Topic 4.2: DeFi Primitives
Lending, AMMs, and Financial Legos

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Learning Objectives

By the end of this topic, you will be able to:

1. **Explain** how AMMs (automated price-setting systems) replace traditional exchanges
2. **Understand** slippage (price moving against you during a trade) and why larger trades cost more
3. **Understand** how DeFi lending protocols automatically adjust interest rates
4. **Describe** impermanent loss (temporary loss from providing liquidity) and when it matters
5. **Analyze** the composability of DeFi protocols ("money legos")
6. **Evaluate** flash loans (instant uncollateralized loans) as both innovation and attack vector

Key Skills: Understanding AMM intuition, LP token mechanics (LP = Liquidity Provider), risk assessment

**Prerequisite: Understanding of smart contracts from T4.1**

From Topic 4.1 – Key Concepts:

Quick Check: Do You Remember?

- What is a smart contract?
- Why can't you change code after deployment?

- Smart contracts are self-executing programs on blockchain
- **Deterministic**: Same input → same output
- **Immutable**: Code cannot be changed after deployment
- **Transparent**: Anyone can verify the logic
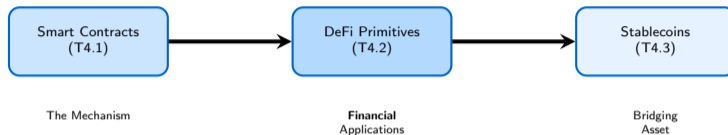- **Composable**: Contracts can call other contracts

Why This Matters for DeFi:

- DeFi protocols are smart contracts
- Trust in code, not institutions
- Permissionless innovation

Smart Contract

Trigger

Code (Logic)

State (Data)   Execute

Balance (Funds)
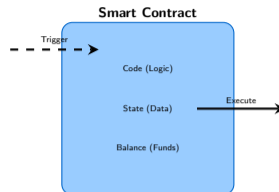
Key Insight

DeFi replaces financial intermediaries with auditable code.

From Smart Contracts to DeFi

The Building Block Progression:

1. **T4.1**: Smart contracts provide the *mechanism* for trustless execution
2. **T4.2**: DeFi primitives build *financial applications* on that mechanism
3. **T4.3**: Stablecoins provide the *stable value unit* for DeFi to function

Today's Focus

How do we build trading, lending, and yield generation using only smart contracts?

What is DeFi?

Definition

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

Concrete Example: Imagine borrowing money directly from strangers worldwide with no bank in the middle. The smart contract automatically manages collateral, interest rates, and repayment.

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 (TVL = Total Value Locked = money deposited in DeFi protocols): $50B+

  That's more than the GDP of some countries!

- Daily trading volume: $2B+
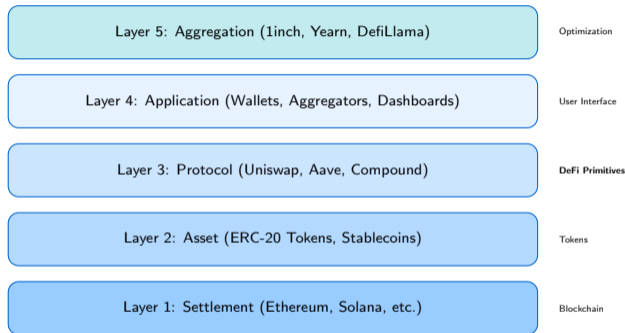- Active protocols: 500+
- Supported chains: 50+

Major Categories:

- Decentralized Exchanges
- Lending Protocols
- Derivatives
- Yield Aggregators

Feature	Traditional Finance	DeFi
Access	KYC (Know Your Customer = proving you are who you say you are), credit checks	Wallet address only
Hours	Business hours, T+2 settlement (2 days to finalize)	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.

