L34: AMM Mechanics

Module E: DeFi Ecosystem

Blockchain & Cryptocurrency

December 2025

Liquidity Pool as Swimming Pool

[COMIC: Liquidity pool as swimming pool]

Placeholder for comic showing swimmers (traders) jumping in/out of pool, with pool depth changing and lifeguards (LPs) maintaining water levels

Why find a trading partner when you can just jump in the pool?

The Setup

- Traditional exchange: find a trading partner
- Order books: wait for someone to match
- Problem: what if no one wants to trade?

The Punchline

- AMM: trade against the pool itself
- Pool always has liquidity
- Price adjusts automatically

Learning Objectives

- Derive the constant product formula ($x \cdot y = k$) and its implications
- Analyze how liquidity provision works in AMMs
- Calculate impermanent loss and its implications
- Calculate slippage and price impact for trades
- Compare AMMs to traditional order book exchanges

Building on L33: Introduction to DeFi

The Problem: How can we trade without order books?

The Challenge

Traditional exchanges require continuous market makers to maintain order books. On blockchain, updating orders is expensive (gas costs) and slow (block times). We need a trading mechanism that works algorithmically without human market makers.

Why It Matters

- Without liquidity, decentralized exchanges can't compete with CEXs
- Order books are vulnerable to manipulation and front-running

What We Need

- System design principles
- Algorithmic pricing that adjusts automatically to supply and demand
- Passive liquidity provision without active management

The Cryptoeconomics Question

Creating systems with desired properties

Today's lesson: How AMM Mechanics addresses this challenge

How Do Traditional Order Book Exchanges Work?

The Mechanics:

- **Buyers** place bids, **sellers** place asks
- **Matching engine** pairs buy/sell orders
- Trade executes when bid meets ask

Example Order Book:

	Price	Size
Bids (Buy)	$1,999	5 ETH
	$1,998	10 ETH

	Price	Size
Asks (Sell)	$2,000	8 ETH
	$2,001	12 ETH

Challenges on Blockchain: Gas costs for order updates, slow block times, front-running.

→ *Problem: How can we trade without order books? — Traditional Order Book Exchanges. Order books cost gas per change. AMMs use math formulas instead of order matching.*

Continued

How Do Automated Market Makers Work?

Key Idea: Replace order books with liquidity pools governed by mathematical formulas.

How It Works:

- Liquidity Providers (LPs) deposit token pairs into a pool
- Algorithm sets price based on pool ratio
- Users trade directly against the pool

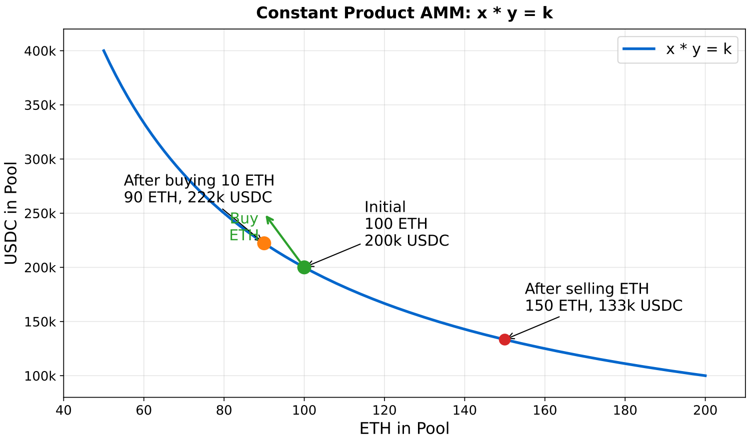
Advantages:

- Always available liquidity (no need to wait for orders)
- Passive income for LPs (earn trading fees)
- Gas efficient (fewer transactions)

Trade-off: Price determined by formula, not market consensus.

Key point: Key Idea

What Is the Constant Product Formula?



Trades move along the curve; price is the slope at any point

How Does the Constant Product Formula Work Mathematically?

Uniswap V2 Model:

$$x \cdot y = k$$

where x = token A quantity, y = token B quantity, k = constant.

