Blockchain/Cryptocurrency Transaction System

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High-Level Design (HLD)

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System Architecture Overview

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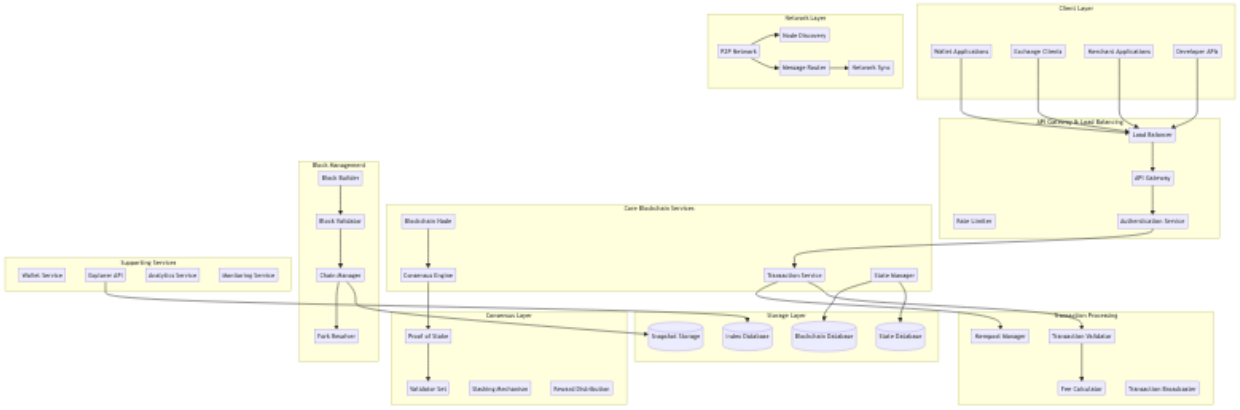

Transaction Flow Architecture

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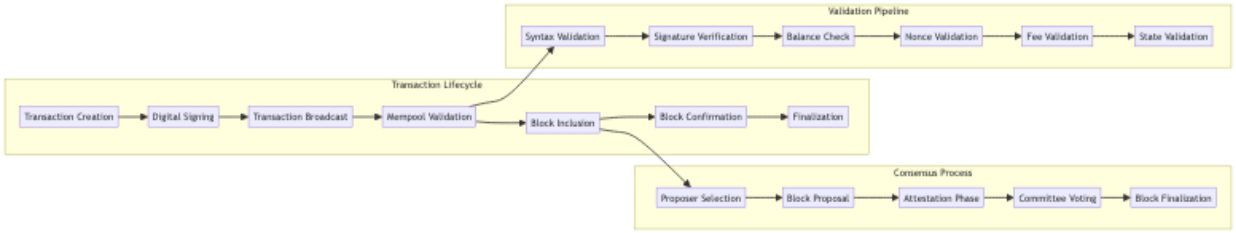

Low-Level Design (LLD)

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Cryptographic Architecture

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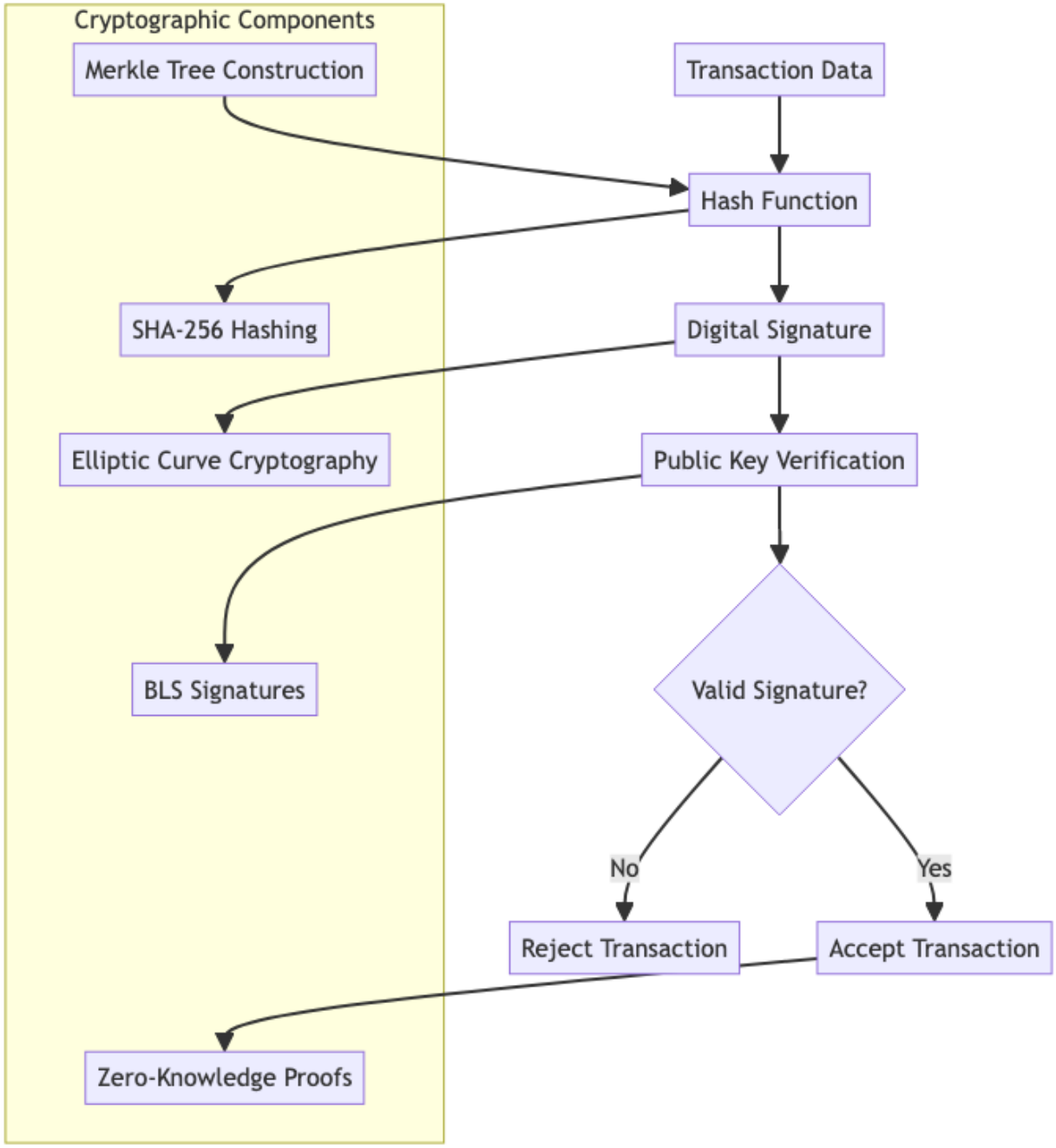