The DeFi Stack

Layer 5: Aggregation (1inch, Yearn, DefiLlama)	Optimization
Layer 4: Application (Wallets, Aggregators, Dashboards)	User Interface
Layer 3: Protocol (Uniswap, Aave, Compound)	**DeFi Primitives**
Layer 2: Asset (ERC-20 Tokens, Stablecoins)	Tokens
Layer 1: Settlement (Ethereum, Solana, etc.)	Blockchain

Today's Focus: Layer 3 – The core protocols that enable decentralized trading and lending

Traditional Exchange:

- Uses an order book[a] with bids/asks
- Market makers[b] quote prices
- Requires active management
- Centralized matching engine

AMM Innovation:

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

[a] Order book = a list of all buy and sell orders, ranked by price

[b] Market makers = firms that continuously offer to buy and sell, providing liquidity

[c] Liquidity pool = a shared fund of two tokens locked in a smart contract, enabling trades
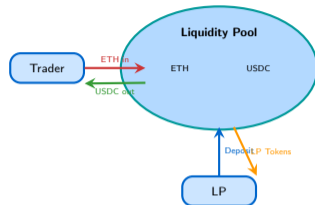
Leading AMM Protocols: Uniswap (most popular), Curve (optimized for stablecoins), Balancer (multi-token pools)

Follow the Money: How AMMs Work (Step-by-Step)

Scenario: You Want to Swap 1 ETH for USDC

Initial Pool State:
- Pool has: 100 ETH + 300,000 USDC
- Current price: 1 ETH = 3,000 USDC

Step 1: You deposit 1 ETH into the pool
- Pool now has: 101 ETH + 300,000 USDC

Step 2: The pool removes USDC to keep the product constant
- Before: $100 \times 300,000 = 30,000,000$
- After: $101 \times ? = 30,000,000$
- Solve: $? = 30,000,000 \div 101 = 297,030$ USDC

Step 3: You receive the difference
- USDC removed: $300,000 - 297,030 = 2,970 USDC$
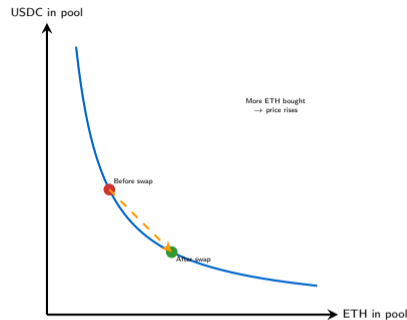- You get slightly less than 3,000 USDC due to price impact!

The Core Idea

The AMM follows a simple rule: **as you buy more of one token, its price goes up** because less of it remains in the pool.

Think of it like a **seesaw**—when one side goes up, the other must go down.

In plain language:

- The pool always keeps a "balance" between its two tokens
- Buying one token makes it scarcer (more expensive)
- Selling one token makes it more abundant (cheaper)
- The price adjusts automatically with every trade

The math behind this is in the Appendix for curious students.

USDC in pool

More ETH bought
→ price rises

Before swap

After swap

ETH in pool

Price Impact

AMM in Action: A Trade Story

Starting Pool
- The pool holds: **100 ETH** and **300,000 USDC**
- Current price: 1 ETH = 3,000 USDC

You want to buy 10 ETH. Here's what happens:

1. You send USDC to the pool and ask for 10 ETH
2. The pool gives you 10 ETH, leaving **90 ETH** behind
3. Because ETH is now scarcer in the pool, its price went *up* during your trade
4. The pool rebalances to about **333,333 USDC**
5. You paid **33,333 USDC** for 10 ETH — that's **3,333 USDC per ETH**

The Cost of a Big Trade
- At the starting price, 10 ETH would cost 30,000 USDC
- You actually paid 33,333 USDC — that's **3,333 USDC extra**
- This "extra cost" is **slippage**: about **11%** price impact
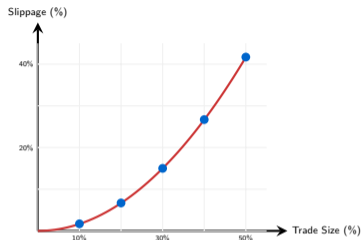- **Lesson**: Bigger trades move the price more against you

Trade Size vs. Slippage:

| Trade	Slippage	Cost
1 ETH	0.99%	$30
5 ETH	4.76%	$714
10 ETH	9.09%	$2,727
20 ETH	16.67%	$10,000
50 ETH	33.33%	$50,000

What This Costs You: Dollar amounts lost compared to no slippage (at $3,000/ETH)

Key Insight: Slippage grows *non-linearly* because larger trades shift the reserve ratio more dramatically.

