruction below for the case that rmode $= 1$.
   (b) If rmode $= 1$, then sample pk $\leftarrow \{0,1\}^{\ell_{\text{pk}}} \setminus \mathcal{K}$ uniformly and set sk $:= \perp$ and $r_k := \perp$.

   Regardless, update $\mathcal{K} := \mathcal{K} \cup \{\text{pk}\}$ in memory and increment ℓ_{pk} until $\{0,1\}^{\ell_{\text{pk}}} \setminus \mathcal{K} \neq \emptyset$. Store (key, sid, P, pk, sk, r_k) in memory and send (public-key, sid, pk) to the caller P.

Signing.

5. Upon receiving (sign, sid, pk, m) from a party P, update $\mathcal{K} := \mathcal{K} \cup \{\text{pk}\}$, and increment ℓ_{pk} until $\{0,1\}^{\ell_{\text{pk}}} \setminus \mathcal{K} \neq \emptyset$. Check if a record of the form (key, sid, P, pk, sk, r_k) exists in memory for any sk $\in \{0,1\}^* \cup \{\perp\}$ and any r_k. If not, return $\perp$ to P. Otherwise:
   (a) If rmode $= 0$, then sample a uniformly random bit-string r_σ of appropriate length,[a] compute $\sigma :=$ Sign(sk, m; r_σ) and check the following conditions:
   - (sig, sid, pk, m', σ, r_σ) exists in memory such that $m \neq m'$.
   - (bad-sig, sid, pk, m, σ) exists in memory.
   - Sign does not terminate in $(|m|+1)\cdot s$ computational steps.

   If any of the above conditions holds, then switch to random mode by setting rmode $:= 1$ and following the instruction below for the case that rmode $= 1$.
   (b) If rmode $= 1$, then sample $\sigma \leftarrow \{0,1\}^{\ell_{\text{sig}}} \setminus \mathcal{Q}$ and set $r_\sigma := \perp$.

   Regardless, update $\mathcal{Q} := \mathcal{Q} \cup \{\sigma\}$ and increment ℓ_{sig} until $\{0,1\}^{\ell_{\text{sig}}} \setminus \mathcal{Q} \neq \emptyset$. Store (sig, sid, pk, m, σ, r_σ) in memory and return (signature, sid, pk, m, σ) to the caller P.

Verification.

6. Upon receiving (verify, sid, pk, m, σ) from some party P, update $\mathcal{K} := \mathcal{K} \cup \{\text{pk}\}$, and increment ℓ_{pk} until $\{0,1\}^{\ell_{\text{pk}}} \setminus \mathcal{K} \neq \emptyset$. Next, scan the memory for records of the form (sig, sid, pk, m, σ, $*$) or (bad-sig, sid, pk, m, σ), for any σ, and for a record of the form (key, sid, P', pk, $*$, $*$) for any P'.[b]
   (a) If the sig record exists, then set $b := 1$.
   (b) If there is no sig record, but there is a key record and P' is an honest party, then set $b := 0$.
   (c) If there is no sig record, but the bad-sig record exists, then set $b := 0$.
   (d) If Steps 6a through 6c do not apply, and rmode $= 1$, then set $b := 0$.
   (e) If Steps 6a through 6c do not apply, and rmode $= 0$, then set $b \leftarrow$ Verify(pk, m, σ). If Verify does not produce output before $(|m|+1)\cdot s$ computational steps have elapsed, then terminate its execution, set $b := 0$, and switch to random mode by setting rmode $:= 1$ in memory.

   If, after evaluating the above conditions, $b = 0$ but the record (bad-sig, sid, pk, m, σ) is not stored in memory, then store it.
   If, after evaluating the above conditions, $b = 1$ but no record of the form (sig, sid, pk, m, σ, $*$) exists in memory, then store (sig, sid, pk, m, σ, $\perp$).
   Regardless, update $\mathcal{Q} := \mathcal{Q} \cup \{\sigma\}$ in memory and increment ℓ_{sig} until $\{0,1\}^{\ell_{\text{sig}}} \setminus \mathcal{Q} \neq \emptyset$. Finally, return (verified, sid, pk, m, σ, b) to P.

Corruption.

7. Upon receiving (corrupt, sid, P) from $\mathcal{S}$, search the memory for all records of the form (key, sid, P, pk, sk, r_k), and for each such record compute the set $\mathcal{C}_{\text{pk}}$ of all (m, σ, r_σ) such that there exists a record of the form (sig, sid, pk, m, σ, r_σ) in memory. Return (corrupt, sid, P, $\mathcal{C}$) to $\mathcal{S}$, where $\mathcal{C}$ is a set containing (pk, sk, r_k, $\mathcal{C}_{\text{pk}}$) for every (key, sid, P, pk, sk, r_k) that was found.

[a] We assume that the amount of randomness that Gen, Sign, and Verify need is part of their description.
[b] P' may or may not be the same as P.

Plugging it into Dolev-Strong

- Requires care to handle other details (e.g., synchrony, parties learning the public keys of other parties)

- Resulting protocol is straightforward

  - Proof is in the PKI and signature hybrid model

Theorem 4.5. *The protocol* π_{DS} perfectly *UC-realizes* $\mathcal{W}_{\mathsf{DS}}(\mathcal{F}_{\mathsf{bc}})$ *in the* $(\mathcal{F}_{\mathsf{sig}}, \mathcal{F}_{\mathsf{pki}})$*-hybrid model against a (possibly unbounded) malicious adversary that can adaptively corrupt any set of parties.*

Summary of Results

- Introduce a new ideal functionality for signatures that can be realized by EUF-CMA* signatures and can’t be disabled by an adversary
- Give the first modular analysis of Dolev-Strong broadcast
- Future Works:
    - Can we simplify it?
    - Adding in other desirable properties such as sharing keys, unique signatures

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