Consensus Mechanism Flow

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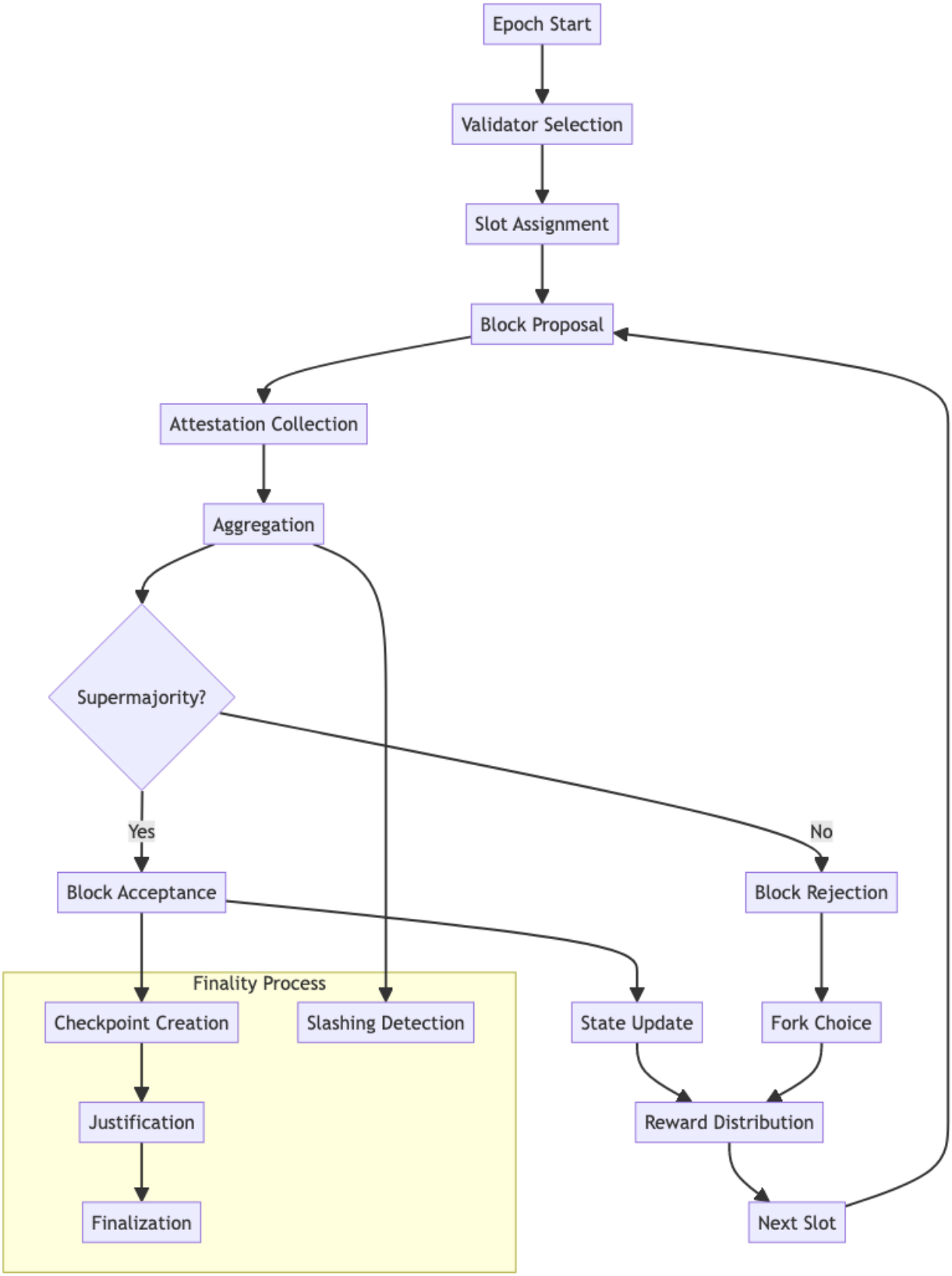
Epoch Start
Validator Selection
Slot Assignment
Block Proposal
Attestation Collection
Aggregation
Supermajority?
Yes
No
Block Acceptance
Block Rejection
Finality Process
Checkpoint Creation
Slashing Detection
State Update
Fork Choice
Justification
Reward Distribution
Finalization
Next Slot

State Management Architecture

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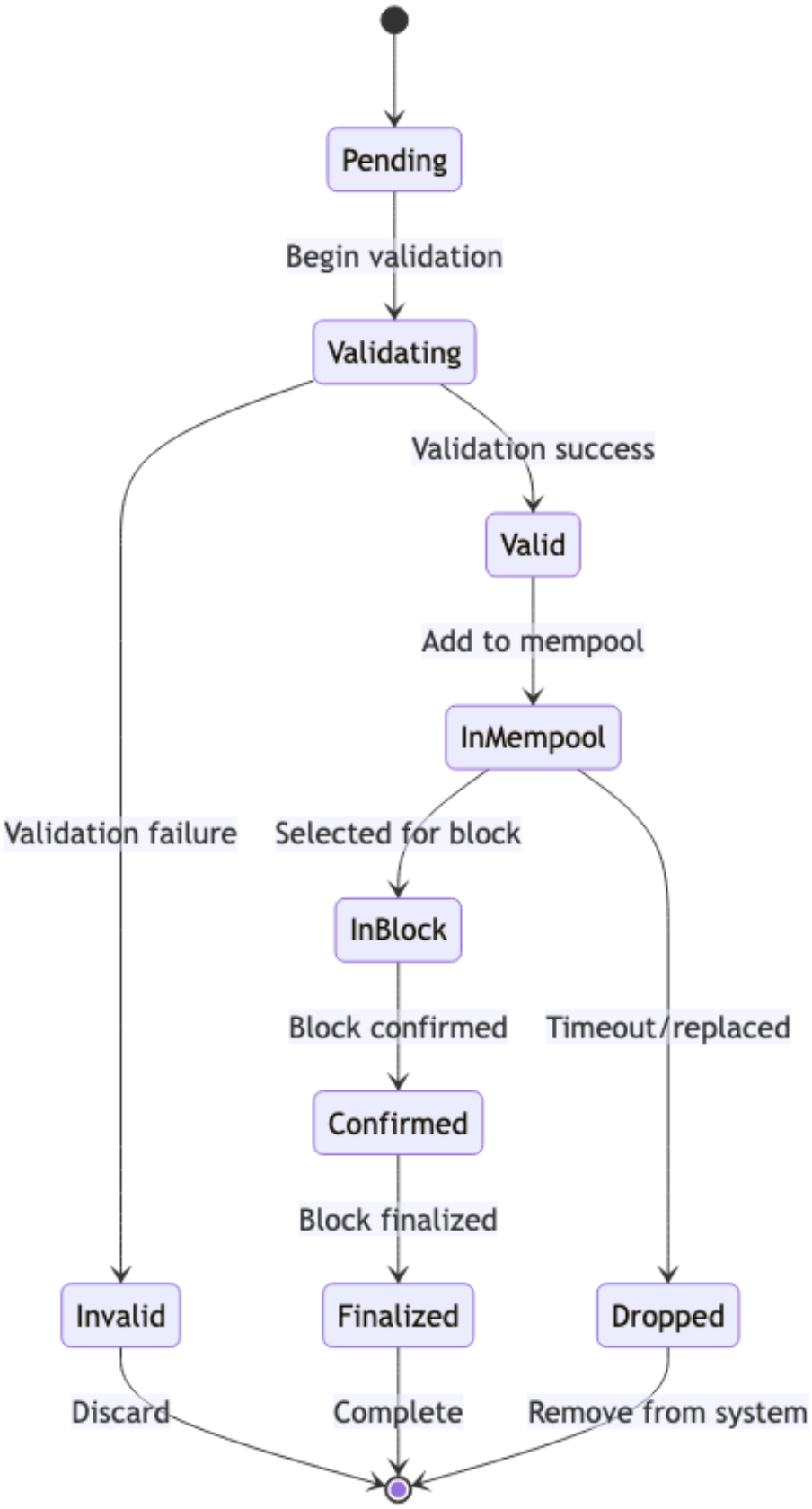
Pending
Begin validation
Validating
Validation success
Valid
Add to mempool
InMempool
Validation failure
Selected for block
InBlock
Block confirmed
Timeout/replaced
Confirmed
Block finalized
Invalid
Finalized
Dropped
Discard
Complete
Remove from system

Core Algorithms

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1. Transaction Validation Algorithm

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Purpose: Validate transactions for correctness, authenticity, and compliance with protocol rules before including them in blocks.