Practical Implication

Deep liquidity pools (high TVL) have less slippage for the same trade size. Always check price impact before executing large trades.

LP 1

LP 2

LP 3

ETH/USDC Pool

100 ETH   300k USDC

0.3% fees

LP Tokens

LP1: 40%

LP2: 35%

LP3: 25%
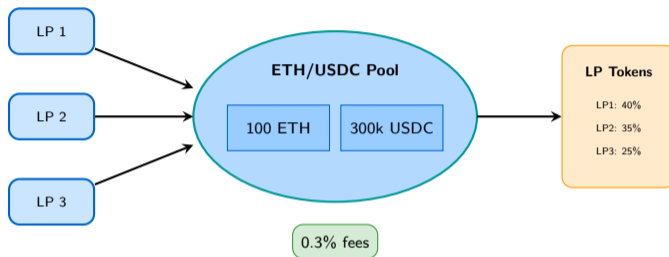
LP Token Mechanics:

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

How LP Tokens Work:

1. Deposit both tokens in equal value
2. Receive LP tokens proportional to contribution
3. First depositor sets the initial ratio
4. Later deposits: proportional to pool share

Example:

- Pool: 1,000 total LP tokens
- You hold: 100 LP tokens (10%)
- You own 10% of all reserves
- Plus 10% of accumulated fees

Fee Accrual Mechanism:

- Trading fees stay in the pool
- Reserves grow with each trade
- LP token supply unchanged
- Each LP token worth more over time

Key Point

Fees aren't distributed separately—they accumulate in the pool. You receive your share when you withdraw by burning LP tokens.

Impermanent Loss Explained

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.

The key insight:

If you provide liquidity and one token's price changes significantly, you end up with **less value** than if you had simply held the tokens. The bigger the price move, the larger the loss.

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%

The formula behind this table is in the Appendix.

Mitigating IL:

- Provide liquidity to correlated pairs (stablecoin-stablecoin: minimal price divergence)
- Choose pools with high trading volume (fees offset IL)
- Use concentrated liquidity (Uniswap V3)
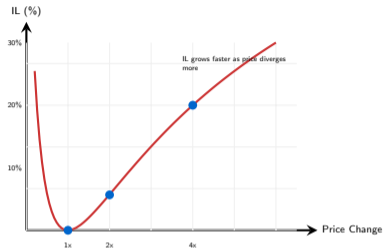
You start by providing liquidity:
- You deposit: 1 ETH + 2,000 USDC
- Total value: $4,000
- ETH price at deposit: $2,000

Then ETH doubles to $4,000:
- Arbitrage traders rebalance the pool
- Your share now has *less* ETH and *more* USDC
- Specifically: about 0.707 ETH + 2,828 USDC
- Your pool value: **$5,657**

What if you had just held instead?
- 1 ETH at $4,000 = $4,000
- 2,000 USDC = $2,000
- Total: **$6,000**

The difference:
- Holding: $6,000
- Pool: $5,657
- **You lost $343 (about 5.7%)** by being in the pool

The Break-Even Question

If the pool earned more than $343 in trading fees during this time, you still come out ahead. If not, you would have been better off just holding.

How Price Discovery Works:

1. External price changes (e.g., on Binance)
2. AMM price diverges from market
3. Arbitrageurs profit by trading the difference
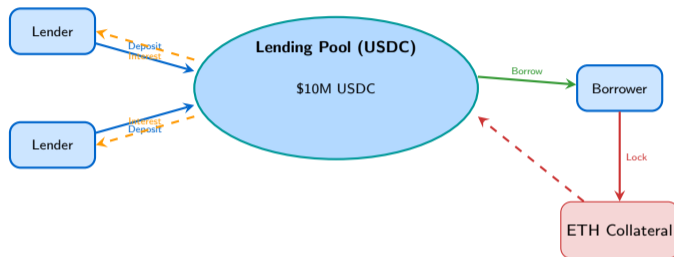4. AMM price converges to market price

Example:

- AMM price: 1 ETH = $2,000
- Binance price: 1 ETH = $2,100
- Arbitrageur buys cheap on AMM
- Sells expensive on Binance
- AMM price increases toward $2,100
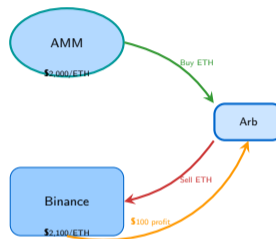
Key Insight

Arbitrage is the mechanism that keeps AMM prices aligned with external markets—without oracles!