Example Pool:

- 100 ETH and 200,000 USDC
- $k = 100 \times 200{,}000 = 20{,}000{,}000$
- Price: $\frac{y}{x} = \frac{200{,}000}{100} = 2{,}000$ USDC per ETH

After Buying 10 ETH:

- New ETH: 90, New USDC: $\frac{20{,}000{,}000}{90} = 222{,}222$
- Cost: 22,222 USDC for 10 ETH = \$2,222/ETH average

Key point: Uniswap V2 Model

Pseudocode: Constant Product Swap

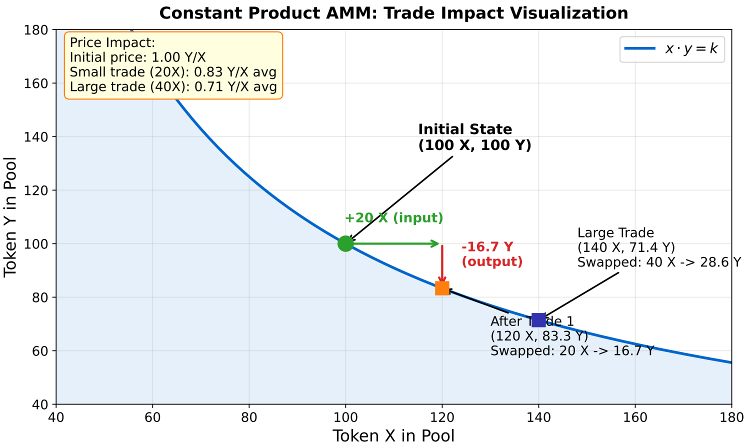
AMM Swap Execution

```
function swap(amount_in, reserve_in, reserve_out):
  fee = amount_in * 0.003
  amount_in_with_fee = amount_in - fee
  // Constant product:  x * y = k
  new_reserve_in = reserve_in + amount_in_with_fee
  new_reserve_out = k / new_reserve_in
  amount_out = reserve_out - new_reserve_out
  // Slippage = (amount_out / amount_in) vs spot price
  assert new_reserve_in * new_reserve_out >= k
  return amount_out
```

Key Insight: The `assert` line enforces the invariant – no trade can reduce k. Fees accumulate in the pool, increasing k over time and benefiting LPs.

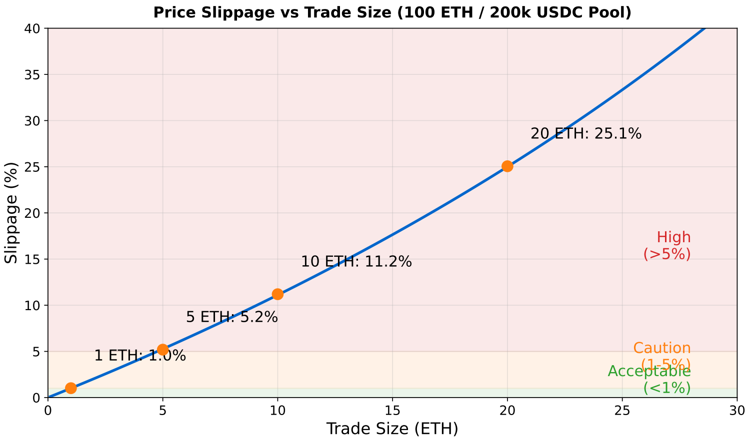
This is the core logic behind every Uniswap V2 swap – 10 lines that move billions daily

How Do Trades Impact the Curve?



Larger trades receive worse average prices; the curve ensures liquidity never runs out

How Does Slippage Vary with Trade Size?



Slippage increases non-linearly; larger pools reduce slippage | → *Problem: How can we trade without order books? — Slippage vs Trade Size. Slippage is the cost of orderbook-free trading – larger trades move price more.*

Why Does Price Change When You Trade?

Definition: The difference between expected price and executed price due to trade size.

Why Slippage Occurs:

- AMM formula moves price as reserves change
- Larger trades = larger price impact
- Smaller pools = more slippage

Slippage Formula:

$$\text{Slippage} = \frac{\text{Executed Price} - \text{Initial Price}}{\text{Initial Price}} \times 100\%$$

Slippage Tolerance: Users set maximum acceptable (e.g., 0.5%, 1%). Transaction reverts if exceeded.

Key point: Definition

How Do You Provide Liquidity?