Multi-Stage Transaction Validation:

```
TransactionValidationConfig = {
  validation: {
    syntaxCheck: true,
    signatureVerification: true,
    balanceVerification: true,
    nonceValidation: true,
    feeValidation: true,
    gasLimitCheck: true
  },

  limits: {
    maxTransactionSize: 32768,      # 32KB max transaction size
    maxGasLimit: 30000000,          # 30M gas units
    minGasPrice: 1000000000,        # 1 Gwei minimum
    maxNonceGap: 1000               # Maximum nonce gap allowed
  },

  security: {
    replayProtection: true,
    maxValueTransfer: 10000000000000000000,  # 1000 ETH equivalent
    addressBlacklist: true,
    timeWindow: 3600000             # 1 hour transaction validity
  }
}

class TransactionValidator:
  constructor(config):
    this.config = config
    this.cryptoEngine = new CryptographicEngine()
    this.stateManager = new StateManager()
```

```
  this.gasCalculator = new GasCalculator()
  this.addressValidator = new AddressValidator()

function validateTransaction(transaction, currentState):
  validationResult = {
    isValid: false,
    errors: [],
    warnings: [],
    gasEstimate: 0,
    priority: 0
  }

  # Stage 1: Syntax and Format Validation
  syntaxResult = this.validateSyntax(transaction)
  if not syntaxResult.isValid:
    validationResult.errors.push(...syntaxResult.errors)
    return validationResult

  # Stage 2: Cryptographic Validation
  cryptoResult = this.validateCryptography(transaction)
  if not cryptoResult.isValid:
    validationResult.errors.push(...cryptoResult.errors)
    return validationResult

  # Stage 3: State-based Validation
  stateResult = this.validateAgainstState(transaction, currentState)
  if not stateResult.isValid:
    validationResult.errors.push(...stateResult.errors)
    return validationResult

  # Stage 4: Economic Validation
  economicResult = this.validateEconomics(transaction, currentState)
  if not economicResult.isValid:
    validationResult.errors.push(...economicResult.errors)
    return validationResult

  # Stage 5: Policy and Compliance Validation
  policyResult = this.validatePolicies(transaction)
  if not policyResult.isValid:
    validationResult.errors.push(...policyResult.errors)
    return validationResult

  # Calculate transaction priority
  validationResult.priority = this.calculateTransactionPriority(transaction, economicR
  validationResult.gasEstimate = economicResult.gasEstimate
```

```
  validationResult.isValid = true

  return validationResult

function validateSyntax(transaction):
  errors = []

  # Check transaction structure
  if not transaction.from or not this.isValidAddress(transaction.from):
    errors.push({ type: 'invalid_from_address', field: 'from' })

  if not transaction.to or not this.isValidAddress(transaction.to):
    errors.push({ type: 'invalid_to_address', field: 'to' })

  # Check value format
  if not this.isValidAmount(transaction.value):
    errors.push({ type: 'invalid_value', field: 'value' })

  # Check nonce format
  if not Number.isInteger(transaction.nonce) or transaction.nonce < 0:
    errors.push({ type: 'invalid_nonce', field: 'nonce' })

  # Check gas parameters
  if not Number.isInteger(transaction.gasLimit) or transaction.gasLimit <= 0:
    errors.push({ type: 'invalid_gas_limit', field: 'gasLimit' })

  if not Number.isInteger(transaction.gasPrice) or transaction.gasPrice < this.config.
    errors.push({ type: 'invalid_gas_price', field: 'gasPrice' })

  # Check transaction size
  transactionSize = this.calculateTransactionSize(transaction)
  if transactionSize > this.config.limits.maxTransactionSize:
    errors.push({ type: 'transaction_too_large', size: transactionSize })

  # Check data field if present
  if transaction.data and not this.isValidHexData(transaction.data):
    errors.push({ type: 'invalid_data_format', field: 'data' })

  return {
    isValid: errors.length === 0,
    errors: errors
  }

function validateCryptography(transaction):
  errors = []
```

```
  # Verify digital signature
  signatureValid = this.cryptoEngine.verifySignature(
    transaction.signature,
    transaction.from,
    this.getTransactionHash(transaction)
  )

  if not signatureValid:
    errors.push({ type: 'invalid_signature', field: 'signature' })

  # Check for replay protection
  if this.config.security.replayProtection:
    replayCheck = this.checkReplayProtection(transaction)
    if not replayCheck.isValid:
      errors.push({ type: 'replay_attack_detected', details: replayCheck.reason })

  # Verify transaction hash integrity
  expectedHash = this.calculateTransactionHash(transaction)
  if transaction.hash !== expectedHash:
    errors.push({ type: 'hash_mismatch', expected: expectedHash, actual: transaction.h

  return {
    isValid: errors.length === 0,
    errors: errors
  }

function validateAgainstState(transaction, currentState):
  errors = []
  warnings = []

  # Get account state
  fromAccount = currentState.getAccount(transaction.from)

  if not fromAccount:
    errors.push({ type: 'account_not_found', address: transaction.from })
    return { isValid: false, errors: errors }

  # Check account balance
  totalCost = transaction.value + (transaction.gasLimit * transaction.gasPrice)
  if fromAccount.balance < totalCost:
    errors.push({
      type: 'insufficient_balance',
      required: totalCost,
      available: fromAccount.balance
```

```
    })

  # Check nonce sequence
  expectedNonce = fromAccount.nonce
  if transaction.nonce < expectedNonce:
    errors.push({
      type: 'nonce_too_low',
      expected: expectedNonce,
      provided: transaction.nonce
    })
  else if transaction.nonce > expectedNonce + this.config.limits.maxNonceGap:
    errors.push({
      type: 'nonce_gap_too_large',
      expected: expectedNonce,
      provided: transaction.nonce
    })
  else if transaction.nonce > expectedNonce:
    warnings.push({
      type: 'future_nonce',
      gap: transaction.nonce - expectedNonce
    })

  # Check recipient account if creating contract
  if transaction.to === null: # Contract creation
    contractAddress = this.calculateContractAddress(transaction.from, transaction.nonc
    if currentState.getAccount(contractAddress):
      errors.push({
        type: 'contract_address_collision',
        address: contractAddress
      })

  return {
    isValid: errors.length === 0,
    errors: errors,
    warnings: warnings
  }

function validateEconomics(transaction, currentState):
  errors = []
  warnings = []

  # Estimate gas usage
  gasEstimate = this.gasCalculator.estimateGas(transaction, currentState)

  # Check if gas limit is sufficient
```

```
  if transaction.gasLimit < gasEstimate.minimumGas:
    errors.push({
      type: 'gas_limit_too_low',
      provided: transaction.gasLimit,
      required: gasEstimate.minimumGas
    })

  # Check for excessive gas limit
  if transaction.gasLimit > this.config.limits.maxGasLimit:
    errors.push({
      type: 'gas_limit_too_high',
      provided: transaction.gasLimit,
      maximum: this.config.limits.maxGasLimit
    })

  # Check gas price against network conditions
  networkGasPrice = this.getNetworkGasPrice()
  if transaction.gasPrice < networkGasPrice.minimum:
    warnings.push({
      type: 'low_gas_price',
      provided: transaction.gasPrice,
      recommended: networkGasPrice.recommended
    })

  # Check for value transfer limits
  if transaction.value > this.config.security.maxValueTransfer:
    errors.push({
      type: 'value_transfer_too_large',
      amount: transaction.value,
      limit: this.config.security.maxValueTransfer
    })

  return {
    isValid: errors.length === 0,
    errors: errors,
    warnings: warnings,
    gasEstimate: gasEstimate
  }

function calculateTransactionPriority(transaction, economicResult):
  # Base priority from gas price
  gasPricePriority = transaction.gasPrice / this.getNetworkGasPrice().average

  # Account age bonus
  accountAge = this.getAccountAge(transaction.from)
```

```
    agePriority = Math.min(accountAge / (365 * 24 * 60 * 60 * 1000), 1) # Normalize to y

    # Transaction size penalty
    sizePenalty = Math.max(0, 1 - (this.calculateTransactionSize(transaction) / 1000))

    # Nonce proximity bonus (prefer sequential nonces)
    nonceBonus = transaction.nonce === this.getExpectedNonce(transaction.from) ? 1.2 : 1

    # Combine factors
    priority = gasPricePriority * 0.6 + agePriority * 0.2 + sizePenalty * 0.1 + (nonceBo

    return Math.max(0, Math.min(10, priority)) # Clamp between 0 and 10
```

2. Proof of Stake Consensus Algorithm

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Purpose: Achieve network consensus using validator staking and economic incentives while maintaining security and decentralization.

