Detecting MEV Vulnerabilities

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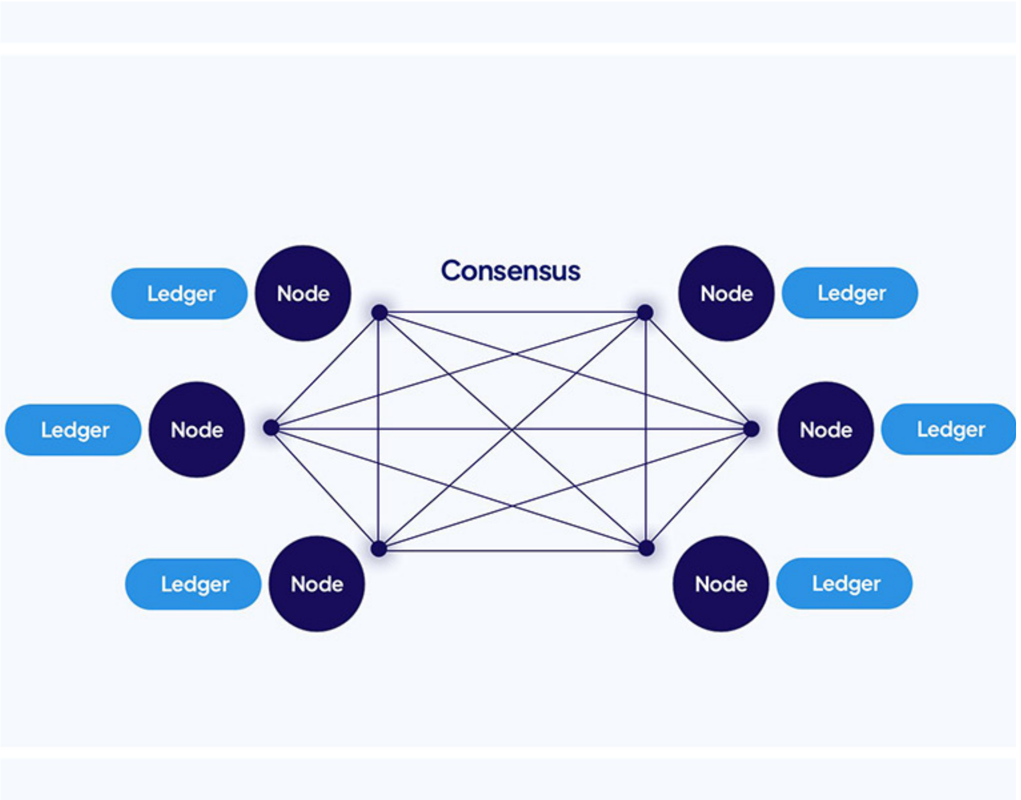
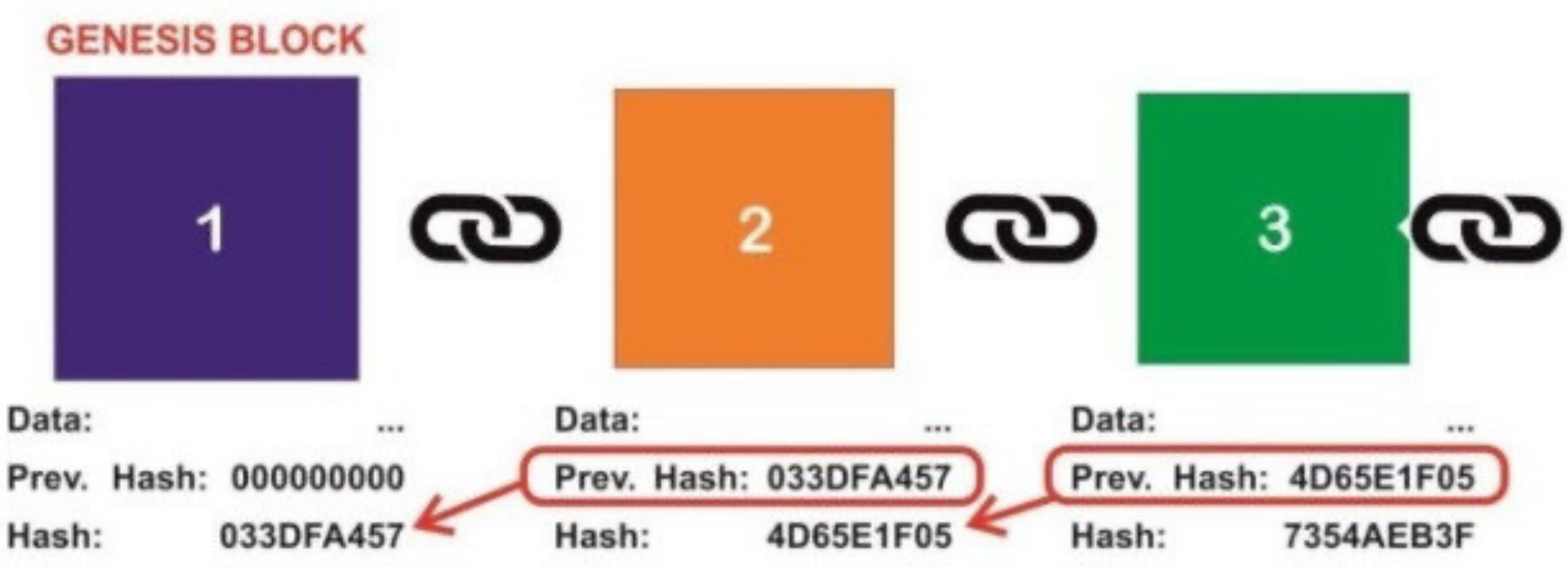
Distributed System: Blockchain



A digital database or ledger that is distributed among the nodes of a peer-to-peer network.

Distributed System: Blockchain



Blocks are cryptographically linked together. Blockchains are collection of blocks. A block is a collection of all the transactions with a cryptographic hash of the previous block.

Problematic

Maximal Extractable Value "MEV"

What is MEV ?

The Additional profit that participants in the blockchain ecosystem can extract through technically legitimate but potentially malicious actions.

