

L22: NFT Metadata and IPFS

Module C: NFTs & Digital Assets

Blockchain & Cryptocurrency Course

December 2025

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

- Understand the JSON metadata format standard for NFTs
- Explain how IPFS content addressing works
- Describe the role of pinning services in NFT permanence
- Compare IPFS and Arweave for decentralized storage
- Evaluate metadata permanence and availability challenges

NFT Metadata: The JSON Standard

Metadata Structure: OpenSea standard (widely adopted)

Core Fields:

- `name` – Display name of the NFT
- `description` – Human-readable description
- `image` – URI to primary visual asset (IPFS, HTTP)
- `external_url` – Link to project website or details
- `attributes` – Array of trait objects

Example Metadata JSON:

```
{  
  "name": "Bored Ape #1234",  
  "description": "A unique Bored Ape Yacht Club NFT",  
  "image": "ipfs://QmXyZ.../1234.png",  
  "attributes": [  
    {"trait_type": "Background", "value": "Blue"},  
    {"trait_type": "Hat", "value": "Beanie"}  
  ]  
}
```

Attributes: Defining Rarity

Attributes Array: Defines traits and properties

Attribute Object Structure:

- trait_type – Category name (e.g., “Hat”, “Eyes”)
- value – Specific value (e.g., “Beanie”, “Laser Eyes”)
- display_type (optional) – How to render (number, date, boost)

Rarity Calculation:

- Each trait has a frequency distribution in the collection
- Rarer traits (low frequency) increase NFT value
- Tools like Rarity Sniper calculate rarity scores

Example Rarity Analysis:

- Background: Blue (20% frequency) vs. Gold (2% frequency)
- Laser Eyes: 1% frequency (highly rare)

IPFS: Decentralized peer-to-peer file storage protocol

Key Concepts:

- **Content Addressing:** Files identified by cryptographic hash
- **CID (Content Identifier):** Unique hash of file content
- **Immutability:** Same content always produces same CID
- **Distributed:** Files stored across multiple nodes
- **Retrieval:** Any node with the file can serve it

Example IPFS URI:

- `ipfs://QmXyZ123abc...` (CID)
- Gateway URL: `https://ipfs.io/ipfs/QmXyZ123abc...`

Content Addressing vs. Location Addressing

Traditional Web (Location Addressing):

- URL points to server location: `https://server.com/file.jpg`
- Content can change without URL changing
- Server failure = file unavailable

IPFS (Content Addressing):

- CID derived from file content: `QmXYZ...`
- Changing content changes CID
- File available from any node that has it
- Verifiable integrity (hash mismatch = tampering detected)

Advantage for NFTs:

- Guarantees metadata/image match the CID in `tokenURI`
- No server dependency (decentralized retrieval)

CID Components:

- **Version:** CIDv0 (QmXyZ...) or CIDv1 (bafybeig...)
- **Multicodec:** Specifies content type (dag-pb, raw, etc.)
- **Multihash:** Hash algorithm (SHA-256) + hash value

Example:

- CIDv0: QmYwAPJzv5CZsnA625s3Xf2nemtYgPpHdWEz79ojWnPbdG
- CIDv1: bafybeigdyrzt5sfp7udm7hu76uh7y26nf3efuylqabf3oclgtqy55fbzdi

Determinism:

- Same file always produces same CID
- Different files always produce different CIDs

Pinning: Ensuring Availability

IPFS Garbage Collection: Nodes delete unpinned files to save space

Pinning: Explicitly keeping a file on IPFS nodes

Without Pinning:

- File may be removed from all nodes (lost)
- NFT metadata/images become unavailable
- Broken image links in wallets and marketplaces

Pinning Services:

- **Pinata:** Popular commercial pinning service
- **NFT.Storage:** Free pinning for NFT data (funded by Filecoin)
- **Infura IPFS:** Enterprise-grade IPFS infrastructure
- **Self-hosting:** Run your own IPFS node and pin files

