

## Day 4: Programmable Finance

Smart Contracts, DeFi, and Tokenization

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Digital Finance Course

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## Day Purpose

This is where crypto meets finance. Learn how smart contracts enable DeFi protocols that replicate (and sometimes improve upon) traditional financial services without intermediaries.

## 4.1 Smart Contracts – Code as Agreement

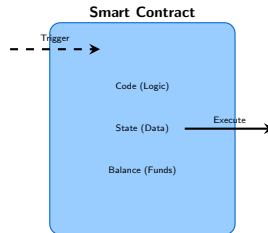
# What is a Smart Contract?

## Definition

A **smart contract** is a program stored on a blockchain that automatically executes when predetermined conditions are met.

## Key Properties:

- **Deterministic:** Same input always produces same output
- **Immutable:** Once deployed, code cannot be changed
- **Transparent:** Anyone can verify the code
- **Self-executing:** No intermediary needed

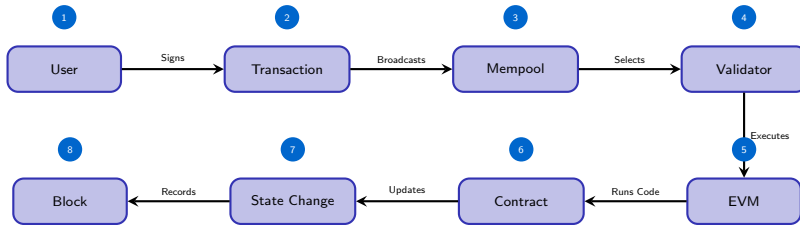


Aspect	Traditional Contract	Smart Contract
Enforcement	Courts, lawyers	Code execution
Trust	Counterparties, institutions	Cryptographic verification
Execution	Manual, subject to delay	Automatic, instant
Amendment	Negotiation, paperwork	Requires new deployment
Cost	High (intermediaries)	Low (gas fees only)
Transparency	Private documents	Public, auditable code

### Important Distinction

“Trustless” means you don’t need to trust *counterparties*—but you still need to trust the *code*, the *blockchain*, and the *oracles*.

# Smart Contract Execution Flow



1. User creates and signs transaction calling contract function
2. Transaction broadcast to network
3. Transaction waits in mempool
4. Validator selects transaction for block
5. Ethereum Virtual Machine (EVM) executes bytecode
6. Contract logic runs with provided inputs
7. State changes recorded (balances, storage)
8. Changes finalized in blockchain block

# Anatomy of a Smart Contract (Solidity)

```
1 // SPDX-License-Identifier: MIT
2 pragma solidity ^0.8.0;
3
4 contract SimpleEscrow {
5     address public buyer;
6     address public seller;
7     uint256 public amount;
8     bool public released;
9
10    constructor(address _seller) payable {
11        buyer = msg.sender;
12        seller = _seller;
13        amount = msg.value;
14    }
15
16    function release() external {
17        require(msg.sender == buyer, "Only buyer can release");
18        require(!released, "Already released");
19        released = true;
20        payable(seller).transfer(amount);
21    }
22 }
```

**Hands-on: NB08 – Interact with smart contracts on testnet**

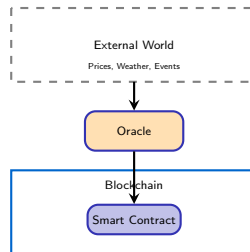


## The Challenge

Smart contracts cannot access external data—they only know what's on the blockchain.

### Examples requiring oracles:

- Price feeds (ETH/USD)
- Weather data for insurance
- Sports scores for betting
- Real-world asset values



### Solutions:

- Chainlink (decentralized)
- API3, Band Protocol
- Optimistic oracles (UMA)

## Technical Risks:

- **Bugs:** Code is immutable—bugs are forever
- **Reentrancy:** The DAO hack (\$60M, 2016)
- **Integer overflow:** Pre-0.8 Solidity
- **Oracle manipulation:** Flash loan attacks
- **Front-running:** MEV extraction

## Gas Considerations:

- Every operation costs gas
- Complex logic = expensive
- Storage is most expensive
- Out-of-gas reverts transaction

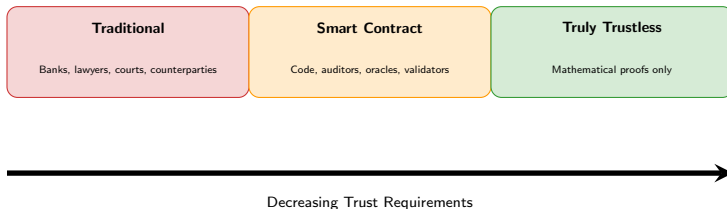
## Design Limitations:

- Cannot handle ambiguity
- No subjective judgments
- Cannot initiate actions
- Limited to on-chain data

## The Immutability Paradox

Immutability provides security guarantees but makes bug fixes impossible. Solutions: proxy patterns, upgradeable contracts—but these reintroduce trust assumptions.

