Attendance Marking System

Title: *A Decentralized Merkle-Based Attendance marking and verification DApp*

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Abstract (Summary)

A decentralized application which provides tamper-evident recording and later verification of class/session attendance on Ethereum testnet (Sepolia). Teachers (or third parties) may subsequently verify any attendee's presence without reconstructing full histories on-chain. The architecture leverages: (1) an AttendanceSystem contract (for class/session lifecycle, root storage, and proof verification); (2) an AttendanceToken contract acting as a restricted minter (authorized system only) for attendance badges; (3) a server that collects addresses, builds sorted-pair Merkle trees, pins finalized records to IPFS (Pinata), and exposes proof endpoints; and (4) a React/TypeScript frontend using viem/wagmi for gasless simulation and transaction flow.

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1. Introduction

1.1 Problem Statement

Traditional attendance systems depend on centralized databases vulnerable to manipulation, opaque auditing, and single points of failure. Verifying historical attendance for a specific individual or date requires trusting the administrator's records. The challenge: provide an immutable, easily verifiable record of who attended a session—without storing large datasets or personally identifiable information directly on-chain, and enabling independent verification at any later time.

Decentralization uniquely addresses:

- **Integrity:** Merkle root commits the entire set; any alteration of off-chain records invalidates proofs.
- **Transparency:** Anyone can recompute the root from the IPFS JSON and compare to the stored commitment.
- **Self-sovereign claims:** Students claim tokens directly; teachers cannot forge claims on their behalf.
- **Auditability:** A transaction hash on Etherscan becomes a permanent anchor for each finalized session.

1.2 Objectives

- Record class sessions and attendee addresses securely.
- Generate deterministic Merkle trees and store only roots + metadata on-chain.
- Pin canonical session JSON to IPFS and link via CID in finalization transactions.
- Provide Merkle proof–based claim flow to mint a non-transferable attendance token.
- Allow off-chain and on-chain verification of any student's attendance.
- Ensure extensibility for per-date session indexing and future privacy-oriented improvements.

1.3 Scope and Limitations

Scope:

- Single-chain (Sepolia testnet) deployment.
- Attendance tracking by wallet address (no identity abstraction).
- One Merkle tree per finalized class.
- Non-transferable ERC-721 token issuance for claimed attendance.

Limitations:

- Privacy: addresses are public.
- Replay safety tied to leaf salts (chainId, contract); porting to new contracts invalidates existing proofs unless roots are migrated.
- No formal third-party audit yet; relies on internal reviews and OpenZeppelin libraries.
- Trust in server for canonical ordering and IPFS pinning (although tampering breaks chain root consistency).
- Single leaf format version; changes require versioned handling.

2. System Architecture

2.1 Overview

Logical components:

1. **Frontend (React/TypeScript):** Provides teacher dashboard (register, create class, rotate off-chain codes, finalize, verify) and student dashboard (mark attendance, claim token).
2. **Server (Node/Express):** In-memory or persistence layer for temporary attendee capture, Merkle tree construction (sorted pairs), proof generation, IPFS pinning (Pinata), and finalize transaction orchestration.
3. **Smart Contracts (Solidity):**
   - AttendanceSystem: Manages class metadata, finalization (root, total, content hash, CID), Merkle proof verification, and gating logic.
   - AttendanceToken: ERC-721 derivative with restricted minting (soulbound semantics).
4. **IPFS (Pinata):** Stores canonical JSON { chainId, contract, uniqueCode, attendees[], timestamp }.
5. **Blockchain (Ethereum Sepolia):** Persists minimal immutable commitments (root + metadata) and token mint events.

Data Flow (Finalization):
Frontend (Teacher) → Server: request finalize → Server builds Merkle tree → Pin JSON to IPFS → Returns CID, root, total, contentHash → Frontend simulates contract call → MetaMask finalizes → On-chain event logs root + CID → Teacher UI displays root & CID.

Claim Flow:
Student marks attendance → Address added off-chain → Teacher finalizes (root includes address) → Student fetches proof from server → Submit claim → Contract verifies proof → Mints soulbound token.

2.2 Component Responsibilities

- **Leaf Construction:** keccak256(abi.encode(chainId, contractAddress, uniqueCode, studentAddress)).
- **Merkle Tree:** Server uses merkletreejs with sortPairs: true.
- **On-chain Storage:** mapping(string => ClassFinalization) or extended structure storing root, total, contentHash, cid.
- **Token Mint:** AttendanceSystem authorized as minter; token ID increments per successful claim.