Logic Reasoning to analyse malicious scenarios

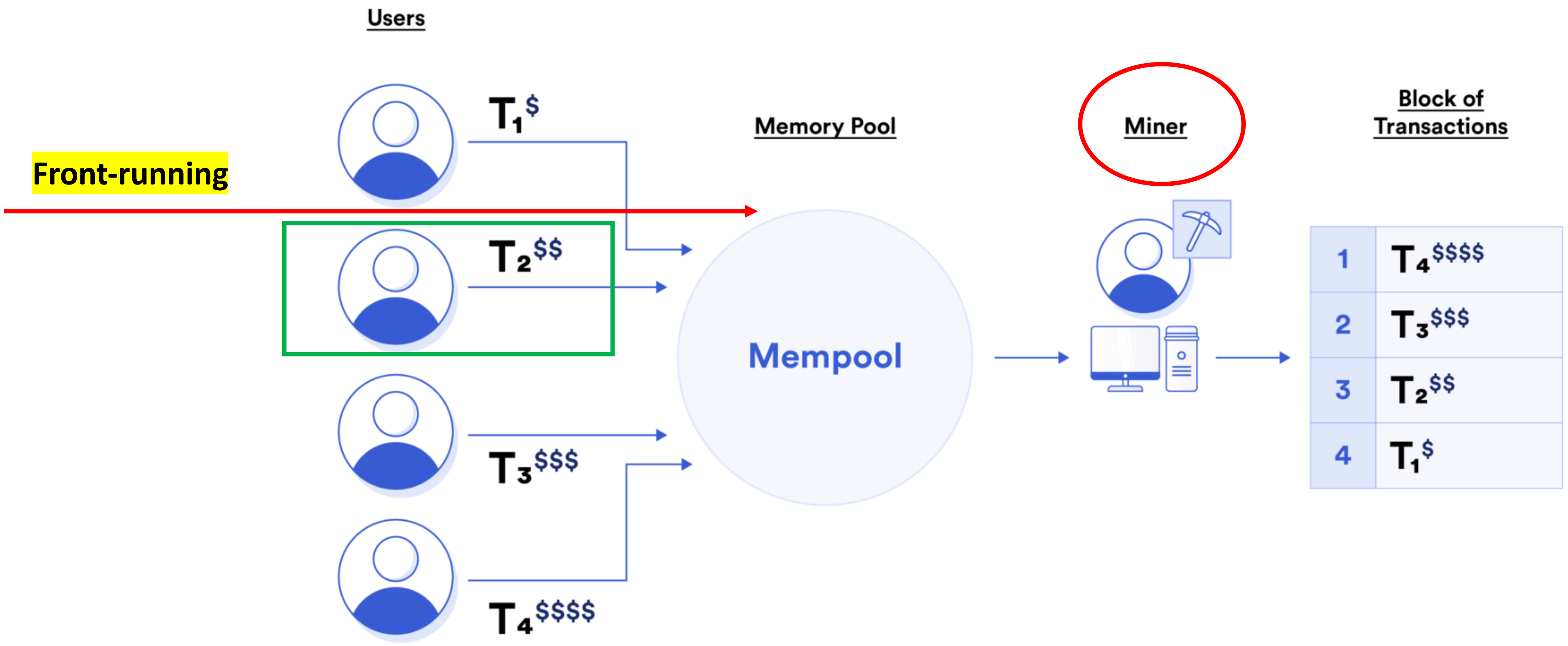
Formal Verification

- Ensuring integrity checks smart contracts to confirm they execute exactly as intended.

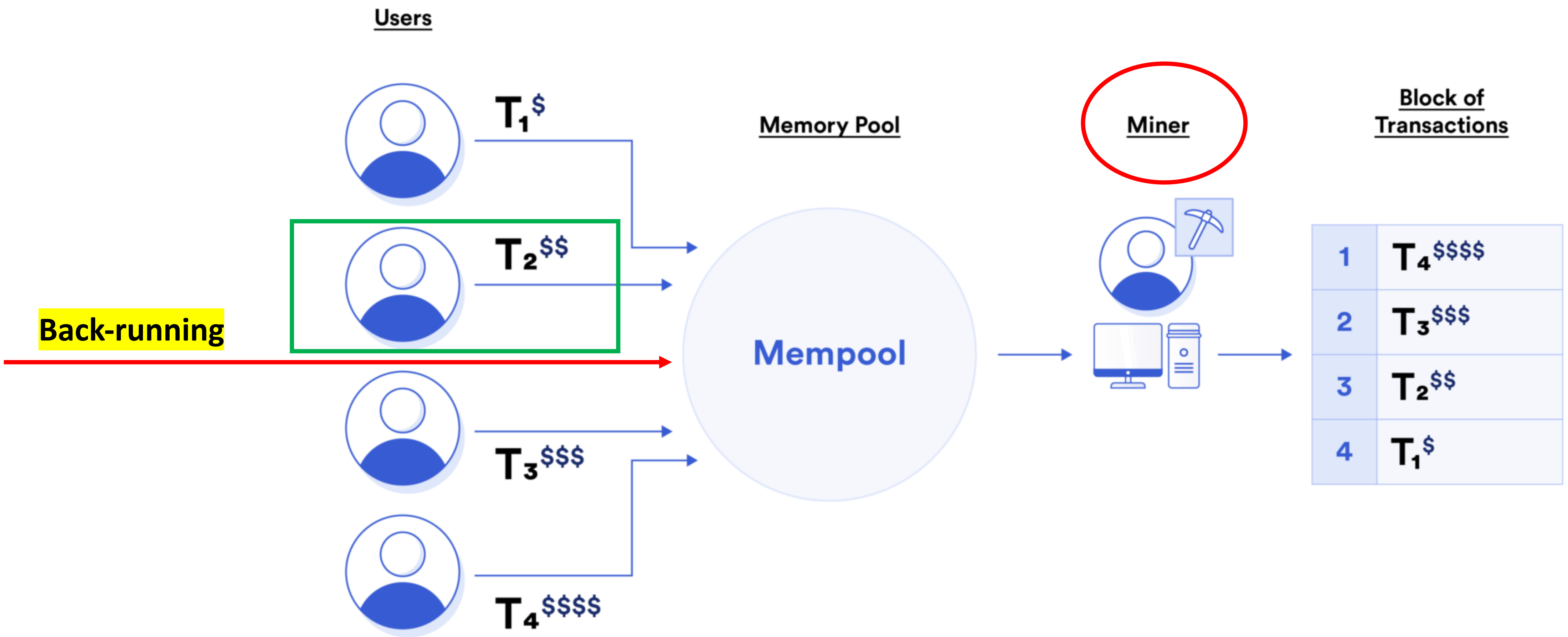
Model Checking

- Verifying Consistency: Model checking simulates all possible states of smart contracts and blockchain protocols to ensure they behave correctly.