## Trust Spectrum



### Key Insight

Smart contracts shift trust from *institutions* to *code and cryptography*. This is valuable—but it's a different kind of trust, not the absence of trust.

### You should be able to:

1. Explain how a smart contract executes on a blockchain
2. Define what “trustless” means (and doesn’t mean)
3. Identify key limitations: oracle problem, immutability risks
4. Read and understand the logic of a simple contract

Hands-on: NB08

**NB08:** Interact with a simple smart contract (token or escrow) on testnet—call functions and observe state changes.

## 4.2 DeFi Primitives – Lending, Trading, and Yield

## Definition

**Decentralized Finance (DeFi)** refers to financial services built on public blockchains that operate without traditional intermediaries.

## Core Principles:

- **Permissionless:** Anyone can participate
- **Non-custodial:** Users control their assets
- **Transparent:** All code and transactions public
- **Composable:** Protocols can be combined

## DeFi Ecosystem (2024):

- Total Value Locked: \$50B+
- Daily trading volume: \$2B+
- Active protocols: 500+
- Supported chains: 50+

## Major Categories:

- Decentralized Exchanges
- Lending Protocols
- Derivatives
- Yield Aggregators

Feature	Traditional Finance	DeFi
Access	KYC, credit checks	Wallet address only
Hours	Business hours, T+2 settlement	24/7/365, instant
Custody	Institutions hold assets	User self-custody
Transparency	Private ledgers	Public blockchain
Innovation	Regulatory approval needed	Permissionless deployment
Risk	Counterparty, institution	Smart contract, oracle

### The Composability Advantage

DeFi protocols are like “money legos”—they can be combined in ways their creators never anticipated. A flash loan can be used in an arbitrage that spans 5 different protocols in a single transaction.

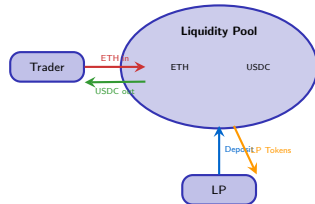
## Traditional Exchange:

- Order book with bids/asks
- Market makers provide liquidity
- Requires active management
- Centralized matching engine

## AMM Innovation:

- No order book needed
- Liquidity pools replace market makers
- Algorithmic pricing
- Anyone can provide liquidity

**Key Protocols:** Uniswap, SushiSwap, Curve, Balancer





# Constant Product Formula: $x \cdot y = k$

## The Core Equation

$$x \cdot y = k$$

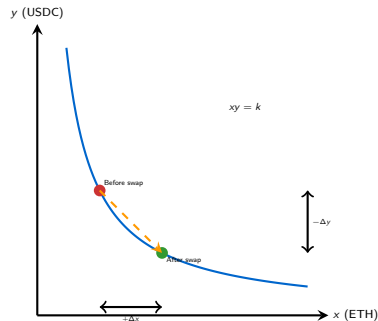
- $x$  = Token A reserves
- $y$  = Token B reserves
- $k$  = Constant (invariant)

## Price Determination:

$$\text{Price of A in B} = \frac{y}{x}$$

## After swap of $\Delta x$ :

$$\Delta y = y - \frac{k}{x + \Delta x}$$



## Price Impact

Larger trades move further along the curve, resulting in worse prices. This is called **slippage** or **price impact**.