3. Technology Stack

- **Blockchain:** Ethereum Sepolia testnet.
- **Smart Contracts:** Solidity ^0.8.20, OpenZeppelin (ERC721, Ownable, MerkleProof).
- **Development Framework:** Hardhat + Ignition module deployment, Etherscan verification plugin.
- **Frontend:** React, TypeScript, Vite, wagmi/viem for RPC interactions & simulations.
- **Server:** Node.js, Express, Pinata SDK for IPFS pinning, merkletreejs for tree construction.
- **Hashing:** Keccak256 (Solidity intrinsic / viem / merkletreejs).
- **Wallet Integration:** MetaMask.

- **Dependency Control:** npm with lock file; environment variables for chainId, contract address, Pinata JWT.

4. Smart Contract Development

4.1 Design Patterns & Principles

- **Separation of Concerns:** AttendanceSystem handles logic; AttendanceToken purely stores mintable attendance badges (SBT style).
- **Access Control:** Only registered teachers can finalize; only system (minter) can call token mint.
- **Minimal On-chain Data:** Root, counts, content hash, CID — no full arrays.
- **Deterministic Salting:** Include block.chainid + address(this) + uniqueCode to prevent cross-contract replay.
- **Event Emission:** ClassFinalizedWithCID logs parameters for Etherscan transparency.
- **Soulbound Pattern:** Override transfer hooks or omit exposed transfer functions (or revert on transfer attempts) to keep tokens non-transferable.

4.2 Core Contracts & Functions

AttendanceSystem:

- registerTeacher(): Marks msg.sender eligible for class creation/finalization.
- createClass(string uniqueCode, timestamp ...): Initializes class record.
- finalizeClassWithCID(string uniqueCode, bytes32 root, uint32 total, bytes32 contentHash, string cid): Stores Merkle root & metadata; emits event.
- verifyAttendance(string uniqueCode, address student, bytes32[] proof) view returns (bool): Recomputes leaf; verifies proof.
- claim(string uniqueCode, bytes32[] proof): Validates proof and mints attendance token if not already claimed.
- getFinalization(string uniqueCode) view: Returns root, total, contentHash, cid (and optionally timestamp).

AttendanceToken:

- setMinter(address system) onlyOwner: Authorizes AttendanceSystem.
- mintAttendance(address to, string uniqueCode): Called only by authorized system; mints new token ID.
- Override/guard transfers: Enforce soulbound semantics (implementation-dependent).

Merkle Proof:

- Uses sorted pair hashing; server ensures ordering, contract relies on OpenZeppelin MerkleProof.verify.

4.3 Security Considerations

- **Reentrancy:** Not critical (no external calls during state changes except safe ERC-721 mint); still could apply ReentrancyGuard if extended.
- **Input Validation:** Reject zero roots, empty CID, duplicate class codes.

- **Replay Protection:** Leaf salts incorporate chain and contract address.
- **Authorization:** Teacher registration gating; minter restriction in token contract.
- **Proof Correctness:** Sorted pairs requirement documented; mismatch triggers Invalid proof revert.
- **Gas Efficiency:** Store fixed-size data; avoid arrays. Single SSTORE per field on finalization.
- **Upgradability Risks:** Absent; migrations require manual data bridging.
- **External Libraries:** OpenZeppelin audited components reduce implementation attack surface.