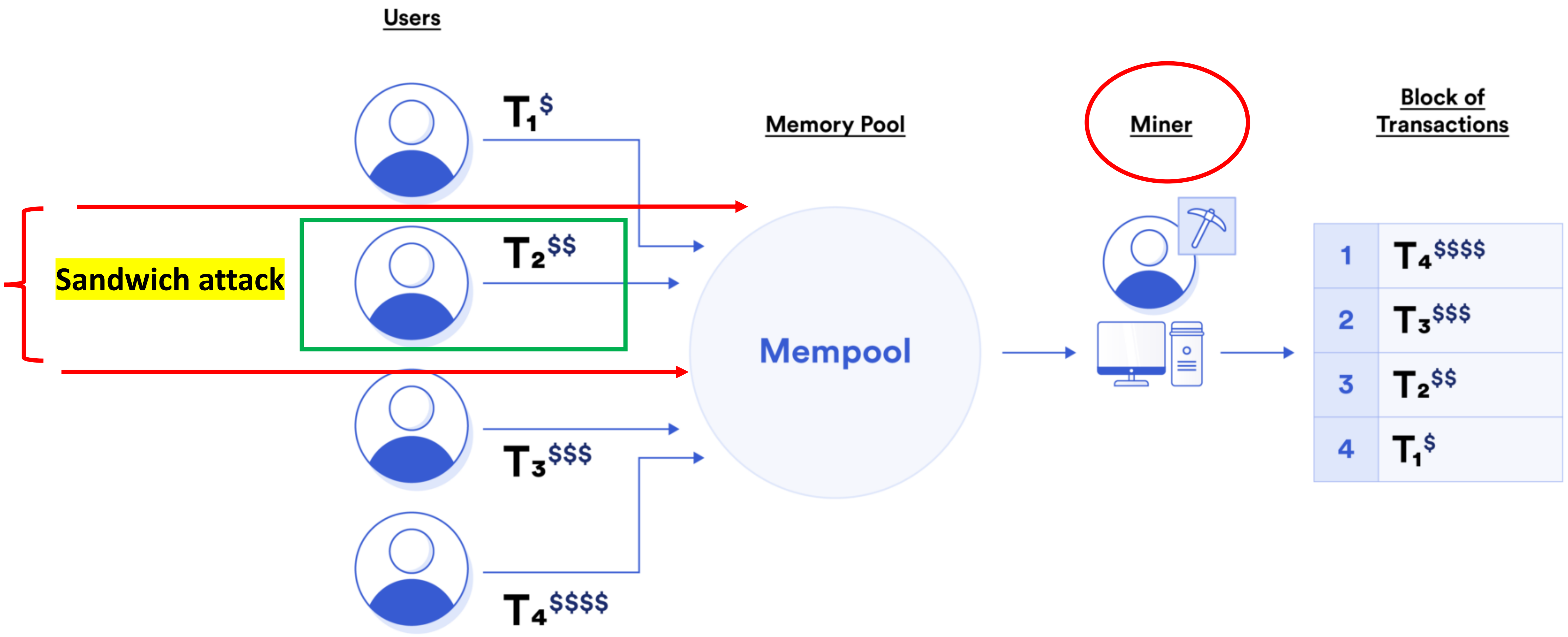
MEV Vulnerabilities



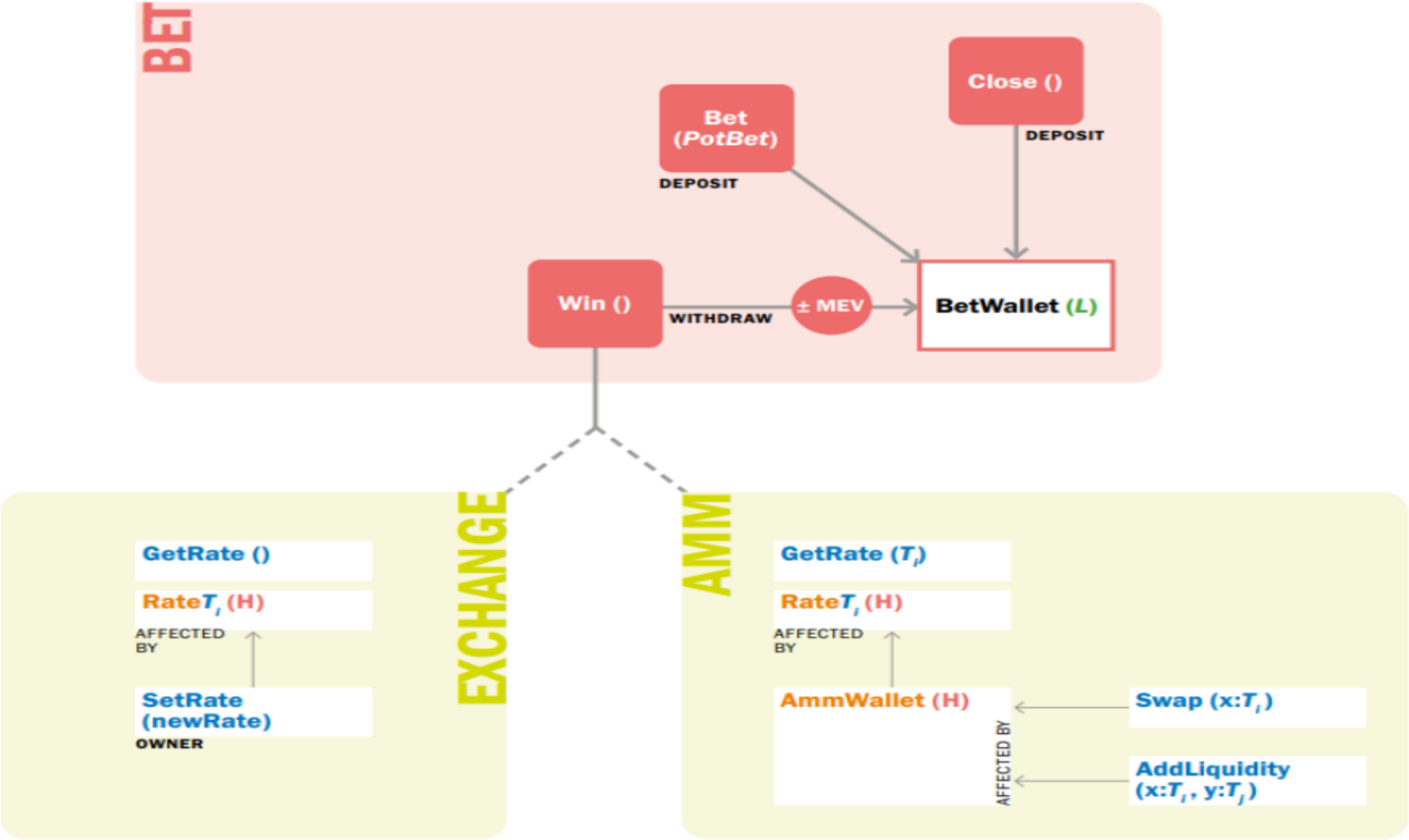
MEV Vulnerabilities



MEV Vulnerabilities