## Initial Pool State

- 100 ETH + 300,000 USDC
- $k = 100 \times 300,000 = 30,000,000$
- Price: 1 ETH = 3,000 USDC

## Trader swaps 10 ETH for USDC:

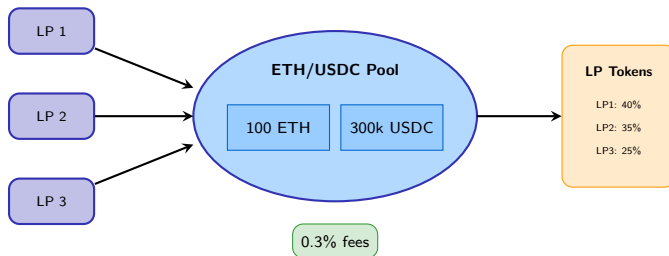
$$\text{New ETH reserves: } x' = 100 + 10 = 110$$

$$\text{New USDC reserves: } y' = \frac{30,000,000}{110} = 272,727.27$$

$$\text{USDC received: } \Delta y = 300,000 - 272,727.27 = 27,272.73$$

## Price Impact Analysis

- Expected (no impact):  $10 \times 3,000 = 30,000$  USDC
- Actual received: 27,272.73 USDC
- Slippage:  $\frac{30,000 - 27,272.73}{30,000} = 9.09\%$
- New price:  $\frac{272,727.27}{110} = 2,479.34$  USDC/ETH



## LP Token Mechanics:

- LP tokens represent proportional claim on pool reserves
- Fees accumulate in pool, increasing LP token value
- Withdrawal returns proportional share of *current* reserves

## Definition

**Impermanent Loss (IL)** is the difference between holding assets in a liquidity pool vs. simply holding them in your wallet.

### Why it happens:

1. You deposit equal value: 1 ETH (\$3,000) + 3,000 USDC
2. ETH price doubles to \$6,000
3. Arbitrageurs rebalance the pool
4. Your LP position: 0.707 ETH + 4,243 USDC = \$8,485
5. If you had just held: 1 ETH + 3,000 USDC = \$9,000
6. **Impermanent Loss: \$515 (5.72%)**

## Key Insight

Loss is “impermanent” because if prices return to original levels, the loss disappears. It becomes *permanent* when you withdraw at different prices.

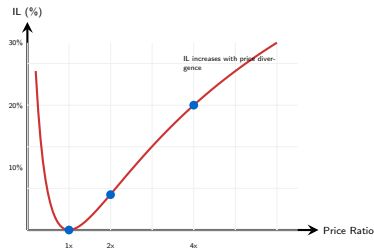
# Impermanent Loss Formula and Visualization

## IL Formula:

$$IL = \frac{2\sqrt{r}}{1+r} - 1$$

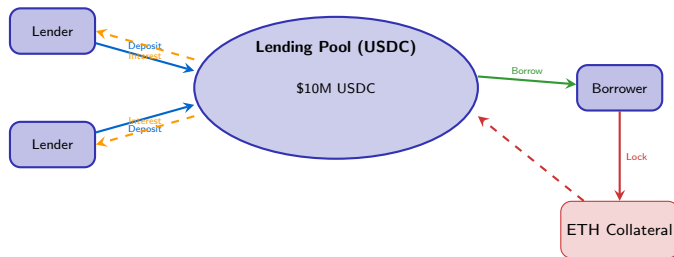
where  $r = \frac{P_1}{P_0}$  (price ratio)

Price Change	IL
1.25x (25% up)	0.6%
1.50x (50% up)	2.0%
2x (100% up)	5.7%
3x (200% up)	13.4%
4x (300% up)	20.0%
5x (400% up)	25.5%



## Mitigating IL:

- Provide liquidity to correlated pairs (stablecoin-stablecoin)
- Choose pools with high trading volume (fees offset IL)
- Use concentrated liquidity (Uniswap V3)



## Key Mechanics:

- **Over-collateralization:** Borrow \$1,000 requires \$1,500+ collateral
- **Algorithmic rates:** Interest adjusts with utilization
- **Liquidation:** If collateral falls below threshold, anyone can liquidate

## Utilization Rate:

$$U = \frac{\text{Borrowed}}{\text{Supplied}}$$

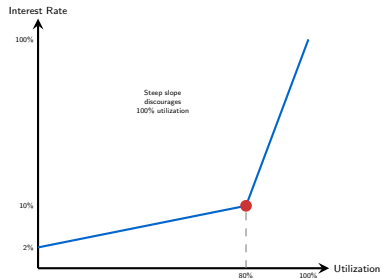
## Borrow Rate (kinked model):

$$R_{\text{borrow}} = \begin{cases} R_0 + U \cdot R_{\text{slope1}} & U < U_{\text{optimal}} \\ R_0 + U_{\text{opt}} \cdot R_1 + (U - U_{\text{opt}}) \cdot R_2 & U \geq U_{\text{optimal}} \end{cases}$$

## Supply Rate:

$$R_{\text{supply}} = R_{\text{borrow}} \times U \times (1 - \text{fee})$$

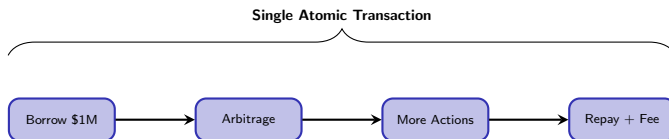
**Key Protocols:** Aave, Compound, MakerDAO



**Hands-on:** NB09 – Simulate AMM and observe impermanent loss

## Definition

A **flash loan** is an uncollateralized loan that must be borrowed and repaid within a single transaction.