How to Become an LP:

1. Deposit equal value of both tokens (e.g., 1 ETH + 2,000 USDC)
2. Receive LP tokens (receipts proving your share of a liquidity pool) representing pool share
3. Earn trading fees proportional to share
4. Withdraw anytime (burn LP tokens, receive reserves)

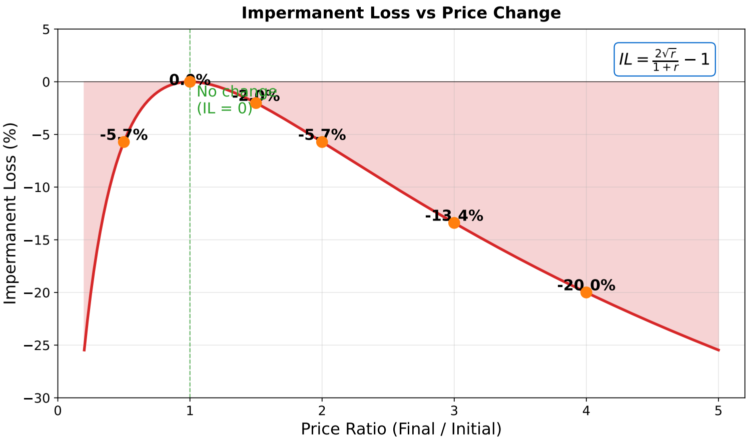
Example:

- Pool has 100 ETH + 200,000 USDC
- You deposit 10 ETH + 20,000 USDC
- Your share: $\frac{10}{110} = 9.09\%$ of pool

Fee Earnings: Uniswap charges 0.3% per trade; fees compound in pool reserves.

Key point: How to Become an LP

What Is Impermanent Loss?



IL increases with price divergence; symmetric whether price rises or falls

What Causes Impermanent Loss?

Definition: The opportunity cost of providing liquidity vs. simply holding tokens.

Occurs when:

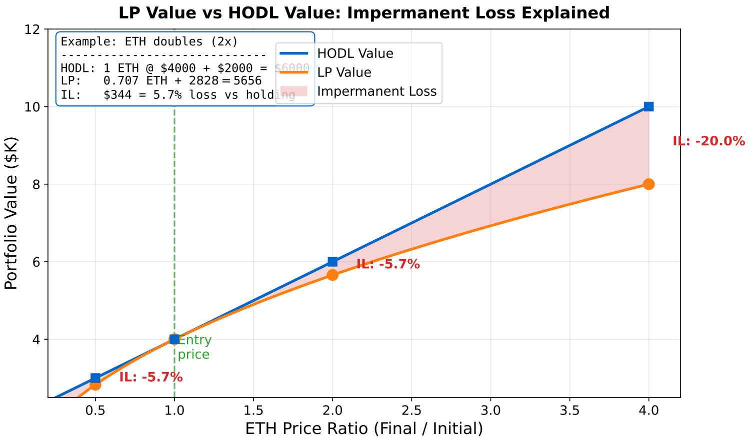
- Token prices diverge from deposit ratio
- Arbitrageurs rebalance pool to match external prices
- LPs end up with more of the depreciated token

Example: ETH doubles to $4,000

- Initial: 1 ETH + 2,000 USDC = $4,000 total
- If held: 1 ETH @ $4,000 + 2,000 USDC = $6,000
- If LP: 0.707 ETH + 2,828 USDC = $5,656
- **IL: $344 (5.7%)**

→ Problem: How can we trade without order books? — Impermanent Loss: Concept. Impermanent loss is what LPs pay for orderbook-free trading – they lose vs. just holding.

How Does LP Value Compare to HODL Value?



LP always underperforms HODL when prices diverge; gap widens with larger moves

Problem Check-In: AMM Mechanics

Recall Our Problem

How can we trade without order books?

What We've Learned So Far

- The formula $x \cdot y = k$ sets prices automatically – no humans needed to match buyers and sellers
- Liquidity providers (LPs) deposit token pairs and earn trading fees (0.3% per trade)
- Math replaces the order book: pools always have liquidity, prices adjust automatically

Still to Address

- Impermanent loss: LPs can lose money if token prices diverge significantly
- Are trading fees enough to compensate LPs for the risk of impermanent loss?

Think About

- Based on what you've seen, how would *you* solve this problem?
- What trade-offs do you expect?

Pause and reflect: How does what we've learned so far address "How can we trade without order books?"?

How Much Can You Lose to Impermanent Loss?

Formula:

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

where r is the price ratio (final/initial).