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

How it works (supply & demand):
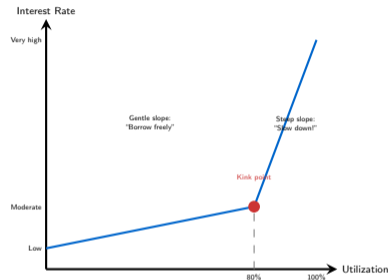Lending protocols automatically adjust interest rates:

- **Few borrowers** (low utilization) → rates stay *low* to encourage borrowing
- **Many borrowers** (high utilization) → rates rise *sharply* to attract more lenders
- There is a "**kink**" point (typically 80%) where rates jump steeply

Why the kink?
The protocol *wants* some funds always available for withdrawals. The steep rate above 80% discourages draining the pool completely.

The mathematical model is in the Appendix.

Key Protocols: Aave, Compound, MakerDAO

Interest Rate

Very high

Gentle slope:
"Borrow freely"

Steep slope:
"Slow down!"

Kink point

Moderate

Low

80%   100%   Utilization

Scenario:

- You have 10 ETH worth $30,000
- Need $15,000 USDC liquidity
- Don't want to sell your ETH

DeFi Solution (Aave):

1. Deposit 10 ETH as collateral
2. Borrow up to 75% LTV = $22,500
3. You borrow $15,000 USDC
4. Pay 5% APR interest

Position Metrics:

- Collateral: $30,000 (10 ETH)
- Debt: $15,000 (USDC)
- Health Factor: 1.65 (safe zone—above 1.0)
- Liquidation at: Health Factor below 1.0

Liquidation Risk

If ETH drops 40% to $1,800:

- New collateral: $18,000
- Health Factor drops to 0.99
- Position liquidated!

Flash Loans: Innovation or Attack Vector?

Definition

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

Single Atomic Transaction

Borrow $1M → Arbitrage → More Actions → Repay + Fee
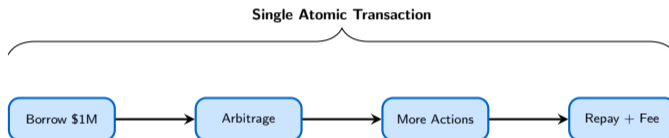
Legitimate Uses: Arbitrage, collateral swaps, self-liquidation
Attack Uses: Oracle manipulation, governance attacks, protocol exploits

The Double-Edged Sword

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

What is Composability?

- Protocols can call other protocols
- Build complex strategies from simple parts
- No permission needed to integrate
- Innovation without coordination

Example Stack:

1. Deposit ETH into Aave
2. Receive aETH (interest-bearing)
3. Deposit aETH into Uniswap
4. Earn trading fees + lending interest

Your Strategy

Yearn

Compound

Aave

Uniswap
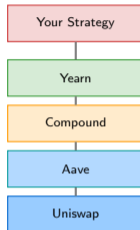
Risk Compounds Too

Composability creates *systemic risk*—a bug in one protocol can cascade through the stack.

Total Value Locked (TVL):

- Total assets deposited in protocol
- Indicator of protocol usage
- ETH/USDC Pool with 1,000 ETH ($2M) + 2M USDC = $4M TVL

Other Key Metrics:

- **Volume**: Daily trading volume
- **Fees**: Revenue generated
- **APY**: Annual percentage yield
- **Health Factor**: Lending safety

Top DeFi Protocols (2024):

Protocol	TVL
Lido	$20B+
Aave	$10B+
MakerDAO	$8B+
Uniswap	$5B+
Curve	$2B+

Why TVL Matters:

- Higher TVL = deeper liquidity
- Less slippage for traders
- More attractive to LPs

Smart Contract Risk:
- Bugs in code (The DAO: $60M)
- Reentrancy attacks
- Logic errors
- Governance exploits

Oracle Risk:
- Price manipulation
- Flash loan attacks
- Stale data

Economic Risk:
- Impermanent loss
- Liquidation cascades
- Bank runs on pools

Systemic Risk:
- Protocol dependencies
- Stablecoin de-pegs
- Contagion effects

Key Insight

DeFi doesn't eliminate risk—it transforms and redistributes it.