Validator Selection and Consensus Protocol:

```
ProofOfStakeConfig = {
  consensus: {
    slotsPerEpoch: 32,
    slotDuration: 12000,            # 12 seconds per slot
    epochDuration: 384000,          # 6.4 minutes per epoch
    finalityDelay: 2                # 2 epochs for finality
  },

  validators: {
    minStake: 32000000000000000000,  # 32 ETH equivalent
    maxValidators: 1000000,          # 1M max validators
    shufflePeriod: 256,              # Reshuffle every 256 epochs
    inactivityPenalty: 0.01          # 1% penalty for inactivity
  },

  rewards: {
    baseReward: 64,                  # Base reward per validator
    attestationReward: 0.125,        # Attestation reward multiplier
    proposerReward: 0.125,           # Block proposer reward multiplier
    maxReward: 1000000000000000      # 0.001 ETH max reward
  },

  slashing: {
```

```
    minSlashingPenalty: 1000000000000000000,  # 1 ETH minimum
    whistleblowerReward: 0.125,               # 12.5% of slashed amount
    correlationPenalty: true                  # Increase penalty for correlated failures
  }
}

class ProofOfStakeConsensus:
  constructor(config):
    this.config = config
    this.validatorRegistry = new ValidatorRegistry()
    this.epochManager = new EpochManager()
    this.slashingDetector = new SlashingDetector()
    this.rewardCalculator = new RewardCalculator()

  function processEpoch(epochNumber, validators, attestations):
    epochStart = Date.now()

    # Shuffle validators for the new epoch
    epochValidators = this.shuffleValidators(validators, epochNumber)

    # Assign validators to slots
    slotAssignments = this.assignValidatorsToSlots(epochValidators, epochNumber)

    # Process each slot in the epoch
    epochResults = {
      epochNumber: epochNumber,
      proposedBlocks: [],
      attestations: [],
      slashings: [],
      rewards: [],
      penalties: []
    }

    for slotNumber in range(this.config.consensus.slotsPerEpoch):
      slotResult = this.processSlot(epochNumber, slotNumber, slotAssignments[slotNumber]

      epochResults.proposedBlocks.push(...slotResult.proposedBlocks)
      epochResults.attestations.push(...slotResult.attestations)
      epochResults.slashings.push(...slotResult.slashings)

    # Calculate rewards and penalties for the epoch
    rewardResults = this.calculateEpochRewards(epochNumber, epochResults, epochValidator
    epochResults.rewards = rewardResults.rewards
    epochResults.penalties = rewardResults.penalties
```

```
  # Update validator balances
  this.updateValidatorBalances(epochResults)

  # Check for finality
  finalityResult = this.checkFinality(epochNumber, epochResults)
  epochResults.finalized = finalityResult.finalized
  epochResults.justifiedCheckpoints = finalityResult.justifiedCheckpoints

  return epochResults

function shuffleValidators(validators, epochNumber):
  # Use deterministic shuffling based on epoch number and randomness beacon
  randomnessSeed = this.getRandomnessSeed(epochNumber)

  # Create list of active validator indices
  activeValidators = validators
    .filter(v => v.status === 'active')
    .map(v => v.index)

  # Shuffle using Fisher-Yates algorithm with deterministic randomness
  shuffledValidators = [...activeValidators]

  for i in range(shuffledValidators.length - 1, 0, -1):
    # Generate deterministic random index
    randomIndex = this.deterministicRandom(randomnessSeed, i) % (i + 1)

    # Swap elements
    [shuffledValidators[i], shuffledValidators[randomIndex]] =
      [shuffledValidators[randomIndex], shuffledValidators[i]]

  return shuffledValidators

function assignValidatorsToSlots(shuffledValidators, epochNumber):
  slotAssignments = new Array(this.config.consensus.slotsPerEpoch)
  validatorsPerSlot = Math.floor(shuffledValidators.length / this.config.consensus.slo

  for slotIndex in range(this.config.consensus.slotsPerEpoch):
    startIndex = slotIndex * validatorsPerSlot
    endIndex = startIndex + validatorsPerSlot

    # Assign validators to this slot
    slotValidators = shuffledValidators.slice(startIndex, endIndex)

    # Select block proposer (first validator in the slot)
    proposer = slotValidators[0]
```

```
    # Remaining validators are attesters
    attesters = slotValidators.slice(1)

    slotAssignments[slotIndex] = {
      slotNumber: slotIndex,
      proposer: proposer,
      attesters: attesters,
      committee: slotValidators
    }

  return slotAssignments

function processSlot(epochNumber, slotNumber, slotAssignment):
  slotStart = Date.now()
  slotResults = {
    proposedBlocks: [],
    attestations: [],
    slashings: []
  }

  # Block proposal phase
  if slotAssignment.proposer:
    proposalResult = this.processBlockProposal(epochNumber, slotNumber, slotAssignment
    if proposalResult.block:
      slotResults.proposedBlocks.push(proposalResult.block)

  # Attestation phase
  attestationResults = this.processAttestations(epochNumber, slotNumber, slotAssignmen
  slotResults.attestations.push(...attestationResults.attestations)

  # Slashing detection
  slashingResults = this.detectSlashing(slotResults.attestations, slotResults.proposed
  slotResults.slashings.push(...slashingResults)

  return slotResults

function processBlockProposal(epochNumber, slotNumber, proposerIndex):
  proposer = this.validatorRegistry.getValidator(proposerIndex)

  if not proposer or not this.isValidatorEligible(proposer, epochNumber, slotNumber):
    return { block: null, reason: 'ineligible_proposer' }

  # Create block proposal
  block = this.createBlock(epochNumber, slotNumber, proposer)
```

```
  # Validate block proposal
  validationResult = this.validateBlockProposal(block, proposer)

  if not validationResult.isValid:
    return { block: null, reason: 'invalid_proposal', errors: validationResult.errors

  # Sign the block
  blockSignature = this.signBlock(block, proposer.privateKey)
  block.signature = blockSignature

  # Broadcast block to network
  this.broadcastBlock(block)

  return { block: block, proposer: proposer }

function processAttestations(epochNumber, slotNumber, attesterIndices):
  attestations = []

  for attesterIndex in attesterIndices:
    attester = this.validatorRegistry.getValidator(attesterIndex)

    if not attester or not this.isValidatorEligible(attester, epochNumber, slotNumber)
      continue

    # Create attestation
    attestation = this.createAttestation(epochNumber, slotNumber, attester)

    # Validate attestation
    if this.validateAttestation(attestation, attester):
      attestations.push(attestation)

  return { attestations: attestations }

function calculateEpochRewards(epochNumber, epochResults, epochValidators):
  rewards = []
  penalties = []

  # Calculate base rewards
  totalActiveBalance = this.getTotalActiveBalance(epochValidators)
  baseRewardPerValidator = this.calculateBaseReward(totalActiveBalance)

  for validatorIndex in epochValidators:
    validator = this.validatorRegistry.getValidator(validatorIndex)
    validatorReward = 0
```

```
    validatorPenalty = 0

    # Attestation rewards
    attestationReward = this.calculateAttestationReward(
      validator, epochResults.attestations, baseRewardPerValidator
    )
    validatorReward += attestationReward

    # Block proposal rewards
    proposalReward = this.calculateProposalReward(
      validator, epochResults.proposedBlocks, baseRewardPerValidator
    )
    validatorReward += proposalReward

    # Inactivity penalties
    if this.isValidatorInactive(validator, epochResults):
      inactivityPenalty = this.calculateInactivityPenalty(validator, epochNumber)
      validatorPenalty += inactivityPenalty

    # Slashing penalties
    slashingPenalty = this.calculateSlashingPenalty(validator, epochResults.slashings)
    validatorPenalty += slashingPenalty

    if validatorReward > 0:
      rewards.push({
        validatorIndex: validatorIndex,
        amount: validatorReward,
        type: 'epoch_reward'
      })

    if validatorPenalty > 0:
      penalties.push({
        validatorIndex: validatorIndex,
        amount: validatorPenalty,
        type: 'epoch_penalty'
      })

  return { rewards: rewards, penalties: penalties }

function detectSlashing(attestations, proposedBlocks):
  slashingEvents = []

  # Double voting detection
  doubleVotes = this.detectDoubleVoting(attestations)
  slashingEvents.push(...doubleVotes)
```

```
  # Surround voting detection
  surroundVotes = this.detectSurroundVoting(attestations)
  slashingEvents.push(...surroundVotes)

  # Double block proposal detection
  doubleProposals = this.detectDoubleProposal(proposedBlocks)
  slashingEvents.push(...doubleProposals)

  return slashingEvents

function detectDoubleVoting(attestations):
  # Group attestations by validator and target epoch
  attestationsByValidator = new Map()

  for attestation in attestations:
    validatorIndex = attestation.validatorIndex
    targetEpoch = attestation.data.target.epoch

    key = `${validatorIndex}:${targetEpoch}`

    if not attestationsByValidator.has(key):
      attestationsByValidator.set(key, [])

    attestationsByValidator.get(key).push(attestation)

  # Check for double voting
  doubleVotes = []

  for [key, validatorAttestations] in attestationsByValidator:
    if validatorAttestations.length > 1:
      # Multiple attestations for same target epoch - potential double vote
      for i in range(validatorAttestations.length):
        for j in range(i + 1, validatorAttestations.length):
          att1 = validatorAttestations[i]
          att2 = validatorAttestations[j]

          # Check if attestations are conflicting
          if this.areAttestationsConflicting(att1, att2):
            doubleVotes.push({
              type: 'double_vote',
              validatorIndex: att1.validatorIndex,
              attestation1: att1,
              attestation2: att2,
              penalty: this.calculateSlashingAmount(att1.validatorIndex, 'double_vote'
```

```
          })

  return doubleVotes

function checkFinality(epochNumber, epochResults):
  # Check if we have supermajority attestations for justification
  totalActiveValidators = this.getTotalActiveValidators()
  requiredAttestations = Math.floor(totalActiveValidators * 2 / 3) + 1

  # Count attestations for current and previous epochs
  currentEpochAttestations = epochResults.attestations.filter(
    att => att.data.target.epoch === epochNumber
  ).length

  previousEpochAttestations = epochResults.attestations.filter(
    att => att.data.target.epoch === epochNumber - 1
  ).length

  # Check justification conditions
  justifiedCheckpoints = []

  if currentEpochAttestations >= requiredAttestations:
    justifiedCheckpoints.push({
      epoch: epochNumber,
      attestations: currentEpochAttestations,
      justified: true
    })

  if previousEpochAttestations >= requiredAttestations:
    justifiedCheckpoints.push({
      epoch: epochNumber - 1,
      attestations: previousEpochAttestations,
      justified: true
    })

  # Check finality (requires 2 consecutive justified epochs)
  finalized = false
  if justifiedCheckpoints.length >= 2:
    consecutive = justifiedCheckpoints.some((checkpoint, index) =>
      index > 0 && checkpoint.epoch === justifiedCheckpoints[index - 1].epoch + 1
    )

    if consecutive:
      finalized = true
```

```
    return {
      finalized: finalized,
      justifiedCheckpoints: justifiedCheckpoints,
      attestationCounts: {
        current: currentEpochAttestations,
        previous: previousEpochAttestations,
        required: requiredAttestations
      }
    }
```

3. Mempool Management Algorithm

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Purpose: Efficiently manage pending transactions in memory, prioritizing them for block inclusion based on fees and other factors.