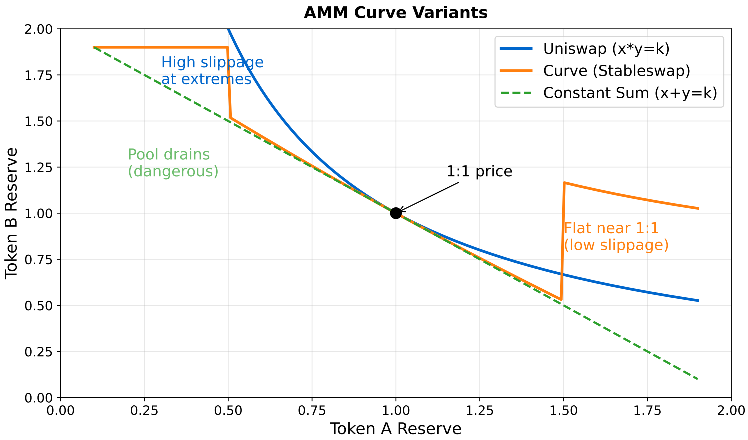
Common Scenarios:

- 1.25x price change: -0.6% IL
- 1.5x price change: -2.0% IL
- 2x price change: -5.7% IL
- 3x price change: -13.4% IL
- 4x price change: -20.0% IL

Why "Impermanent"? Loss only realized on withdrawal; if prices return, loss disappears.

Key point: Formula

What Are the Different AMM Curve Variants?



Different curves optimize for different use cases

How Do Different AMM Variants Work?

Uniswap (Constant Product): $x \cdot y = k$

- General purpose, works for any pair
- Higher slippage near extremes

Curve (Stableswap): Hybrid formula

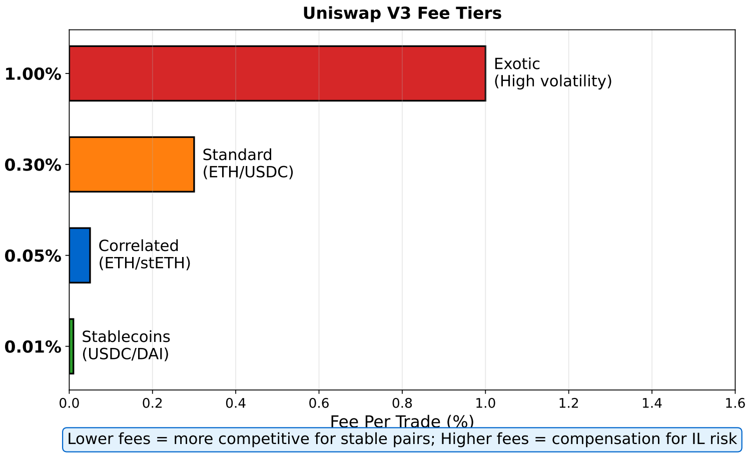
- Flat curve near 1:1 (low slippage for stables)
- Dominates stablecoin swaps (USDC/DAI)

Balancer (Weighted): $\prod x_i^{w_i} = k$

- Custom weights (e.g., 80/20 instead of 50/50)
- Index fund functionality

Key point: Uniswap (Constant Product): $x\ y = k$

How Do Fee Tiers Work in AMMs?



Higher fees compensate LPs for impermanent loss risk in volatile pairs | → Problem: How can we trade without order books? — Fee Tiers in AMMs. Fee tiers let markets price liquidity – volatile pairs need higher fees despite IL risk.

How Do AMM Prices Stay Accurate?

How Arbitrage Works:

1. External market price deviates from AMM price
2. Arbitrageur buys cheaper asset, sells expensive one
3. AMM pool rebalances to match external price

Example:

- CEX: 1 ETH = $2,100
- Uniswap pool: 1 ETH = $2,000
- Arbitrageur: Buy on Uniswap, sell on CEX, profit $100/ETH

Benefit: Keeps AMM prices aligned with global markets.
Cost: LPs experience impermanent loss from adjustments.

Key point: How Arbitrage Works

What Is MEV and How Does It Extract Value?

MEV (Maximal Extractable Value—profit from reordering transactions):

- Profit from reordering/inserting transactions in mempool
- Particularly prevalent in AMM trades

Common MEV Strategies:

1. **Front-Running:** See large buy, buy first, sell after
2. **Sandwich Attacks:** Buy before user, sell after
3. **Arbitrage:** Exploit price differences

Mitigation:

- Private mempools (Flashbots Protect)
- Batch auctions (CoW Swap)

Key point: MEV (Maximal Extractable Value—profit from reordering transactions)

How Do AMMs Compare to Order Books?

AMM (Uniswap)

- Always available liquidity
- Passive LP income
- Slippage on large trades
- Impermanent loss risk

Order Book (Binance)

- Liquidity depends on makers
- Active market making
- Better for large trades
- No impermanent loss

Trend: Hybrid models emerging (e.g., dYdX order book on Cosmos).