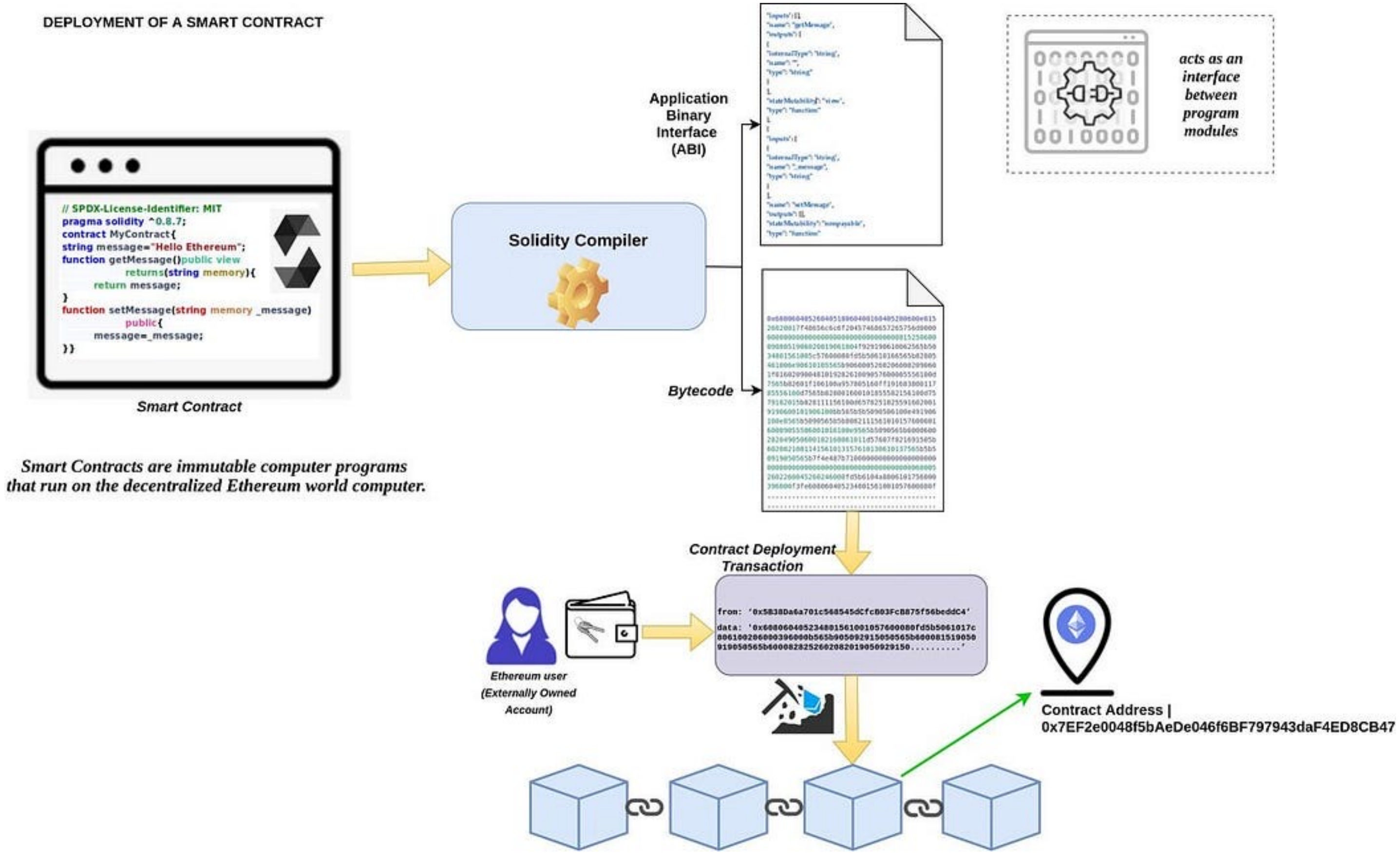


MEV Example: Bet Contract

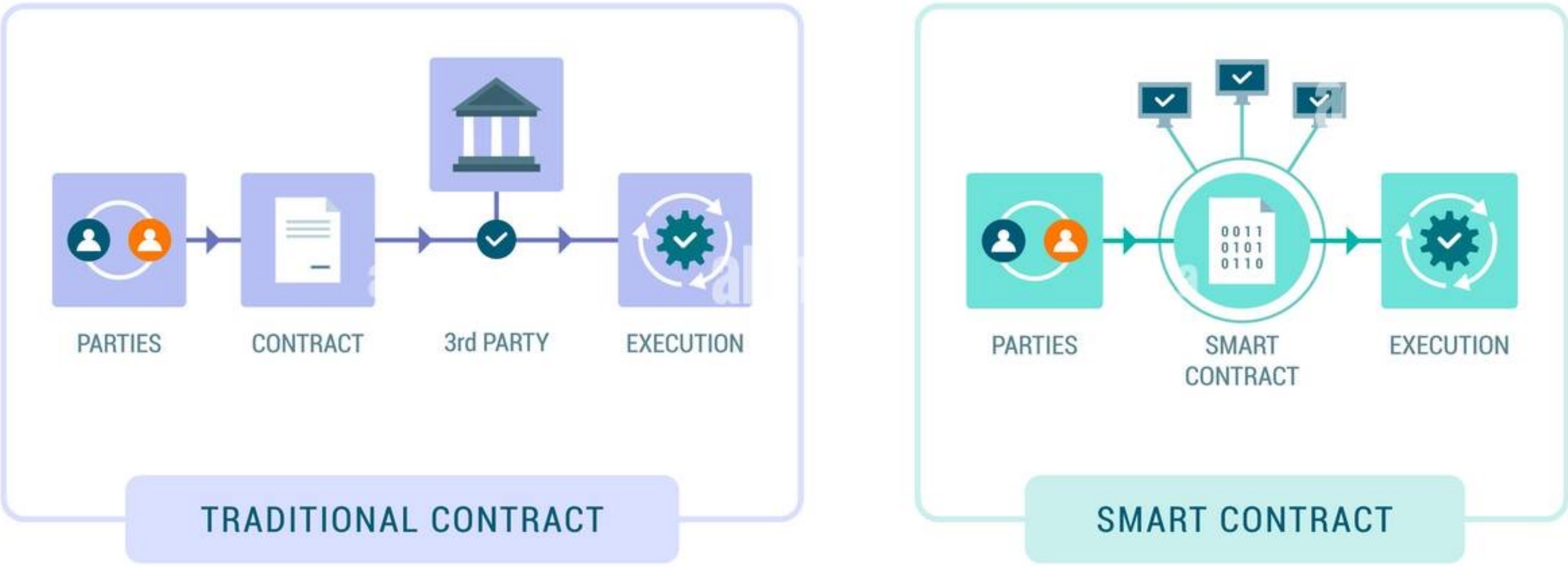



What are Smart Contracts?