**Legitimate Uses:** Arbitrage, collateral swaps, self-liquidation

**Attack Uses:** Oracle manipulation, governance attacks, protocol exploits

## The Double-Edged Sword

Flash loans democratize access to capital but have enabled over \$500M in DeFi exploits.



You should be able to:

1. Explain how an AMM prices assets using  $x \cdot y = k$
2. Calculate price impact/slippage for a given trade
3. Understand how DeFi lending determines interest rates algorithmically
4. Calculate impermanent loss for price changes

Hands-on: NB09

**NB09:** Simulate a constant-product AMM—provide liquidity, execute swaps, observe price impact and impermanent loss.

## 4.3 Stablecoins – The Bridge Between Two Worlds

## Definition

**Stablecoins** are cryptocurrencies designed to maintain a stable value relative to a reference asset (typically USD).

## The Problem They Solve:

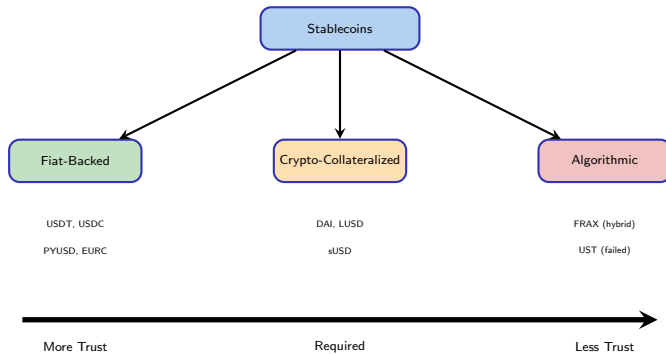
- Crypto volatility makes it unsuitable for payments
- Traditional banking hours and fees
- Need for on-chain “cash” in DeFi
- Cross-border payment friction

## Market Size (2024):

- Total supply: \$170B+
- Daily volume: \$50B+
- Surpasses Visa in some metrics

## Use Cases:

- Trading pairs on exchanges
- DeFi collateral and lending
- Remittances
- Savings in dollarized economies

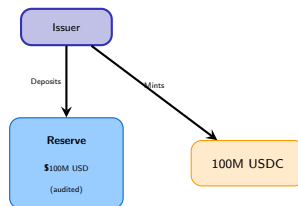


## How It Works:

1. User sends \$1 to issuer
2. Issuer holds \$1 in reserves
3. Issuer mints 1 stablecoin
4. User can redeem anytime

## Examples:

- **USDT** (Tether): \$110B, largest
- **USDC** (Circle): \$35B, regulated
- **PYUSD** (PayPal): Newest entrant

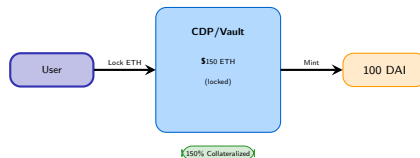


## Risks:

- Centralized—can freeze funds
- Reserve quality concerns
- Regulatory uncertainty
- Banking system dependence

## How It Works:

1. User deposits \$150 ETH
2. Protocol mints 100 DAI
3. Collateral ratio: 150%
4. If ETH drops, liquidation



## MakerDAO/DAI:

- Decentralized governance
- Multiple collateral types
- Stability fee (interest)
- Liquidation at 150%

## Advantages:

- Decentralized
- Transparent reserves
- No counterparty risk

## Disadvantages:

- Capital inefficient
- Liquidation risk
- Complexity

## Pure Algorithmic (Failed):

- No collateral backing
- Dual-token: stable + governance
- Expand supply when above peg
- Contract supply when below peg

## The Death Spiral:

1. Price drops below peg
2. Redemptions spike
3. Confidence collapses
4. Governance token crashes
5. System becomes insolvent