Compare the approaches shown above

Problem Solved? AMM Mechanics

The Original Problem

How can we trade without order books?

How AMM Mechanics Solves It

- The constant product formula ($x \cdot y = k$) provides algorithmic pricing without manual order placement
- Liquidity providers deposit token pairs and earn passive trading fees (0.3% per trade)
- Pool always has liquidity available 24/7, no need to wait for matching orders

Remaining Limitations

- Impermanent loss: LPs face opportunity cost when token prices diverge (up to 20%+ for 4x price moves)
- Capital inefficiency: Liquidity spread across entire price curve, not concentrated where trades occur
- MEV extraction: Sandwich attacks and front-running impose hidden costs on traders

Open Questions

- Can AMMs ever achieve the capital efficiency of centralized exchange order books?
- Risk: Are trading fees sufficient to compensate LPs for impermanent loss in volatile pairs?

AMM Mechanics solves the order book problem but introduces new trade-offs between accessibility and efficiency

Cryptoeconomics

The Economics of AMM Mechanics

Incentive Structure

- Creating systems with desired properties
- Mechanism design for target behaviors
- Complexity vs simplicity

Economic Security

- Attack cost must exceed potential gain
- Honest behavior = Nash equilibrium

Key Economic Question

Who Pays, Who Earns?

Complexity vs simplicity

Design Principle

$$\text{Attack Cost} > \text{Potential Gain}$$

Cryptoeconomic security: Honest behavior must be the Nash equilibrium

Design Space: AMM Mechanics

Alternatives Considered

1. **Chosen Design:** Architecture patterns, upgrade mechanisms
2. **Alternative:** Alternative design patterns

Trade-offs Made

- Every design optimizes some properties
- ... at the expense of others

Design Questions

- What would YOU change?
- What's optimized? What's sacrificed?
- Are there other approaches?

Key Insight

No Perfect Solution

All blockchain designs involve trade-offs between decentralization, security, and scalability.

Every design is a trade-off. Understanding alternatives reveals the "why" behind choices.

Failure Modes: AMM Mechanics

Critical Failure Mode

- **What breaks:** Unintended consequences, edge cases
- **Why it happens:** Economic incentives misaligned

Root Cause

- Assumption violated
- Incentive structure broken
- External shock

Historical Context

- Multiple real-world failures documented
- Patterns repeating across protocols

Early Warning Signs

! Unusual economic behavior

! Incentive misalignment

! Centralization drift

Prediction: What could cause this to fail? How would you detect it early?

Impermanent Loss Realization

[COMIC: Impermanent loss realization]

Placeholder for comic showing LP happily providing liquidity, then shocked face when withdrawing with less value than if they had just held

"Impermanent" loss becomes very permanent when you withdraw

The Hidden Cost

- "Impermanent" sounds temporary
- Reality: loss crystallizes on withdrawal
- Price divergence = guaranteed underperformance vs. HODL

The Math Doesn't Lie

- 2x price change: -5.7% IL
- 4x price change: -20% IL
- Fees must exceed IL to profit

Continued

What Are the Key Takeaways?

Core Concepts:

- AMMs use $x \cdot y = k$ to provide algorithmic liquidity
- Price determined by reserve ratio; trades move price
- Slippage increases non-linearly with trade size
- LPs earn fees but face impermanent loss when prices diverge
- IL formula: $\frac{2\sqrt{r}}{1+r} - 1$ (up to 20%+ for 4x moves)
- Curve optimizes for stables; Balancer for weighted pools
- MEV is a hidden cost for AMM traders

Next Lecture: Uniswap Deep Dive - V1 to V4 evolution, concentrated liquidity.

Next Lesson: L35 – Uniswap Deep Dive

Key point: Core Concepts

1. Calculate the cost to buy 5 ETH from a pool with 100 ETH and 200,000 USDC.
2. Why does slippage increase non-linearly with trade size?
3. How do trading fees help offset impermanent loss for LPs?
4. Why is Curve more suitable for stablecoin trading than Uniswap V2?
5. What are the trade-offs of concentrated liquidity in Uniswap V3?

Key point: Questions for Reflection

Quiz Questions (1–5)

Q1. In the constant product formula $x \cdot y = k$, what happens to k when a trade occurs?
A) Increases B) Decreases C) Remains constant D) Becomes zero
Answer: C – The constant k remains the same; only x and y change inversely.