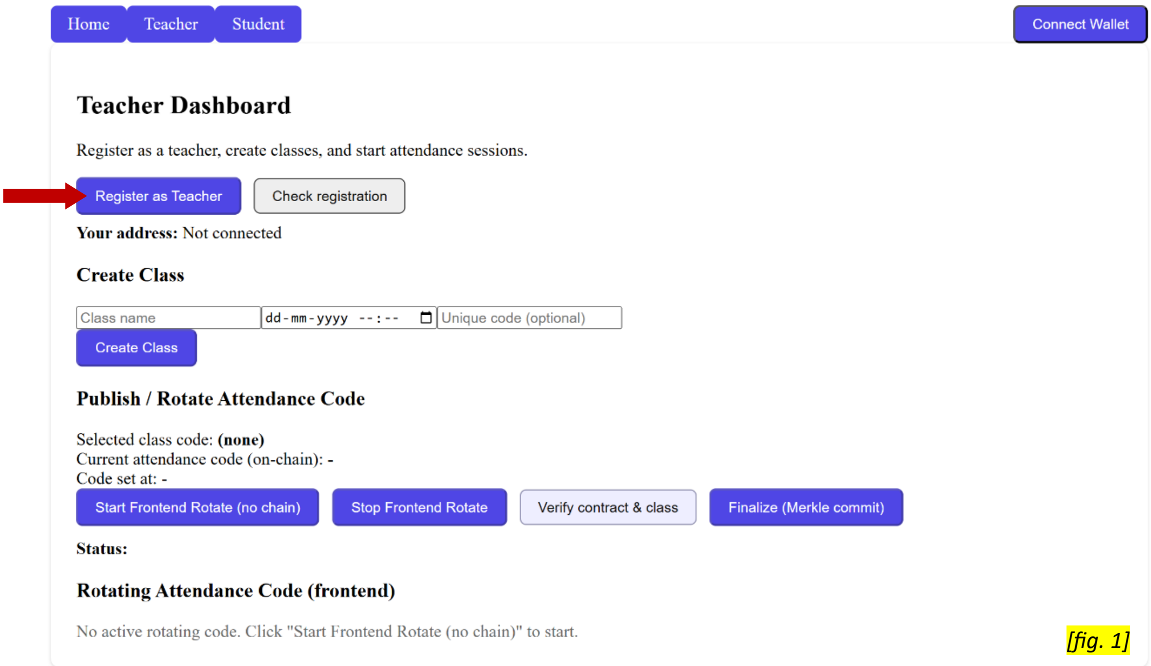
4.4 Deployment Process

- **Compilation:** npx hardhat compile.
- **Ignition Deployment:** npx hardhat ignition deploy [AttendanceSystem.ts](http://_vscodecontentref_/0) --network sepolia --deployment-id AttendanceDeployment-v2.
- **Verification:** npx hardhat verify --network sepolia <AttendanceSystemAddress> after flatten or artifact availability.
- **Address Propagation:** Update frontend contracts.ts and server env CONTRACT_ADDRESS, restart processes.
- **Pinata Setup:** Provide PINATA_JWT in .env; server pins JSON and obtains CID prior to finalization.

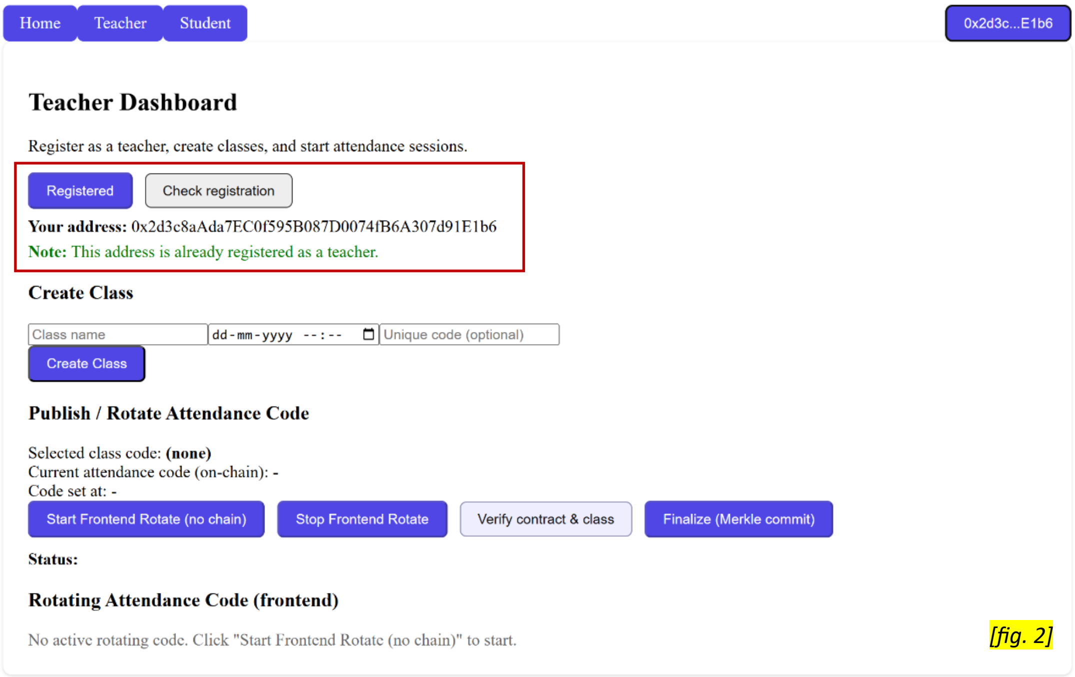
5. Frontend Implementation

The interface is split into Teacher and Student tabs. Teacher workflow:

1.Register as teacher (button (see fig. 1) triggers transaction; status reflected (see fig. 2)).