Priority-based Transaction Pool:

```
MempoolConfig = {
  limits: {
    maxTransactions: 100000,        # Maximum transactions in mempool
    maxPerAccount: 1000,            # Maximum transactions per account
    maxMemoryUsage: 1073741824,     # 1GB maximum memory usage
    maxTransactionAge: 3600000      # 1 hour maximum age
  },

  prioritization: {
    gasPrice: { weight: 0.6 },
    accountAge: { weight: 0.2 },
    transactionSize: { weight: 0.1 },
    nonce: { weight: 0.1 }
  },

  eviction: {
    strategy: 'lowest_priority_first',
    batchSize: 1000,
    triggerThreshold: 0.9           # Trigger eviction at 90% capacity
  }
}

class MempoolManager:
  constructor(config):
    this.config = config
    this.transactions = new Map()           # txHash -> transaction
```

```
  this.accountTransactions = new Map()    # account -> transaction list
  this.priorityQueue = new PriorityQueue()
  this.nonceQueues = new Map()           # account -> nonce-ordered queue
  this.memoryUsage = 0

function addTransaction(transaction):
  # Validate transaction format
  if not this.isValidTransaction(transaction):
    return { success: false, reason: 'invalid_transaction' }

  # Check if transaction already exists
  if this.transactions.has(transaction.hash):
    return { success: false, reason: 'duplicate_transaction' }

  # Check mempool capacity
  if this.isMemPoolFull():
    evictionResult = this.evictLowPriorityTransactions()
    if not evictionResult.success:
      return { success: false, reason: 'mempool_full' }

  # Check account transaction limits
  accountTxCount = this.getAccountTransactionCount(transaction.from)
  if accountTxCount >= this.config.limits.maxPerAccount:
    return { success: false, reason: 'account_limit_exceeded' }

  # Calculate transaction priority
  priority = this.calculateTransactionPriority(transaction)

  # Check if transaction can replace existing transaction
  replacementResult = this.checkTransactionReplacement(transaction)
  if replacementResult.shouldReplace:
    this.removeTransaction(replacementResult.replacedTransaction.hash)

  # Add transaction to mempool
  this.insertTransaction(transaction, priority)

  # Update account nonce queue
  this.updateAccountNonceQueue(transaction)

  # Notify listeners
  this.notifyTransactionAdded(transaction, priority)

  return {
    success: true,
    transactionHash: transaction.hash,
```

```
    priority: priority,
    estimatedInclusionTime: this.estimateInclusionTime(priority)
  }

function calculateTransactionPriority(transaction):
  priorityScore = 0

  # Gas price component (normalized)
  gasPriceScore = this.normalizeGasPrice(transaction.gasPrice)
  priorityScore += gasPriceScore * this.config.prioritization.gasPrice.weight

  # Account age component
  accountAge = this.getAccountAge(transaction.from)
  ageScore = Math.min(accountAge / (365 * 24 * 60 * 60 * 1000), 1) # Normalize to year
  priorityScore += ageScore * this.config.prioritization.accountAge.weight

  # Transaction size component (smaller is better)
  transactionSize = this.calculateTransactionSize(transaction)
  sizeScore = Math.max(0, 1 - (transactionSize / 10000)) # Normalize by 10KB
  priorityScore += sizeScore * this.config.prioritization.transactionSize.weight

  # Nonce proximity component (sequential nonces preferred)
  expectedNonce = this.getExpectedNonce(transaction.from)
  nonceGap = Math.abs(transaction.nonce - expectedNonce)
  nonceScore = Math.max(0, 1 - (nonceGap / 100)) # Normalize by 100 nonce gap
  priorityScore += nonceScore * this.config.prioritization.nonce.weight

  return priorityScore

function selectTransactionsForBlock(gasLimit, maxTransactions):
  selectedTransactions = []
  totalGasUsed = 0
  usedNonces = new Map() # account -> Set of used nonces

  # Create a copy of priority queue for selection
  candidateTransactions = this.priorityQueue.copy()

  while not candidateTransactions.isEmpty() and
        selectedTransactions.length < maxTransactions and
        totalGasUsed < gasLimit:

    # Get highest priority transaction
    candidate = candidateTransactions.dequeue()
    transaction = candidate.transaction
```

```
    # Check if transaction is still valid
    if not this.isTransactionValid(transaction):
      continue

    # Check nonce ordering
    if not this.canIncludeTransaction(transaction, usedNonces):
      continue

    # Check gas limit
    if totalGasUsed + transaction.gasLimit > gasLimit:
      continue

    # Add transaction to selection
    selectedTransactions.push(transaction)
    totalGasUsed += transaction.gasLimit

    # Update used nonces
    if not usedNonces.has(transaction.from):
      usedNonces.set(transaction.from, new Set())
    usedNonces.get(transaction.from).add(transaction.nonce)

  return {
    transactions: selectedTransactions,
    totalGasUsed: totalGasUsed,
    totalFees: this.calculateTotalFees(selectedTransactions)
  }

function canIncludeTransaction(transaction, usedNonces):
  # Check if account has used nonces
  accountNonces = usedNonces.get(transaction.from)

  if not accountNonces:
    # First transaction from this account - check if nonce is next expected
    expectedNonce = this.getExpectedNonce(transaction.from)
    return transaction.nonce === expectedNonce

  # Check if nonce follows sequence
  maxUsedNonce = Math.max(...accountNonces)
  return transaction.nonce === maxUsedNonce + 1

function evictLowPriorityTransactions():
  # Calculate how many transactions to evict
  currentCount = this.transactions.size
  targetCount = Math.floor(currentCount * 0.8) # Evict to 80% capacity
  evictionCount = currentCount - targetCount
```

```
  evictedTransactions = []

  # Evict oldest and lowest priority transactions first
  sortedTransactions = Array.from(this.transactions.values())
    .sort((a, b) => {
      # Sort by priority (ascending) then by age (descending)
      priorityDiff = a.priority - b.priority
      if priorityDiff !== 0:
        return priorityDiff

      return b.addedAt - a.addedAt
    })

  for i in range(Math.min(evictionCount, sortedTransactions.length)):
    transaction = sortedTransactions[i]
    this.removeTransaction(transaction.hash)
    evictedTransactions.push(transaction)

  # Notify about evictions
  this.notifyTransactionsEvicted(evictedTransactions)

  return {
    success: true,
    evictedCount: evictedTransactions.length,
    evictedTransactions: evictedTransactions
  }

function updateAccountNonceQueue(transaction):
  account = transaction.from

  if not this.nonceQueues.has(account):
    this.nonceQueues.set(account, new SortedQueue('nonce'))

  nonceQueue = this.nonceQueues.get(account)
  nonceQueue.enqueue(transaction)

  # Remove executed transactions
  this.cleanupNonceQueue(account)

function cleanupNonceQueue(account):
  nonceQueue = this.nonceQueues.get(account)
  expectedNonce = this.getExpectedNonce(account)

  # Remove transactions with nonces that are too old
```

```
  while not nonceQueue.isEmpty():
    frontTransaction = nonceQueue.peek()

    if frontTransaction.nonce < expectedNonce:
      # Transaction nonce is too old - remove it
      removedTx = nonceQueue.dequeue()
      this.removeTransaction(removedTx.hash)
    else:
      break

function getExecutableTransactions(account):
  nonceQueue = this.nonceQueues.get(account)

  if not nonceQueue or nonceQueue.isEmpty():
    return []

  executableTransactions = []
  expectedNonce = this.getExpectedNonce(account)

  # Get consecutive transactions starting from expected nonce
  queueCopy = nonceQueue.copy()

  while not queueCopy.isEmpty():
    transaction = queueCopy.dequeue()

    if transaction.nonce === expectedNonce:
      executableTransactions.push(transaction)
      expectedNonce++
    else:
      break # Gap in nonce sequence

  return executableTransactions

function removeTransaction(transactionHash):
  transaction = this.transactions.get(transactionHash)

  if not transaction:
    return false

  # Remove from main storage
  this.transactions.delete(transactionHash)

  # Remove from priority queue
  this.priorityQueue.remove(transaction)
```

```
  # Remove from account transactions
  accountTxs = this.accountTransactions.get(transaction.from)
  if accountTxs:
    accountTxs.delete(transactionHash)
    if accountTxs.size === 0:
      this.accountTransactions.delete(transaction.from)

  # Remove from nonce queue
  nonceQueue = this.nonceQueues.get(transaction.from)
  if nonceQueue:
    nonceQueue.remove(transaction)

  # Update memory usage
  this.memoryUsage -= this.calculateTransactionMemoryUsage(transaction)

  return true

function checkTransactionReplacement(newTransaction):
  # Check if there's an existing transaction with same nonce from same account
  accountTxs = this.accountTransactions.get(newTransaction.from)

  if not accountTxs:
    return { shouldReplace: false }

  for existingTxHash of accountTxs:
    existingTx = this.transactions.get(existingTxHash)

    if existingTx.nonce === newTransaction.nonce:
      # Same nonce - check if new transaction has higher gas price
      gasPriceIncrease = (newTransaction.gasPrice - existingTx.gasPrice) / existingTx.

      if gasPriceIncrease >= 0.1: # Require 10% increase
        return {
          shouldReplace: true,
          replacedTransaction: existingTx,
          gasPriceIncrease: gasPriceIncrease
        }
      else:
        return {
          shouldReplace: false,
          reason: 'insufficient_gas_price_increase',
          required: existingTx.gasPrice * 1.1,
          provided: newTransaction.gasPrice
        }
```

```
    return { shouldReplace: false }
```

4. Block Creation and Validation Algorithm

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Purpose: Create valid blocks with optimal transaction selection and validate incoming blocks for consensus compliance.