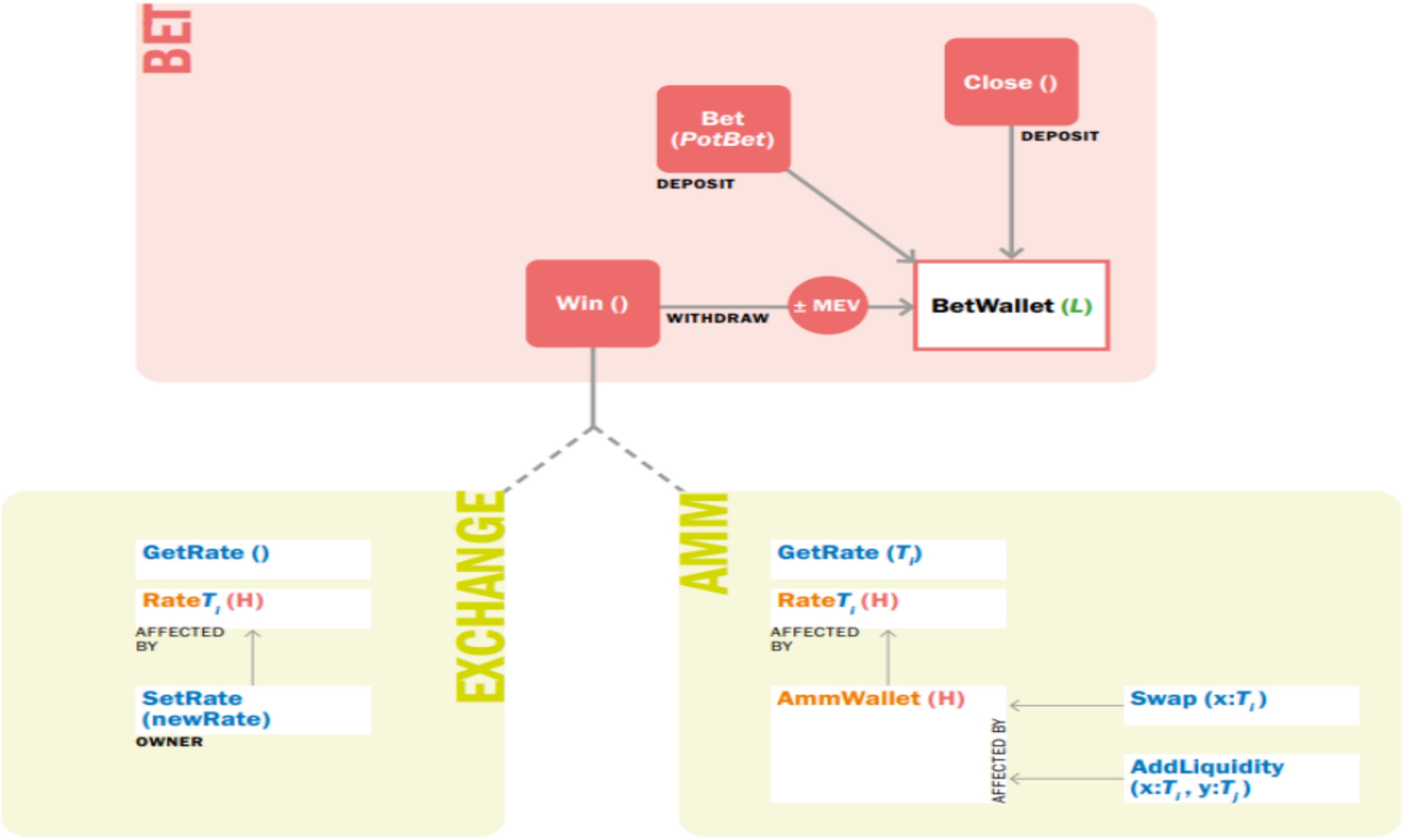
Smart contract



MEV Example: Bet Contract



MEV Example: Bet Contract



MEV Example: Bet Contract

Initial state:

Adversary Wallet

AMM wallet

AMM Exchange Rate (ETH) = $\frac{600}{600}$ = 1 (T)

$$S = \mathtt{M}[310:\mathtt{ETH}] \mid \mathtt{AMM}[600:\mathtt{ETH}, 600:\mathtt{T}] \mid \mathtt{block.num} = n - k \mid \cdots$$

$$\Delta = \mathtt{Bet}[10:\mathtt{ETH}, \mathtt{tok} = \mathtt{T}, \mathtt{rate} = 2, \mathtt{owner} = \mathtt{A}, \mathtt{deadline} = n]$$

Fixed Bet Rate = 2

Bet Wallet

MEV Example: Bet Contract

attack scenario

$$S \mid \Delta \xrightarrow{\texttt{M:Bet.bet}(?\,10:\texttt{ETH})} \texttt{M}[300:\texttt{ETH}] \mid \texttt{AMM}[600:\texttt{ETH}, 600:\texttt{T}] \mid \texttt{Bet}[20:\texttt{ETH}, \cdots]$$

$$\xrightarrow{\texttt{M:AMM.swap}(?\,300:\texttt{ETH},0)} \texttt{M}[200:\texttt{T}] \mid \texttt{AMM}[900:\texttt{ETH}, 400:\texttt{T}] \mid \texttt{Bet}[20:\texttt{ETH}, \cdots]$$

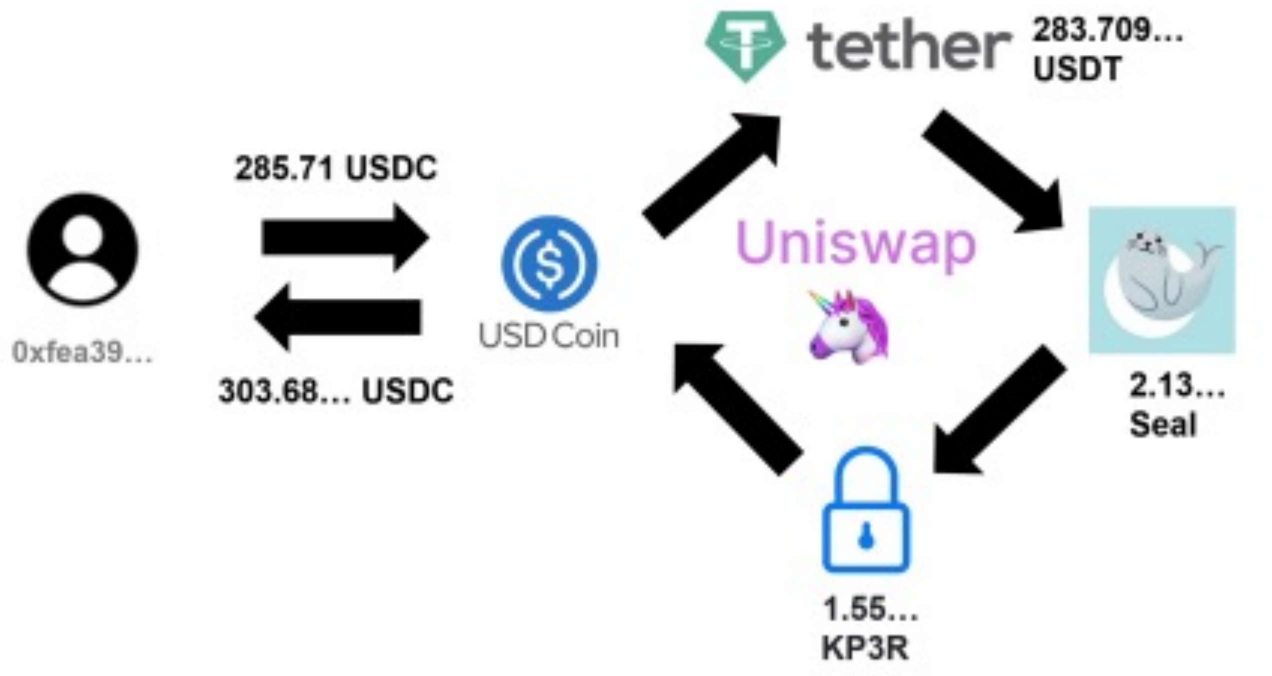
MEV :Front-running Transaction

AMM Exchange Rate (ETH) = $\frac{900}{400}$ > Fixed Bet Rate = 2

$$\xrightarrow{\texttt{M:Bet.win}()} \texttt{M}[20:\texttt{ETH}, 200:\texttt{T}] \mid \texttt{AMM}[900:\texttt{ETH}, 400:\texttt{T}] \mid \texttt{Bet}[0:\texttt{ETH}, \cdots]$$

$$\xrightarrow{\texttt{M:AMM.swap}(?\,200:\texttt{T},0)} \texttt{M}[320:\texttt{ETH}] \mid \texttt{AMM}[600:\texttt{ETH}, 600:\texttt{T}] \mid \texttt{Bet}[0:\texttt{ETH}, \cdots]$$

MEV Vulnerabilities



Cyclic Arbitrage in Decentralized Exchange Protocols

Our aim

Detect | Allocate | Analyze

Identify and mitigate MEV vulnerabilities within the instructions of smart contracts in the decentralized finance ecosystem.

⟶ Formal Verification methods

State of the art

Adversary perspective: Secure if the global MEV does not significantly increase.

Global MEV $MEV(S) = \max\left\{gain_{Adv}\,(S, \underline{X})\ \middle|\ \underline{X} \in K(Adv)^*\right\}$

Δ interacts safely with S $\leftrightarrow$ $MEV\ (S|\Delta) \leq (1+\varepsilon)\ MEV(S)$

$(\varepsilon - composability, see\ Clockwork\ Finance\ bt\ Babel, Daian, Kelkar, Juels)$

Contract perspective: Secure if being in a composition does not cause loss.