Notebook NB09: AMM Simulation

What You Will Do:

1. **Create a Liquidity Pool**: Initialize with ETH and USDC reserves
2. **Execute Swaps**: Trade tokens and observe price changes
3. **Provide Liquidity**: Add liquidity and receive LP tokens
4. **Measure Impermanent Loss**: Calculate IL for various price scenarios
5. **Analyze Arbitrage**: See how arbitrage keeps prices aligned

Key Learning Outcomes:

- Practical understanding of how AMMs price tokens
- Visualize slippage and price impact
- Experience the LP perspective

NB09 Preview: Core AMM Functions

Optional: For Students with Programming Experience

The code below shows the inner workings of an AMM. In the notebook, all code runs automatically—you will interact with the AMM through simple inputs and observe the results visually.

```python
 1  class SimpleAMM:
 2      def __init__(self, reserve_x, reserve_y):
 3          self.x = reserve_x  # ETH reserves
 4          self.y = reserve_y  # USDC reserves
 5          self.k = reserve_x * reserve_y  # constant product
 6
 7      def get_spot_price(self):
 8          return self.y / self.x  # Price of ETH in USDC
 9
10      def swap_x_for_y(self, amount_x):
11          new_x = self.x + amount_x
12          new_y = self.k / new_x
13          amount_y_out = self.y - new_y
14          self.x, self.y = new_x, new_y
15          return amount_y_out
```

NB09 includes interactive visualizations of the bonding curve and IL

Discussion: DeFi in Practice

Case Study: The 2020 DeFi Summer

- TVL grew from \$1B to \$15B in 6 months
- Yield farming introduced liquidity mining
- Composability enabled rapid innovation
- Also: exploits, rug pulls, gas wars

Discussion Questions:

1. Why did DeFi grow so rapidly in 2020?
2. What are the barriers to mainstream DeFi adoption?
3. How do DeFi risks compare to traditional finance risks?
4. Can DeFi truly be "decentralized" if most users access it through centralized frontends?

For Individuals:
- **Trading**: Swap tokens 24/7 without KYC
- **Lending**: Earn yield on idle assets
- **Borrowing**: Access liquidity without selling
- **Yield Farming**: Optimize returns across protocols

For Institutions:
- Treasury management
- On-chain settlement
- Tokenized collateral
- Automated market making

Success Stories:
- Uniswap: $1.5T+ cumulative volume
- Aave: $10B+ in active loans
- Curve: $100B+ stablecoin swaps

Emerging Use Cases:
- Real-world asset lending
- Cross-border payments
- Institutional DeFi (permissioned pools)
- DeFi-TradFi bridges

Centralization Points:

- **Frontends**: Most users access via websites
- **Oracles**: Price feeds are critical dependencies
- **Governance**: Token holders control protocols
- **Infrastructure**: RPC providers, block builders

The Ownership Question:

- Top 1% often holds majority tokens
- VC funding creates concentrated ownership
- "Decentralization theater"?

What IS Decentralized:

- Smart contract execution
- Permissionless access
- Transparent rules
- No single point of failure

Nuanced View

DeFi is more accurately "disintermediated" than "decentralized." It removes certain intermediaries while creating new dependencies and power structures.

Technical Evolution:

- **Layer 2**: Lower fees, faster transactions
- **Cross-chain**: Unified liquidity across chains
- **Account Abstraction**: Better UX
- **Intent-based**: Express what, not how

Market Evolution:

- Institutional adoption growing
- Regulatory clarity emerging
- TradFi-DeFi convergence
- Real-world asset integration

Key Challenges:

- Scalability limitations
- User experience complexity
- Regulatory uncertainty
- Smart contract risks