Optimized Block Assembly:

```
BlockConfig = {
  block: {
    maxGasLimit: 30000000,          # 30M gas units per block
    maxTransactions: 1000,          # Maximum transactions per block
    maxBlockSize: 2097152,          # 2MB maximum block size
    targetBlockTime: 12000          # 12 seconds target block time
  },

  validation: {
    strictValidation: true,
    allowEmptyBlocks: false,
    requireMinimumFees: true,
    validateStateRoot: true
  },

  optimization: {
    preferHighFeeTx: true,
    balanceGasUsage: true,
    optimizeInclusion: true,
    parallelize: true
  }
}

class BlockManager:
  constructor(config):
    this.config = config
    this.transactionPool = new TransactionPool()
    this.stateManager = new StateManager()
    this.gasCalculator = new GasCalculator()
    this.merkleTree = new MerkleTree()

  function createBlock(previousBlockHash, validatorIndex, timestamp):
    blockStart = Date.now()
```

```
# Get current state root
currentStateRoot = this.stateManager.getCurrentStateRoot()

# Select transactions for inclusion
transactionSelection = this.selectOptimalTransactions()

# Execute transactions and update state
executionResult = this.executeTransactions(transactionSelection.transactions)

# Calculate new state root
newStateRoot = this.stateManager.calculateStateRoot(executionResult.stateChanges)

# Create transaction Merkle tree
transactionMerkleRoot = this.merkleTree.calculateRoot(
  transactionSelection.transactions.map(tx => tx.hash)
)

# Create receipt Merkle tree
receiptMerkleRoot = this.merkleTree.calculateRoot(
  executionResult.receipts.map(receipt => receipt.hash)
)

# Build block header
blockHeader = {
  parentHash: previousBlockHash,
  stateRoot: newStateRoot,
  transactionRoot: transactionMerkleRoot,
  receiptRoot: receiptMerkleRoot,
  number: this.getNextBlockNumber(),
  timestamp: timestamp,
  gasUsed: executionResult.totalGasUsed,
  gasLimit: this.config.block.maxGasLimit,
  validatorIndex: validatorIndex,
  difficulty: 0, # Not used in PoS
  extraData: this.createExtraData()
}

# Calculate block hash
blockHash = this.calculateBlockHash(blockHeader)
blockHeader.hash = blockHash

# Assemble complete block
block = {
  header: blockHeader,
  transactions: transactionSelection.transactions,
```

```
    receipts: executionResult.receipts,
    stateChanges: executionResult.stateChanges,

    # Metadata
    createdAt: blockStart,
    processingTime: Date.now() - blockStart,
    transactionCount: transactionSelection.transactions.length,
    totalFees: executionResult.totalFees
  }

  return block

function selectOptimalTransactions():
  # Get available transactions from mempool
  availableTransactions = this.transactionPool.getPendingTransactions()

  # Group transactions by account and sort by nonce
  accountTransactions = this.groupTransactionsByAccount(availableTransactions)

  # Select transactions using greedy algorithm with optimizations
  selectedTransactions = []
  totalGasUsed = 0
  totalFees = 0

  # Create priority queue based on effective gas price
  transactionQueue = new PriorityQueue()

  # Add first transaction from each account to queue
  for [account, txList] in accountTransactions:
    if txList.length > 0:
      firstTx = txList[0]
      effectiveGasPrice = this.calculateEffectiveGasPrice(firstTx)
      transactionQueue.enqueue(firstTx, effectiveGasPrice)

  while not transactionQueue.isEmpty() and
        selectedTransactions.length < this.config.block.maxTransactions and
        totalGasUsed < this.config.block.maxGasLimit:

    # Get highest priority transaction
    transaction = transactionQueue.dequeue()

    # Check if transaction fits in remaining gas limit
    if totalGasUsed + transaction.gasLimit > this.config.block.maxGasLimit:
      continue
```

```
    # Validate transaction is still executable
    if not this.isTransactionExecutable(transaction):
      continue

    # Add transaction to selection
    selectedTransactions.push(transaction)
    totalGasUsed += transaction.gasLimit
    totalFees += transaction.gasPrice * transaction.gasLimit

    # Add next transaction from same account if available
    nextTx = this.getNextTransactionFromAccount(transaction.from, transaction.nonce +
    if nextTx:
      effectiveGasPrice = this.calculateEffectiveGasPrice(nextTx)
      transactionQueue.enqueue(nextTx, effectiveGasPrice)

  return {
    transactions: selectedTransactions,
    totalGasUsed: totalGasUsed,
    totalFees: totalFees,
    selectionTime: Date.now() - selectionStart
  }

function executeTransactions(transactions):
  executionStart = Date.now()
  receipts = []
  stateChanges = []
  totalGasUsed = 0
  totalFees = 0

  # Create execution context
  executionContext = {
    blockNumber: this.getNextBlockNumber(),
    timestamp: Date.now(),
    gasLimit: this.config.block.maxGasLimit,
    coinbase: this.getCoinbaseAddress()
  }

  # Execute transactions sequentially
  for i, transaction in transactions.entries():
    try:
      # Execute single transaction
      txResult = this.executeTransaction(transaction, executionContext)

      # Create transaction receipt
      receipt = {
```

```
        transactionHash: transaction.hash,
        transactionIndex: i,
        blockHash: null, # Will be set when block is created
        blockNumber: executionContext.blockNumber,
        from: transaction.from,
        to: transaction.to,
        gasUsed: txResult.gasUsed,
        cumulativeGasUsed: totalGasUsed + txResult.gasUsed,
        contractAddress: txResult.contractAddress,
        logs: txResult.logs,
        status: txResult.success ? 1 : 0,
        effectiveGasPrice: transaction.gasPrice
      }

      receipts.push(receipt)
      stateChanges.push(...txResult.stateChanges)
      totalGasUsed += txResult.gasUsed
      totalFees += txResult.gasUsed * transaction.gasPrice

      # Update execution context
      executionContext.gasUsed = totalGasUsed

    catch error:
      # Handle transaction execution error
      errorReceipt = this.createErrorReceipt(transaction, i, error)
      receipts.push(errorReceipt)

  return {
    receipts: receipts,
    stateChanges: stateChanges,
    totalGasUsed: totalGasUsed,
    totalFees: totalFees,
    executionTime: Date.now() - executionStart
  }

function validateBlock(block, parentBlock):
  validationStart = Date.now()
  validationErrors = []

  # Validate block header
  headerValidation = this.validateBlockHeader(block.header, parentBlock)
  if not headerValidation.isValid:
    validationErrors.push(...headerValidation.errors)

  # Validate transaction list
```

```
  transactionValidation = this.validateTransactions(block.transactions)
  if not transactionValidation.isValid:
    validationErrors.push(...transactionValidation.errors)

  # Validate gas usage
  gasValidation = this.validateGasUsage(block)
  if not gasValidation.isValid:
    validationErrors.push(...gasValidation.errors)

  # Validate state root
  if this.config.validation.validateStateRoot:
    stateValidation = this.validateStateRoot(block)
    if not stateValidation.isValid:
      validationErrors.push(...stateValidation.errors)

  # Validate Merkle roots
  merkleValidation = this.validateMerkleRoots(block)
  if not merkleValidation.isValid:
    validationErrors.push(...merkleValidation.errors)

  # Validate consensus rules
  consensusValidation = this.validateConsensusRules(block, parentBlock)
  if not consensusValidation.isValid:
    validationErrors.push(...consensusValidation.errors)

  return {
    isValid: validationErrors.length === 0,
    errors: validationErrors,
    validationTime: Date.now() - validationStart
  }

function validateBlockHeader(header, parentBlock):
  errors = []

  # Check parent hash
  if header.parentHash !== parentBlock.header.hash:
    errors.push({
      type: 'invalid_parent_hash',
      expected: parentBlock.header.hash,
      actual: header.parentHash
    })

  # Check block number
  expectedBlockNumber = parentBlock.header.number + 1
  if header.number !== expectedBlockNumber:
```

```
    errors.push({
      type: 'invalid_block_number',
      expected: expectedBlockNumber,
      actual: header.number
    })

  # Check timestamp
  if header.timestamp <= parentBlock.header.timestamp:
    errors.push({
      type: 'invalid_timestamp',
      parentTimestamp: parentBlock.header.timestamp,
      blockTimestamp: header.timestamp
    })

  # Check gas limit
  if header.gasLimit > this.config.block.maxGasLimit:
    errors.push({
      type: 'gas_limit_too_high',
      limit: header.gasLimit,
      maximum: this.config.block.maxGasLimit
    })

  # Check gas used
  if header.gasUsed > header.gasLimit:
    errors.push({
      type: 'gas_used_exceeds_limit',
      gasUsed: header.gasUsed,
      gasLimit: header.gasLimit
    })

  return {
    isValid: errors.length === 0,
    errors: errors
  }

function validateTransactions(transactions):
  errors = []
  accountNonces = new Map()

  for i, transaction in transactions.entries():
    # Validate individual transaction
    txValidation = this.validateTransaction(transaction)
    if not txValidation.isValid:
      errors.push({
        type: 'invalid_transaction',
```

```
          transactionIndex: i,
          transactionHash: transaction.hash,
          errors: txValidation.errors
        })
        continue

      # Check nonce ordering
      account = transaction.from
      expectedNonce = accountNonces.get(account) || this.getAccountNonce(account)

      if transaction.nonce !== expectedNonce:
        errors.push({
          type: 'invalid_nonce_order',
          transactionIndex: i,
          account: account,
          expected: expectedNonce,
          actual: transaction.nonce
        })

      # Update expected nonce for account
      accountNonces.set(account, transaction.nonce + 1)

    return {
      isValid: errors.length === 0,
      errors: errors
    }
```