Local MEV $MEV(S, \Delta) = \max\left\{loss_{\Delta}\,(S, \underline{X})\ \middle|\ \underline{X} \in K(Adv)^*\right\}$

S does not interfere with the new contract Δ if: $MEV\ (S \mid \Delta, \Delta) = MEV_{\Delta}\ (S \mid \Delta, \Delta)$

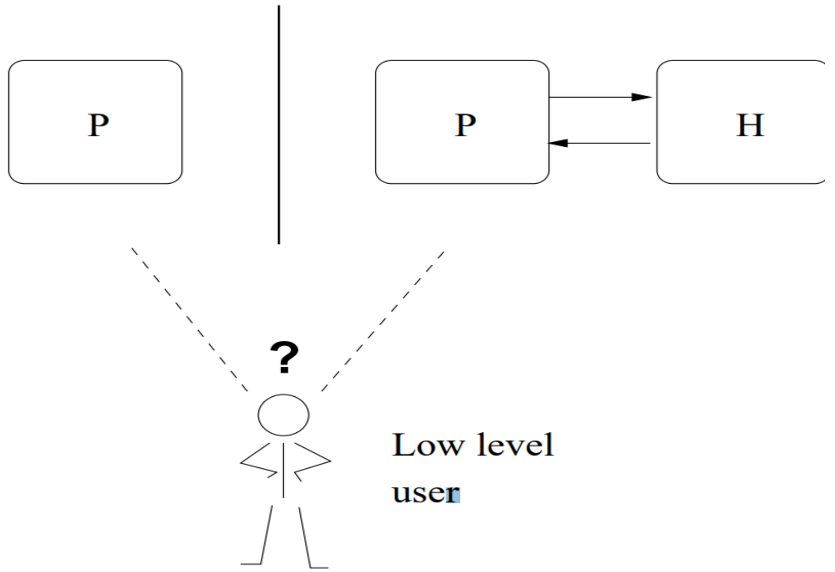
$(DeFi\ composability\ as\ MEV\ non-interference\ Bartoletti, Marchesin, Roberto\ )$

Noninterference

Noninterference aims to capture unwanted information flows in multi-level systems.

The notion of confidentiality: High and low levels.

A flow of information from high to low could represent the public disclosure of private data.



Generalized Unwinding Condition $\mathcal{W}(\doteq, \mathcal{R}, \div)$

Contract perspective in Computational framework:

- ✓ formalizing noninterference through unwinding conditions to analyze MEV.
- ✓ Guarantees that any reachable state resulting from high-level interactions still maintains indistinguishability with respect to low-level observations.

$$
\begin{array}{ccccc}
\langle F, \psi \rangle & \xrightarrow{\text{high}} & \langle G, \varphi \rangle & \rightsquigarrow & \langle \text{end}, \varphi' \rangle \\
\updownarrow & & & & \updownarrow \\
\pi =_l \psi & & & & \varphi' =_l \rho' \\
\updownarrow & & & & \updownarrow \\
\langle F, \pi \rangle & \rightsquigarrow & \cdots & \rightsquigarrow & \langle \text{end}, \rho' \rangle
\end{array}
$$

A pictorial representation of the unwinding condition

(Paper DLT2024: Noninterference Analysis for Smart Contracts: Would you Bet on it Samia G, Carla P, Sabina)

Information Flow

attack scenario: Interference from High level to Low level

$$S \mid \Delta \xrightarrow{\texttt{M:Bet.bet}(?\,10:\texttt{ETH})} \texttt{M}[300:\texttt{ETH}] \mid \texttt{AMM}[600:\texttt{ETH}, 600:\texttt{T}] \mid \texttt{Bet}[20:\texttt{ETH}, \cdots]$$

$$\xrightarrow{\texttt{M:AMM.swap}(?\,300:\texttt{ETH},0)} \texttt{M}[200:\texttt{T}] \mid \texttt{AMM}[900:\texttt{ETH}, 400:\texttt{T}] \mid \texttt{Bet}[20:\texttt{ETH}, \cdots]$$

$$\xrightarrow{\texttt{M:Bet.win}()} \texttt{M}[20:\texttt{ETH}, 200:\texttt{T}] \mid \texttt{AMM}[900:\texttt{ETH}, 400:\texttt{T}] \mid \texttt{Bet}[0:\texttt{ETH}, \cdots]$$

$$\xrightarrow{\texttt{M:AMM.swap}(?\,200:\texttt{T},0)} \texttt{M}[320:\texttt{ETH}] \mid \texttt{AMM}[600:\texttt{ETH}, 600:\texttt{T}] \mid \texttt{Bet}[0:\texttt{ETH}, \cdots]$$

HIGH level action

LOW level variable

LOW level action

HIGH level variable

Operational Semantics: Concurrent Imperative Language

```
Program Bet
    while (Deadline > BlockNum) do
        await (Player = 'NULL' ∧ PotBet ≠0 ) do
            skip
        if (PotBet = BetWallet) then
            Player := SenderBet;
            PlayerWalletEther := PlayerWalletEther − PotBet;
            BetWallet := BetWallet + PotBet
        else
            PotBet := 0;
            SenderBet := 0
```

```
Program Win
    while (Deadline > BlockNum) do
        await ( SenderWin = Player ) do
            skip
        if (BetRate < AmmRateEther) then
            PlayerWalletEther := PlayerWalletEther + BetWallet;
            BetWallet := 0
        else
            SenderWin := 'NULL'
```

Operational Semantics: Concurrent Imperative Language

```
Program Swap
    while true do
        await (AmountToSwap ≠0 ∧ TokenToSwap ≠'NULL' ) do
            skip
        K := AmmWalletT1 * AmmWalletT2
        if (TokenToSwap = 'T1') then
            Y := AmountToSwap * AmmRateT2;
            if (Y < AmmWalletT2) then
                AmmWalletT1 := AmmWalletT1 + AmountToSwap;
                AmmWalletT2 := K / AmmWalletT1;
                ZeroAMM
            else
                ZeroAMM
        else if (TokenToSwap = 'T2' ) then
            Y := AmountToSwap * AmmRateT1;
            if (Y < AmmWalletT1) then
                AmmWalletT2 := AmmWalletT2 + AmountToSwap;
                AmmWalletT1 := K / AmmWalletT2;
                ZeroAMM
            else
                ZeroAMM
```

```
Program GetRate
    while true do
        await ( T ≠'NULL') do
            skip
        if (T = 'T1') then
            AmmRateT1 := AmmWalletT1 / AmmWalletT2;
            T := 'NULL'
        else if (T = 'T2') then
            AmmRateT2 := AmmWalletT2 / AmmWalletT1;
            T := 'NULL'
        else
            T := 'NULL'
```