## Case Study: UST/LUNA (May 2022)

- Peak market cap: \$18B
- Collapsed in 72 hours
- \$60B total value destroyed
- Triggered crypto contagion

## Hybrid Models (Surviving):

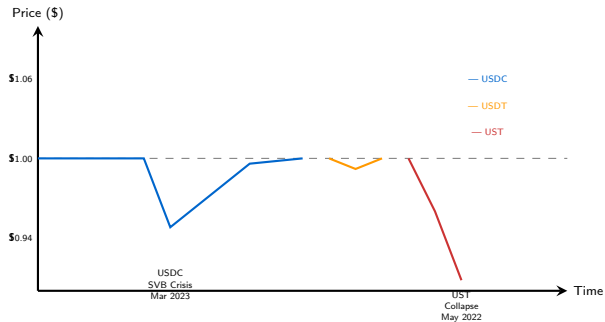
- **FRAX**: Partially collateralized
- Dynamic collateral ratio
- More resilient to de-peg

Attribute	Fiat-Backed	Crypto-Collateral	Algorithmic
Collateral	Fiat in bank	Crypto (150%+)	None/Partial
Centralization	High	Medium	Low
Capital Efficiency	High (1:1)	Low (over-collateral)	High (0 collateral)
Scalability	Limited by reserves	Limited by collateral	Theoretically unlimited
Peg Stability	Strong	Strong	Weak
Regulatory Risk	High	Medium	Low
Censorship Risk	High	Low	Very Low

## The Stablecoin Trilemma

You can optimize for two of three: **Decentralization, Stability, Capital Efficiency**





## Key Lessons:

- Fiat-backed: Banking system dependencies (SVB, Silvergate)
- Algorithmic: Fundamental design flaws lead to death spirals
- All designs: Confidence is fragile and self-reinforcing

## Why Regulators Care:

- Systemic risk (too big to fail?)
- Consumer protection
- Money laundering concerns
- Monetary policy implications
- Bank-like activities

## Regulatory Developments:

- EU: MiCA framework (2024)
- US: Congressional debate ongoing
- Singapore: Clear framework
- China: Banned

## Key Requirements Emerging

- 1:1 reserve backing
- Regular audits/attestations
- Redemption guarantees
- Segregated reserves
- Licensing requirements

## Impact on Market:

- USDC: Embracing regulation
- USDT: Offshore strategy
- DAI: Decentralization defense

You should be able to:

1. Classify stablecoins by design type (fiat-backed, crypto-collateralized, algorithmic)
2. Explain the tradeoffs of each design approach
3. Assess de-peg risk factors for different stablecoins
4. Articulate why stablecoins face heavy regulatory scrutiny

Hands-on: NB10

**NB10:** Analyze stablecoin price stability data—examine de-peg events and compare resilience across designs.

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**Hands-on: NB10 – Stablecoin price stability analysis**

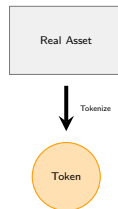
## 4.4 Tokenization and CBDCs

## Definition

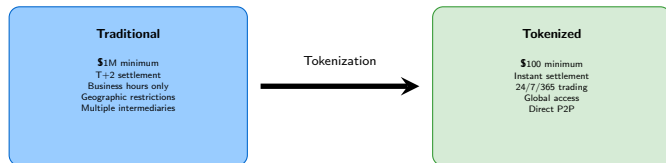
**Tokenization** is the process of creating a digital representation of a real-world asset on a blockchain.

## What Can Be Tokenized:

- Real estate
- Securities (stocks, bonds)
- Commodities (gold, oil)
- Art and collectibles
- Intellectual property
- Carbon credits



- ✓ Fractional ownership
- ✓ 24/7 trading
- ✓ Instant settlement
- ✓ Global access



## Market Size Projections:

- Boston Consulting Group: \$16 trillion by 2030
- BlackRock, JP Morgan actively building infrastructure
- US Treasuries on-chain: \$1B+ (2024)

Asset Class	Example	Platform	Value Proposition
Real Estate	Tokenized apartments	RealT, Lofty	Fractional ownership, rental income
US Treasuries	T-bills on-chain	Ondo, Franklin Templeton	DeFi-compatible yield
Private Credit	Corporate loans	Centrifuge, Goldfinch	Access to institutional yields
Commodities	Gold tokens	Paxos Gold (PAXG)	Redeemable for physical
Art	Fractionalized art	Masterworks	Access to blue-chip art

## The Legal Challenge

Tokens represent claims on assets, but enforcement still requires legal systems. “Code is law” doesn’t apply when real-world assets need real-world courts.