5. Wallet and Address Management Algorithm

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Purpose: Manage cryptographic wallets, generate addresses, and handle secure key operations for blockchain interactions.

Hierarchical Deterministic Wallet System:

```
WalletConfig = {
  keyDerivation: {
    standard: 'bip44',              # BIP44 for hierarchical deterministic wallets
    purpose: 44,                    # BIP44 purpose
    coinType: 60,                   # Ethereum coin type
    maxAccounts: 1000,              # Maximum accounts per wallet
    maxAddresses: 10000             # Maximum addresses per account
  },
```

```
  security: {
    encryptionAlgorithm: 'aes-256-gcm',
    keyStrengthBits: 256,
    scryptParams: { N: 262144, r: 8, p: 1 },
    mnemonicStrength: 256           # 24-word mnemonic
  },

  addressGeneration: {
    checksumValidation: true,
    addressFormat: 'eip55',         # EIP-55 checksum addresses
    compressionEnabled: true
  }
}

class WalletManager:
  constructor(config):
    this.config = config
    this.hdWallets = new Map()              # walletId -> HD wallet
    this.addresses = new Map()              # address -> wallet info
    this.cryptoEngine = new CryptographicEngine()
    this.keyDerivation = new KeyDerivation()

  function createWallet(passphrase = '', options = {}):
    walletCreationStart = Date.now()

    # Generate entropy for mnemonic
    entropy = this.cryptoEngine.generateEntropy(this.config.security.mnemonicStrength)

    # Generate mnemonic phrase
    mnemonic = this.generateMnemonic(entropy)

    # Derive master seed from mnemonic
    masterSeed = this.deriveMasterSeed(mnemonic, passphrase)

    # Generate master key pair
    masterKeyPair = this.generateMasterKeyPair(masterSeed)

    # Create wallet structure
    wallet = {
      id: this.generateWalletId(),
      mnemonic: mnemonic,
      masterSeed: masterSeed,
      masterPublicKey: masterKeyPair.publicKey,
      masterPrivateKey: masterKeyPair.privateKey,
```

```
    # Derivation info
    derivationPath: `m/44'/${this.config.keyDerivation.coinType}'`,
    accounts: new Map(),

    # Metadata
    createdAt: Date.now(),
    lastUsed: Date.now(),
    isEncrypted: false,
    version: '1.0'
  }

  # Encrypt wallet if passphrase provided
  if passphrase:
    encryptedWallet = this.encryptWallet(wallet, passphrase)
    wallet.encryptedData = encryptedWallet.encryptedData
    wallet.encryptionParams = encryptedWallet.encryptionParams
    wallet.isEncrypted = true

    # Clear sensitive data from memory
    wallet.masterSeed = null
    wallet.masterPrivateKey = null

  # Store wallet
  this.hdWallets.set(wallet.id, wallet)

  # Generate default account
  defaultAccount = this.createAccount(wallet.id, 0)

  return {
    walletId: wallet.id,
    mnemonic: mnemonic,
    defaultAccount: defaultAccount,
    creationTime: Date.now() - walletCreationStart
  }

function createAccount(walletId, accountIndex):
  wallet = this.hdWallets.get(walletId)

  if not wallet:
    throw new Error('Wallet not found')

  if accountIndex >= this.config.keyDerivation.maxAccounts:
    throw new Error('Account index exceeds maximum')

  # Check if account already exists
```

```
  if wallet.accounts.has(accountIndex):
    return wallet.accounts.get(accountIndex)

  # Derive account key
  accountPath = `${wallet.derivationPath}/${accountIndex}'`
  accountKey = this.keyDerivation.deriveKey(wallet.masterPrivateKey, accountPath)

  # Create account structure
  account = {
    index: accountIndex,
    derivationPath: accountPath,
    publicKey: accountKey.publicKey,
    privateKey: accountKey.privateKey,
    addresses: new Map(),

    # Metadata
    createdAt: Date.now(),
    lastUsed: Date.now(),
    transactionCount: 0,
    balance: 0
  }

  # Generate default address (index 0)
  defaultAddress = this.generateAddress(walletId, accountIndex, 0, 0)

  # Store account
  wallet.accounts.set(accountIndex, account)

  return {
    accountIndex: accountIndex,
    derivationPath: accountPath,
    defaultAddress: defaultAddress.address,
    publicKey: account.publicKey
  }

function generateAddress(walletId, accountIndex, change, addressIndex):
  wallet = this.hdWallets.get(walletId)
  account = wallet.accounts.get(accountIndex)

  if not account:
    throw new Error('Account not found')

  if addressIndex >= this.config.keyDerivation.maxAddresses:
    throw new Error('Address index exceeds maximum')
```

```
  # Build full derivation path
  fullPath = `${account.derivationPath}/${change}/${addressIndex}`

  # Derive address key
  addressKey = this.keyDerivation.deriveKey(wallet.masterPrivateKey, fullPath)

  # Generate address from public key
  address = this.generateAddressFromPublicKey(addressKey.publicKey)

  # Apply EIP-55 checksum
  checksumAddress = this.applyChecksumEncoding(address)

  # Create address info
  addressInfo = {
    address: checksumAddress,
    derivationPath: fullPath,
    publicKey: addressKey.publicKey,
    privateKey: addressKey.privateKey,
    accountIndex: accountIndex,
    change: change,
    addressIndex: addressIndex,

    # Metadata
    createdAt: Date.now(),
    lastUsed: Date.now(),
    transactionCount: 0,
    balance: 0
  }

  # Store address mapping
  this.addresses.set(checksumAddress, {
    walletId: walletId,
    accountIndex: accountIndex,
    addressInfo: addressInfo
  })

  # Store in account
  account.addresses.set(addressIndex, addressInfo)

  return addressInfo

function signTransaction(address, transactionData, passphrase = ''):
  # Find address info
  addressMapping = this.addresses.get(address)
```

```
  if not addressMapping:
    throw new Error('Address not found in wallet')

  wallet = this.hdWallets.get(addressMapping.walletId)

  # Decrypt wallet if encrypted
  if wallet.isEncrypted:
    if not passphrase:
      throw new Error('Passphrase required for encrypted wallet')

    decryptedWallet = this.decryptWallet(wallet, passphrase)
    wallet = decryptedWallet

  # Get private key for address
  addressInfo = addressMapping.addressInfo
  privateKey = addressInfo.privateKey

  # Create transaction hash
  transactionHash = this.createTransactionHash(transactionData)

  # Sign transaction
  signature = this.cryptoEngine.signMessage(transactionHash, privateKey)

  # Create signed transaction
  signedTransaction = {
    ...transactionData,
    hash: transactionHash,
    signature: signature,
    from: address,

    # Signature components
    r: signature.r,
    s: signature.s,
    v: signature.v
  }

  # Update address usage
  addressInfo.lastUsed = Date.now()
  addressInfo.transactionCount++

  return signedTransaction

function generateMnemonic(entropy):
  # Convert entropy to mnemonic using BIP39
  entropyBits = entropy.length * 8
```

```
  checksumBits = entropyBits / 32

  # Calculate checksum
  entropyHash = this.cryptoEngine.sha256(entropy)
  checksum = this.extractBits(entropyHash, 0, checksumBits)

  # Combine entropy and checksum
  combinedBits = this.combineBits(entropy, checksum)

  # Convert to mnemonic words
  wordList = this.getBip39WordList()
  mnemonicWords = []

  for i in range(0, combinedBits.length, 11):
    # Extract 11-bit segments
    wordIndex = this.extractBits(combinedBits, i, 11)
    mnemonicWords.push(wordList[wordIndex])

  return mnemonicWords.join(' ')

function deriveMasterSeed(mnemonic, passphrase):
  # Use PBKDF2 to derive seed from mnemonic
  salt = 'mnemonic' + passphrase

  masterSeed = this.cryptoEngine.pbkdf2(
    mnemonic,
    salt,
    2048,  # iterations
    64     # output length in bytes
  )

  return masterSeed

function generateMasterKeyPair(masterSeed):
  # Use HMAC-SHA512 to generate master key
  hmacKey = 'ed25519 seed'
  hmacOutput = this.cryptoEngine.hmacSha512(hmacKey, masterSeed)

  # Split output into private key and chain code
  privateKey = hmacOutput.slice(0, 32)
  chainCode = hmacOutput.slice(32, 64)

  # Generate public key from private key
  publicKey = this.cryptoEngine.generatePublicKey(privateKey)
```

```
  return {
    privateKey: privateKey,
    publicKey: publicKey,
    chainCode: chainCode
  }

function generateAddressFromPublicKey(publicKey):
  # Use Keccak-256 hash of public key
  publicKeyHash = this.cryptoEngine.keccak256(publicKey)

  # Take last 20 bytes as address
  address = publicKeyHash.slice(-20)

  # Convert to hex string
  addressHex = '0x' + address.toString('hex')

  return addressHex

function applyChecksumEncoding(address):
  # Remove '0x' prefix
  addressLower = address.slice(2).toLowerCase()

  # Hash the lowercase address
  addressHash = this.cryptoEngine.keccak256(addressLower)

  # Apply checksum
  checksumAddress = '0x'

  for i in range(addressLower.length):
    char = addressLower[i]
    hashByte = parseInt(addressHash[Math.floor(i / 2)], 16)

    if i % 2 === 0:
      # Even index - check upper 4 bits
      shouldCapitalize = (hashByte & 0xf0) >= 0x80
    else:
      # Odd index - check lower 4 bits
      shouldCapitalize = (hashByte & 0x0f) >= 0x08

    checksumAddress += shouldCapitalize ? char.toUpperCase() : char

  return checksumAddress

function encryptWallet(wallet, passphrase):
  # Generate salt
```

```
  salt = this.cryptoEngine.generateRandomBytes(32)

  # Derive encryption key using scrypt
  encryptionKey = this.cryptoEngine.scrypt(
    passphrase,
    salt,
    this.config.security.scryptParams.N,
    this.config.security.scryptParams.r,
    this.config.security.scryptParams.p,
    32 # 256 bits
  )

  # Serialize sensitive wallet data
  sensitiveData = JSON.stringify({
    masterSeed: wallet.masterSeed,
    masterPrivateKey: wallet.masterPrivateKey,
    accounts: wallet.accounts
  })

  # Generate initialization vector
  iv = this.cryptoEngine.generateRandomBytes(12)

  # Encrypt using AES-256-GCM
  encryptionResult = this.cryptoEngine.aesGcmEncrypt(sensitiveData, encryptionKey, iv)

  return {
    encryptedData: encryptionResult.ciphertext,
    encryptionParams: {
      algorithm: this.config.security.encryptionAlgorithm,
      salt: salt,
      iv: iv,
      authTag: encryptionResult.authTag,
      scryptParams: this.config.security.scryptParams
    }
  }

function validateAddress(address):
  # Check format
  if not address.startsWith('0x') or address.length !== 42:
    return { isValid: false, reason: 'invalid_format' }

  # Check hex characters
  hexPart = address.slice(2)
  if not /^[0-9a-fA-F]+$/.test(hexPart):
    return { isValid: false, reason: 'invalid_hex_characters' }
```

```
  # Validate checksum if mixed case
  if this.isMixedCase(hexPart):
    expectedChecksum = this.applyChecksumEncoding(address.toLowerCase())
    if address !== expectedChecksum:
      return { isValid: false, reason: 'invalid_checksum' }

  return { isValid: true }

function getWalletBalance(walletId):
  wallet = this.hdWallets.get(walletId)

  if not wallet:
    throw new Error('Wallet not found')

  totalBalance = 0
  accountBalances = []

  for [accountIndex, account] in wallet.accounts:
    accountBalance = 0

    for [addressIndex, addressInfo] in account.addresses:
      # Get current balance for address
      currentBalance = this.getAddressBalance(addressInfo.address)
      addressInfo.balance = currentBalance
      accountBalance += currentBalance

    account.balance = accountBalance
    totalBalance += accountBalance

    accountBalances.push({
      accountIndex: accountIndex,
      balance: accountBalance,
      addressCount: account.addresses.size
    })

  return {
    walletId: walletId,
    totalBalance: totalBalance,
    accountBalances: accountBalances,
    lastUpdated: Date.now()
  }
```