The Big Question

Will DeFi remain a parallel financial system, or will it merge with traditional finance? The answer likely lies somewhere in between.
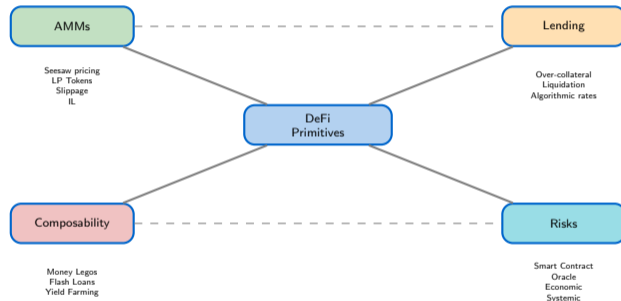
Core Concepts

- **AMMs** replace order books with liquidity pools and automatic pricing (the "seesaw" principle)
- **Liquidity providers** earn fees but face impermanent loss risk
- **DeFi lending** uses over-collateralization and algorithmic rates
- **Composability** enables innovation but creates systemic risk
- **Flash loans** democratize capital but enable attacks

Key Intuitions:

- AMM pricing = seesaw principle
- Bigger trades = more slippage

- IL grows with price divergence
- Interest rates follow supply & demand

Mathematical formulas for all concepts are available in the Appendix slides.

AMMs

Seesaw pricing
LP Tokens
Slippage
IL

Lending

Over-collateral
Liquidation
Algorithmic rates

DeFi
Primitives

Composability

Money Legos
Flash Loans
Yield Farming

Risks

Smart Contract
Oracle
Economic
Systemic

AMM (Automated Market Maker):
A protocol that uses algorithms to price assets instead of order books.

Liquidity Pool:
A smart contract holding reserves of two tokens for trading.

LP Token:
Token representing ownership share in a liquidity pool.

Constant Product Formula:
The mathematical rule behind AMM pricing (see Appendix).

Slippage (Price Impact):
The difference between expected and actual execution price.

Impermanent Loss:
Opportunity cost of providing liquidity vs. holding assets.

TVL (Total Value Locked):
Total assets deposited in a DeFi protocol.

Utilization Rate:
Percentage of supplied assets currently borrowed.

Over-Collateralization:
Requiring more collateral than loan value (e.g., 150%).

Liquidation:
Forced sale of collateral when health factor drops below threshold.

Health Factor:
Ratio measuring loan safety; liquidation occurs when < 1.

Flash Loan:
Uncollateralized loan borrowed and repaid in one transaction.

Composability:
Ability of protocols to interact and build upon each other.

Yield Farming:
Strategy of moving assets between protocols to maximize returns.

Arbitrage:
Profiting from price differences across markets, keeping prices aligned.

Sandwich Attack:
MEV attack that front-runs and back-runs a victim's trade.

Common Misconceptions

Misconception 1:
"LPs always make money from fees"
Reality: Impermanent loss can exceed fee income, especially in volatile pairs.

Misconception 2:
"DeFi is completely trustless"
Reality: You still trust the code, oracles, governance, and infrastructure providers.

Misconception 3:
"Flash loans are only for attacks"
Reality: Most flash loans are used for legitimate arbitrage and collateral management.

Misconception 4:
"Higher APY means better investment"
Reality: High yields often indicate higher risk (smart contract, IL, or token inflation).

Misconception 5:
"Impermanent loss only matters if you withdraw"
Reality: IL represents real opportunity cost—you would have more value if you had just held.

Misconception 6:
"Audited protocols are safe"
Reality: Audits reduce but don't eliminate risk. Many exploited protocols were audited.

Question 1: Liquidity Pools

What is a liquidity pool in the context of AMMs?

A. A database storing all pending trades waiting to be executed

B. A smart contract holding reserves of two tokens that traders can swap against using a pricing formula

C. A group of traders who manually set prices for token pairs

D. A backup storage system for blockchain data

Question 2: Impermanent Loss

If you provide liquidity to an ETH/USDC pool and ETH doubles in price, approximately how much impermanent loss do you face?

A. 0% — price changes don't affect liquidity providers

B. About 2% — a small cost

C. About 5.7% — a meaningful cost that fees need to offset

D. About 50% — you lose half your money

Question 3: Fee Accrual Mechanism

How do trading fees accrue to LP token holders?