Operational Semantics: Concurrent Imperative Language

- Bet Contract $\notin \mathcal{W}(\doteq, \mathcal{R}, \doteqdot)$

$Bet\ \&\ Amm \equiv \boldsymbol{co}\ Bet\_Contract \mid Amm\_Contract\ \boldsymbol{oc}$

$$\langle Bet\ \&\ Amm, \sigma \rangle$$

$$\downarrow$$

$$\ldots\ \%\ execution\ of\ Swap$$ **(HIGH level action)**

$$\downarrow$$

$$\langle Bet\&Amm', \sigma\ [AmmWalletEther/900, AmmWalletT2/400] \rangle$$

$$\downarrow$$

$$\ldots\ \%\ execution\ of\ GateRate$$

$$\downarrow$$

$$\langle Bet, \sigma\ [AmmWalletEther/900, AmmWalletT2/400, AmmRateEther/2.25] \rangle$$

$$\downarrow$$

$$\ldots\ \%\ execution\ of\ Win$$ **(LOW level action)**

$$\downarrow$$

$$\langle end, \sigma\ [AmmWalletEther/900, AmmWalletT2/400, AmmRateEther/2.25, BetWallet/\mathbf{0}] \rangle$$

$$\langle Bet\ \&\ Amm, \sigma \rangle$$

$$\downarrow$$

$$\ldots\ \%\ execution\ of\ Win$$ **(LOW level action)**

$$\downarrow$$

$$\langle Amm, \sigma\ [SenderWin/\text{'}NULL\text{'}\rangle$$

$$\downarrow$$

$$\ldots\ \%\ execution\ of\ GateRate$$

$$\downarrow$$

$$\langle end, \sigma\ [SenderWin/\text{'}NULL\text{'}, AmmWalletEther/600, AmmWalletT2/600, BetWallet/\mathbf{10}]\rangle$$

- ✓ Identify the precise instructions and variables within the code that could potentially lead to information flows.
- ✓ Identify the specific dependencies of the contract that require deeper analysis.

Future Work

✓ Conducting in-depth investigations into the relationships between unwinding conditions and MEV and applying this method to analyze other case studies involving MEV attacks.

✓ Define this framework on fragments of languages for smart contracts, such as solidity.

✓ Model blockchain problem using program logic

✓ Machine Learning for MEV vulnerability detection in Ethereum smart contracts

Unwinding conditions for security in imperative languages

$$\frac{}{\langle \mathtt{skip}, \sigma\rangle \xrightarrow{\text{low}} \langle \text{end}, \sigma\rangle}$$

$$\frac{\langle a, \sigma\rangle \to n}{\langle X := a, \sigma\rangle \xrightarrow{\epsilon} \langle \text{end}, \sigma[X/n]\rangle}\ a \in \epsilon$$

$$\frac{\langle P_0, \sigma\rangle \xrightarrow{\epsilon} \langle P_0', \sigma'\rangle}{\langle P_0; P_1, \sigma\rangle \xrightarrow{\epsilon} \langle P_0'; P_1, \sigma'\rangle}\ P_0' \not\equiv \text{end}$$

$$\frac{\langle P_0, \sigma\rangle \xrightarrow{\epsilon} \langle \text{end}, \sigma'\rangle}{\langle P_0; P_1, \sigma\rangle \xrightarrow{\epsilon} \langle P_1, \sigma'\rangle}$$

$$\frac{\langle b, \sigma\rangle \to \text{true}}{\langle \mathtt{if}(b)\,\{P_0\}\ \mathtt{else}\ \{P_1\}, \sigma\rangle \xrightarrow{\epsilon} \langle P_0, \sigma\rangle}\ b \in \epsilon$$

$$\frac{\langle b, \sigma\rangle \to \text{false}}{\langle \mathtt{if}(b)\,\{P_0\}\ \mathtt{else}\ \{P_1\}, \sigma\rangle \xrightarrow{\epsilon} \langle P_1, \sigma\rangle}\ b \in \epsilon$$

$$\frac{\langle b, \sigma\rangle \to \text{true}}{\langle \mathtt{while}(b)\,\{P\}, \sigma\rangle \xrightarrow{\epsilon} \langle P; \mathtt{while}(b)\,\{P\}, \sigma\rangle}\ b \in \epsilon$$

$$\frac{\langle b, \sigma\rangle \to \text{false}}{\langle \mathtt{while}(b)\,\{P\}, \sigma\rangle \xrightarrow{\epsilon} \langle \text{end}, \sigma\rangle}\ b \in \epsilon$$

$$\frac{\langle b, \sigma\rangle \to \text{true} \qquad \langle S, \sigma\rangle \overset{\epsilon_2}{\rightsquigarrow} \langle \text{end}, \sigma'\rangle}{\langle \mathtt{await}(b)\,\{S\}, \sigma\rangle \xrightarrow{\epsilon_1 \cup \epsilon_2} \langle \text{end}, \sigma'\rangle}\ b \in \epsilon_1$$

$$\frac{\langle b, \sigma\rangle \to \text{false}}{\langle \mathtt{await}(b)\,\{S\}, \sigma\rangle \xrightarrow{\epsilon} \langle \mathtt{await}(b)\,\{S\}, \sigma\rangle}\ b \in \epsilon$$

$$\frac{\langle P_i, \sigma\rangle \xrightarrow{\epsilon} \langle P_i', \sigma'\rangle}{\langle \text{co } P_1 | \ldots | P_i | \ldots | P_n \text{ oc}, \sigma\rangle \xrightarrow{\epsilon} \langle \text{co } P_1 | \ldots | P_i' | \ldots | P_n \text{ oc}, \sigma'\rangle}$$

$$\frac{}{\langle \text{co end} | \ldots | \text{end} | \ldots | \text{end oc}, \sigma\rangle \xrightarrow{\text{low}} \langle \text{end}, \sigma\rangle}$$

$(Compositional\ Information\ Flow\ Security\ for\ Concurrent\ Programs\ Annalisa, Carla, Sabina,)$

THANKS FOR THE ATTENTION.

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