Performance Optimizations

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Blockchain Performance Strategies

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Network and Database Optimization:

```
PerformanceOptimization = {
  networking: {
    connectionPooling: true,
    messageCompression: true,
    batchedBroadcasting: true,
    intelligentPeering: true
  },

  storage: {
    levelDbOptimization: true,
    statePruning: true,
    snapshotGeneration: true,
    parallelValidation: true
  },

  caching: {
    blockCache: { size: 1000, ttl: 3600000 },
    stateCache: { size: 10000, ttl: 1800000 },
    transactionCache: { size: 50000, ttl: 600000 }
  }
}
```

Consensus Optimization

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Validator Performance Enhancement: - Parallel attestation processing - Optimized signature aggregation - Efficient committee selection - Fast finality detection

Security Considerations

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Blockchain Security Framework

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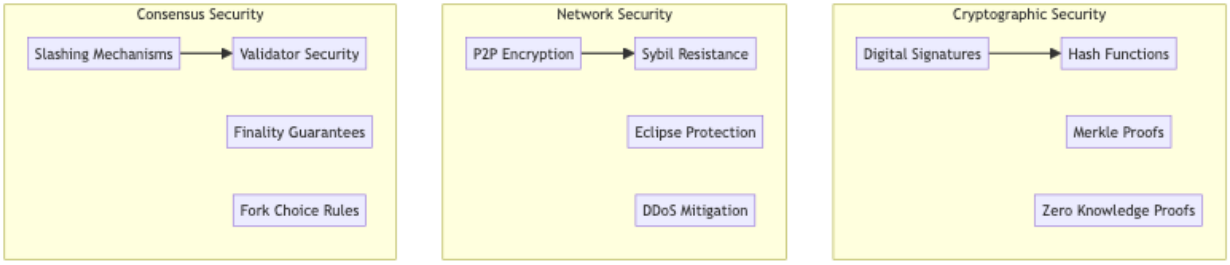

Testing Strategy

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Blockchain Testing Framework

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Comprehensive Testing Approach: - Unit testing for individual components - Integration testing for service interactions - Load testing for transaction throughput - Security testing for vulnerability assessment - Consensus testing for Byzantine fault tolerance

Network Simulation

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Distributed Testing Environment: - Multi-node test networks - Network partition simulation - Latency and failure injection - Validator behavior simulation

Trade-offs and Considerations

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Scalability vs Decentralization

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- **Transaction throughput**: Speed vs network distribution
- **Block size**: Capacity vs propagation time
- **Validator count**: Security vs coordination complexity
- **State storage**: Accessibility vs storage requirements

Security vs Performance

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- **Cryptographic operations**: Security strength vs computational cost
- **Consensus mechanisms**: Byzantine fault tolerance vs speed
- **Transaction validation**: Thoroughness vs processing time
- **Network protocols**: Security vs efficiency

Usability vs Technical Complexity

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- **Wallet interfaces**: User-friendliness vs technical control
- **Transaction fees**: Predictability vs market efficiency
- **Block confirmations**: Speed vs finality guarantees
- **Smart contract complexity**: Functionality vs gas costs

This blockchain/cryptocurrency transaction system provides a comprehensive foundation for distributed ledger technology with features like proof-of-stake consensus, transaction validation, mempool management, block creation, and wallet management while maintaining high security, performance, and decentralization standards.