A. Fees are distributed monthly as separate token rewards

B. Fees are automatically deposited into LP wallets after each trade

C. Fees remain in the pool, increasing the reserves, so each LP token represents a growing share of value

D. Fees must be manually claimed through a governance process

Answers:

- Question 1: **B** — A liquidity pool is a smart contract holding token reserves
- Question 2: **C** — A 2x price change causes about 5.7% IL (see table and Appendix)
- Question 3: **C** — Fees grow the pool; LP tokens represent larger shares

Preview of T4.3:

- Why stablecoins matter for DeFi
- Three design approaches:
  - Fiat-backed (USDC, USDT)
  - Crypto-collateralized (DAI)
  - Algorithmic (and why they fail)
- The stablecoin trilemma
- Regulatory landscape

Connection to T4.2:

- Stablecoins are the "stable leg" in most DeFi pools
- Understanding stability mechanisms is crucial

T4.2
DeFi Primitives

T4.3
Stablecoins
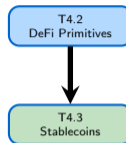
Key Questions:
- How do stablecoins maintain their peg?
- What caused UST to collapse?
- Are stablecoins securities?

Hands-on: NB10 – Stablecoin price stability analysis

Resources for Further Learning

Essential Reading:
- Uniswap V2 Whitepaper
- Aave Documentation
- "DeFi and the Future of Finance" (Campbell Harvey)

Interactive Tools:
- DefiLlama (TVL tracking)
- Dune Analytics (on-chain data)
- Impermanent Loss calculators

Technical Resources:
- Ethereum.org DeFi docs
- Curve Finance resources
- Chainlink education

Stay Updated:
- The Defiant newsletter
- Bankless podcast
- Week in Ethereum News

Course Materials

Notebook NB09: AMM Simulation – practice with AMM pricing, slippage, and impermanent loss

Topic 4.2: DeFi Primitives

Lending, AMMs, and Financial Legos

Questions & Discussion

Next Topic: T4.3 – Stablecoins: The Bridge Between Two Worlds

Joerg Osterrieder — Digital Finance — 2025

The Constant Product Formula

$$x \cdot y = k$$

- x = Token A reserves, y = Token B reserves, k = constant (invariant)

Price Determination: The spot price of token A in terms of token B is the ratio of reserves:

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

Calculating the output of a swap: When you add Δx of token A, you receive:

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

Example: Pool has 100 ETH and 300,000 USDC ($k = 30,000,000$). Swap 10 ETH in:

- New ETH $= 110$, New USDC $= 30,000,000/110 = 272,727$
- You receive $300,000 - 272,727 = 27,273$ USDC
- Slippage: $(30,000 - 27,273)/30,000 = 9.09\%$

IL Formula

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

where $r = \frac{P_1}{P_0}$ is the price ratio (new price / original price).

Derivation intuition:

1. In a constant-product pool, if the price ratio changes to r, your holdings rebalance to $\sqrt{r}$ times the original token A and $\frac{1}{\sqrt{r}}$ times token B

2. The value of your pool position is $\frac{2\sqrt{r}}{1+r}$ of what simple holding would be worth

3. The difference is impermanent loss

Worked example (ETH doubles, $r = 2$):

- $IL = \frac{2\sqrt{2}}{1+2} - 1 = \frac{2 \times 1.414}{3} - 1 = 0.943 - 1 = -5.72\%$
- On a \$6,000 holding value: loss $= 6,000 \times 0.0572 = \$343$

Utilization Rate

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

Borrow Rate (kinked model):

$$R_{\text{borrow}} = \begin{cases} R_0 + U \cdot R_{\text{slope1}} & \text{if } U < U_{\text{optimal}} \\ R_0 + U_{\text{optimal}} \cdot R_{\text{slope1}} + (U - U_{\text{optimal}}) \cdot R_{\text{slope2}} & \text{if } U \geq U_{\text{optimal}} \end{cases}$$

Supply Rate (what lenders earn):

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

Typical parameters (Aave):

- $U_{\text{optimal}} = 80\%$, $R_0 = 0\%$, $R_{\text{slope1}} = 4\%$, $R_{\text{slope2}} = 75\%$
- At 50% utilization: rate $\approx 2\%$. At 90% utilization: rate $\approx 10.7\%$. At 100%: rate $\approx 18.2\%$