## Definition

A **CBDC** is a digital form of central bank money, denominated in the national unit of account and a direct liability of the central bank.

## Global Status (2024):

- 130+ countries exploring
- 3 fully launched (Bahamas, Nigeria, Jamaica)
- 20+ in pilot phase
- Major economies in research

## Two Main Types:

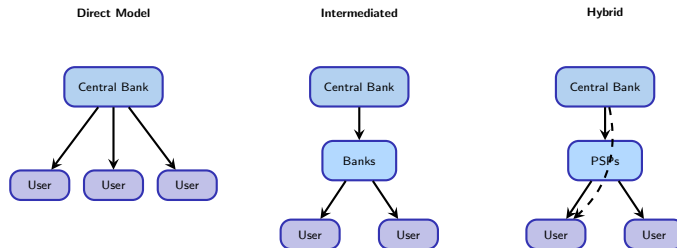
### Retail CBDC:

- For general public
- Replaces/complements cash
- Direct central bank relationship

### Wholesale CBDC:

- For financial institutions
- Interbank settlements
- Less disruptive to banking





## Trade-offs:

- Direct: Maximum control, but central bank becomes retail bank
- Intermediated: Preserves banking system, but less innovative
- Hybrid: Balance, but complex implementation

# CBDC vs. Stablecoin Comparison

Attribute	CBDC	Stablecoin
Issuer	Central bank (sovereign)	Private company
Liability	Central bank balance sheet	Private balance sheet
Legal Status	Legal tender	Private money
Backing	Full faith of government	Reserves (varies)
Programmability	Policy-controlled	Open/permissionless
Privacy	Policy-dependent	Pseudonymous (public chains)
Innovation Speed	Slow (government)	Fast (private)
Interoperability	National focus	Global by default
Risk Profile	Sovereign risk only	Counterparty + operational

## Key Question

Will CBDCs complement, compete with, or regulate away private stablecoins?

## What Programmability Enables:

- Conditional payments
- Automatic tax withholding
- Stimulus with expiration dates
- Supply chain financing
- Smart contract integration

## Opportunities:

- Financial inclusion
- Reduced fraud
- Efficient policy transmission
- New business models

## Concerns

- **Privacy:** Complete transaction surveillance
- **Control:** Money that “expires” or can be frozen
- **Exclusion:** Programmable discrimination
- **Security:** Single point of failure

## Design Choices Matter:

- Token-based vs. account-based
- Privacy-preserving tech
- Offline capability
- Holding limits

**The Convergence Thesis:** Traditional finance (TradFi) and decentralized finance (DeFi) are converging. The future is not “either/or” but hybrid systems combining the best of both.

### You should be able to:

1. Explain the mechanics and value proposition of RWA tokenization
2. Compare different CBDC architectural models
3. Evaluate the tradeoffs between CBDCs and stablecoins
4. Assess the implications of programmable sovereign money

### Discussion Questions

- Should central banks issue retail CBDCs? What are the risks?
- Will tokenization democratize access to investments or create new risks?
- How should programmable money be governed?

### 4.1 Smart Contracts:

- Self-executing code on blockchain
- “Trustless” shifts trust, doesn't eliminate it
- Oracle problem limits external data access

### 4.2 DeFi Primitives:

- AMMs use  $x \cdot y = k$  for pricing
- Impermanent loss affects liquidity providers
- Composability enables innovation (and attacks)

### 4.3 Stablecoins:

- Three designs: fiat-backed, crypto-collateral, algorithmic
- Stablecoin trilemma constrains design
- Heavy regulatory focus globally

### 4.4 Tokenization & CBDCs:

- RWA tokenization unlocks liquidity
- CBDCs represent sovereign response
- Programmable money raises privacy concerns

Notebook	Topic	Key Activities
NB08	Smart Contract Interaction	Interact with contracts on testnet, call functions, observe state changes
NB09	AMM Simulation	Provide liquidity, execute swaps, measure impermanent loss
NB10	Stablecoin Analysis	Analyze price stability data, examine de-peg events

### Preparation for Day 5

Tomorrow we explore the **AI-Finance Intersection**: Machine learning for markets, LLMs in finance, and the automation of financial decisions.

# Day 4: Programmable Finance

Smart Contracts, DeFi, and Tokenization

Questions & Discussion

**Next:** Day 5 – AI and Finance