Q2. A pool has 100 ETH and 200,000 USDC. What is the current price per ETH?
A) $1,000 B) $2,000 C) $100 D) $20,000
Answer: B – Price $= y/x = 200{,}000/100 = 2{,}000$ USDC per ETH.

Q3. Which factor does NOT contribute to slippage in an AMM?
A) Trade size B) Pool depth C) Block time D) Reserve ratio
Answer: C – Block time affects confirmation speed, not price slippage from AMM mechanics.

Q4. What is the primary benefit of providing liquidity to an AMM pool?
A) Guaranteed returns B) Earning trading fees C) Price speculation D) Voting rights
Answer: B – LPs earn a share of trading fees (e.g., 0.3% in Uniswap V2).

Q5. If you set a 1% slippage tolerance and actual slippage is 1.5%, what happens?
A) Trade executes normally B) Transaction reverts C) Fees double D) Pool pauses
Answer: B – Transaction reverts to protect user from excessive slippage.

Quiz Questions (6–10)

Q6. Impermanent loss occurs when:
A) Fees are too low   B) Token prices diverge   C) Pool is empty   D) Gas costs rise
Answer: B – IL happens when token prices change relative to deposit ratio.

Q7. If ETH price doubles (2x), what is the approximate impermanent loss?
A) 2.0%   B) 5.7%   C) 13.4%   D) 20.0%
Answer: B – 2x price change results in approximately 5.7% IL.

Q8. Why is impermanent loss called "impermanent"?
A) It's always small   B) Fees offset it   C) Loss disappears if prices return   D) It's paid by traders
Answer: C – If token prices return to original ratio, the loss vanishes.

Q9. You deposit 1 ETH + 2,000 USDC into a pool. What do you receive?
A) Interest payments   B) LP tokens   C) More ETH   D) Governance rights
Answer: B – LPs receive LP tokens representing their share of the pool.

Q10. In a pool with 0.3% trading fee, who receives the fees?
A) Protocol treasury   B) Validators   C) Liquidity providers   D) Traders
Answer: C – Trading fees accrue to LPs proportional to their pool share.

Quiz

Quiz Questions (11–15)

Q11. Which AMM variant is optimized for stablecoin trading?
A) Uniswap V2 B) Curve C) Balancer D) Sushiswap
Answer: B – Curve's StableSwap formula minimizes slippage near 1:1 ratios.

Q12. Balancer's weighted pools allow custom ratios like:
A) Only 50/50 B) Only 33/33/33 C) 80/20 or any weights D) Must equal 100
Answer: C – Balancer supports arbitrary weights (e.g., 80/20, 60/40).

Q13. What is the main role of arbitrageurs in AMMs?
A) Provide liquidity B) Pay gas fees C) Align AMM prices with external markets D) Vote on upgrades
Answer: C – Arbitrageurs exploit price differences, keeping AMM prices accurate.

Q14. A sandwich attack involves:
A) Buying before and selling after victim's trade B) Hacking the pool C) Withdrawing all liquidity D) Freezing transactions
Answer: A – Attacker front-runs victim's buy, then back-runs with a sell.

Q15. What does MEV stand for?
A) Maximum Ethereum Value B) Miner Extractable Value C) Maximal Extractable Value D) Market Efficient Value
Answer: C – MEV (formerly "Miner") is now "Maximal Extractable Value".

Quiz Questions (16–20)

Q16. Compared to order books, AMMs have:
A) No liquidity B) Always available liquidity C) Better prices for large trades D) No fees
Answer: B – AMMs provide algorithmic liquidity 24/7 without waiting for makers.

Q17. After buying 10 ETH from a 100 ETH pool with $k = 20{,}000{,}000$**, the new ETH reserve is:**
A) 90 ETH B) 100 ETH C) 110 ETH D) 80 ETH
Answer: A – Pool loses 10 ETH, leaving 90 ETH (USDC increases to maintain k).

Q18. Uniswap V2's standard fee per trade is:
A) 0.05% B) 0.3% C) 1.0% D) 5.0%
Answer: B – Uniswap V2 charges 0.3% on all trades.

Q19. Which factor INCREASES impermanent loss?
A) Price stability B) High trading fees C) Large price divergence D) Low slippage
Answer: C – Greater price divergence (e.g., 4x) causes higher IL (up to 20%+).

Q20. To withdraw liquidity from an AMM, you must:
A) Wait 30 days B) Burn LP tokens C) Pay a penalty D) Sell all assets
Answer: B – Burning LP tokens returns your share of pool reserves.