Critical Issue: If all pinning stops, files may disappear from IPFS

Gateway: HTTP bridge to access IPFS content

Public Gateways:

- [https://ipfs.io/ipfs/\[CID\]](https://ipfs.io/ipfs/[CID])
- [https://gateway.pinata.cloud/ipfs/\[CID\]](https://gateway.pinata.cloud/ipfs/[CID])
- [https://cloudflare-ipfs.com/ipfs/\[CID\]](https://cloudflare-ipfs.com/ipfs/[CID])

Why Gateways Matter:

- Browsers do not natively support `ipfs://` protocol
- Wallets and marketplaces use gateways to display NFTs
- Gateway downtime = NFTs appear broken (even if IPFS file exists)

Centralization Risk:

- Most users rely on centralized gateways (ipfs.io, Cloudflare)
- Gateway can censor or throttle content
- Solution: Native IPFS support in browsers (IPFS Companion extension)

Arweave: Permanent Decentralized Storage

Arweave: Blockchain designed for permanent data storage

Key Differences from IPFS:

- **Permanence:** One-time payment for perpetual storage
- **Blockchain-based:** Data stored on Arweave blockchain
- **Economic model:** Storage endowment fund pays miners forever
- **No pinning needed:** Data guaranteed to persist

Arweave URI:

- ar://[Transaction ID]
- Gateway: [https://arweave.net/\[Transaction ID\]](https://arweave.net/[Transaction ID])

Use Cases:

- High-value NFTs requiring guaranteed permanence
- Historical records and archives
- Alternative to IPFS for critical metadata

IPFS vs. Arweave Comparison

Feature	IPFS	Arweave
Storage Model	Peer-to-peer distributed	Blockchain-based
Permanence	Requires pinning	Guaranteed (one-time fee)
Cost	Free + pinning service fees	Pay once (e.g., \$5-10/GB)
Retrieval	Fast (popular files cached)	Slower (blockchain retrieval)
Adoption	High (majority of NFTs)	Growing (premium projects)
Censorship Risk	Gateway-dependent	Minimal (blockchain-based)
Data Mutability	Immutable (new CID if changed)	Immutable (on-chain)

Recommendation:

- IPFS: Most NFT projects (cost-effective, fast)
- Arweave: Premium/historical NFTs (guaranteed permanence)

Real-World Issues:

- ① **Unpinned IPFS files:** Project abandons pinning, files lost
- ② **Centralized metadata servers:** Company shuts down, NFTs break
- ③ **Mutable tokenURI:** Smart contract allows owner to change metadata
- ④ **Gateway failures:** IPFS gateways go offline, NFTs appear broken
- ⑤ **Link rot:** HTTP URLs stop working (404 errors)

Case Study: Nifty Gateway (2021):

- Platform used centralized servers for metadata
- Outage caused all NFTs to display broken images
- Community backlash led to IPFS migration

Mutable Metadata:

- Smart contract owner can update tokenURI
- Allows bug fixes and metadata improvements
- Risk: Owner could change artwork or traits (rug pull)

Immutable Metadata:

- tokenURI frozen after minting (contract locked)
- Guarantees metadata cannot be altered
- Standard for high-value collections (e.g., CryptoPunks)

Verification:

- Check smart contract code for `setTokenURI()` functions
- Verify contract ownership is renounced (no admin control)
- Use Etherscan to audit contract mutability

For NFT Projects:

- ① **Use IPFS or Arweave:** Avoid centralized servers
- ② **Pin all files:** Use reputable pinning services (Pinata, NFT.Storage)
- ③ **Freeze metadata:** Make tokenURI immutable after reveal
- ④ **Redundancy:** Pin to multiple services (IPFS + Arweave)
- ⑤ **Document storage:** Inform buyers where metadata is hosted
- ⑥ **Community pinning:** Encourage holders to pin collection files

For NFT Buyers:

- Verify metadata is on IPFS/Arweave (not HTTP)
- Check if tokenURI is immutable
- Confirm pinning service reputation

Current NFT Storage Breakdown (Estimated):

- **IPFS:** 60-70% of NFT projects
- **Centralized servers:** 20-25% (HTTP URLs)
- **Arweave:** 5-10% (growing)
- **Fully on-chain:** <5% (rare, expensive)

Trends:

- Migration from centralized to IPFS accelerating
- Premium projects adopting Arweave for permanence guarantees
- Layer 2 solutions (Polygon) enabling cheaper on-chain storage

NFT.Storage: Free IPFS Pinning

NFT.Storage: Protocol Labs initiative (Filecoin Foundation)

Service Features:

- Free IPFS pinning for NFT data
- Automatic backup to Filecoin network
- Simple API for developers
- No usage limits or expiration

How It Works:

- ① Developer uploads NFT metadata/images via API
- ② Files pinned to IPFS nodes
- ③ Backed up to Filecoin decentralized storage
- ④ Retrieval via standard IPFS gateways

Sustainability: Funded by Filecoin ecosystem to support Web3 adoption

Warning Signs of Poor Metadata Practices:

- ① **HTTP URLs:** `https://project.com/metadata/123.json`
 - Centralized, subject to server failure
- ② **Mutable tokenURI:** Contract has `setTokenURI()` function
 - Owner can change metadata at will
- ③ **No pinning documentation:** Project silent on storage strategy
 - Files may not be pinned (risk of loss)
- ④ **Unknown IPFS gateway:** Custom gateway not reputable
 - Gateway failure = broken NFTs
- ⑤ **Unrevealed metadata:** Placeholder images before reveal
 - Risk of metadata not matching expectations

CryptoPunks (2017): Early NFT project, metadata evolution

Original Implementation:

- Images and traits stored on-chain (contract storage)
- No external metadata files needed
- True permanence and decentralization

Wrapped Punks (2021):

- ERC-721 wrapper for original punks (compatibility)
- Metadata on IPFS for marketplace display
- Maintains on-chain source of truth

Lesson: On-chain storage provides maximum permanence but at high cost

Lazy Metadata Loading

Lazy Loading: Metadata generated on-demand, not pre-stored

Approach:

- Smart contract computes metadata dynamically
- `tokenURI()` function generates JSON on-chain
- No external storage needed (fully on-chain)

Example: Loot (2021):

- Randomized adventure gear NFTs
- Metadata generated as Base64-encoded SVG in contract
- Zero external dependencies

Trade-offs:

- Maximum decentralization and permanence
- Limited to text/simple graphics (gas constraints)
- Not suitable for complex images or videos

Key Takeaways

- ① NFT metadata follows a JSON standard (name, description, image, attributes)
- ② IPFS uses content addressing (CIDs) for decentralized, immutable storage
- ③ Pinning is critical for IPFS file permanence (unpinned files can be lost)
- ④ Arweave provides guaranteed permanent storage for a one-time fee
- ⑤ Metadata permanence challenges include unpinned files, mutable URIs, and centralized servers
- ⑥ Best practice: Use IPFS/Arweave, pin to multiple services, freeze metadata after minting

- ① What are the trade-offs between IPFS and Arweave for NFT metadata storage?
- ② Should NFT metadata be immutable, or is mutability acceptable for bug fixes?
- ③ How can the NFT community ensure long-term metadata availability without centralized pinning services?
- ④ Is fully on-chain metadata the ideal, or are off-chain solutions sufficient?
- ⑤ What happens to NFT value if metadata becomes unavailable but ownership records remain?

L23: NFT Marketplaces

We will explore:

- OpenSea, Blur, and Rarible business models
- Listing mechanics and order book systems
- Marketplace fees and royalty enforcement
- Wash trading and market manipulation detection
- Aggregators and cross-marketplace trading

Preparation: Create a wallet and browse NFT collections on OpenSea