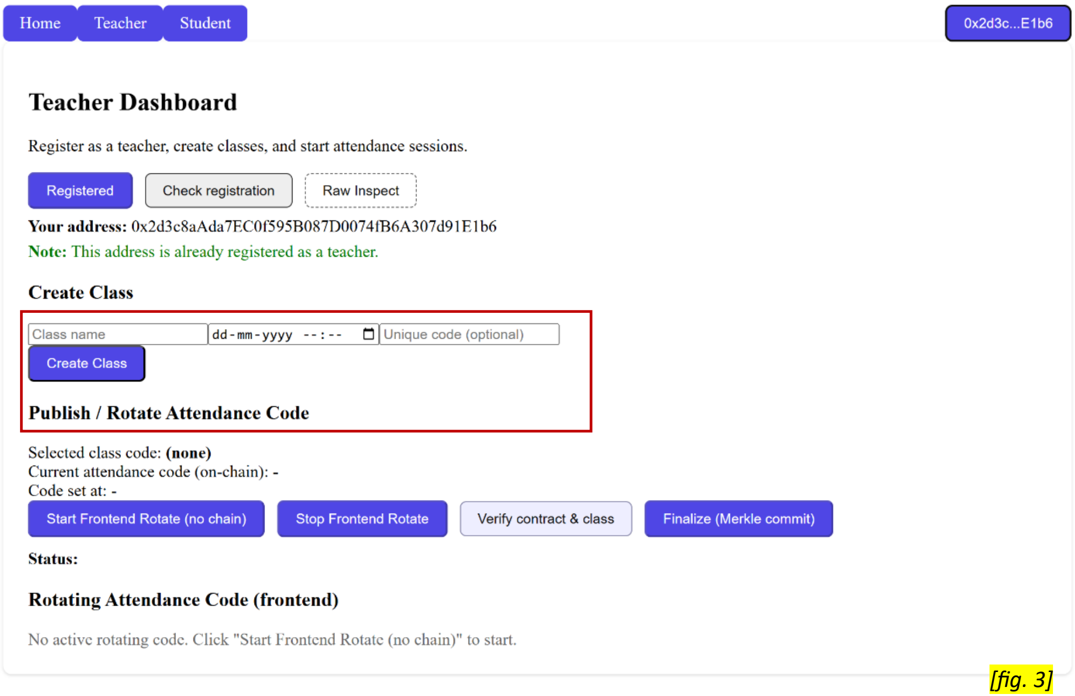


[fig. 1]



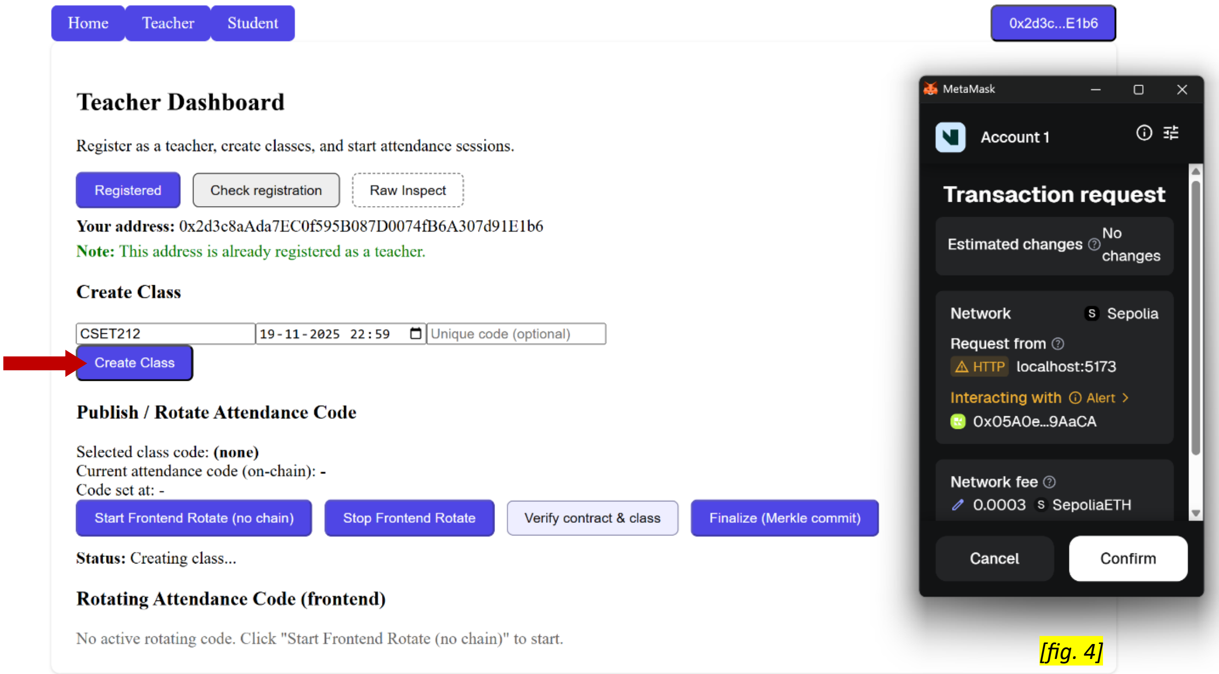
[fig. 2]

2.Create class (inputs: course code, optional unique session code, date/time); (see fig. 3).



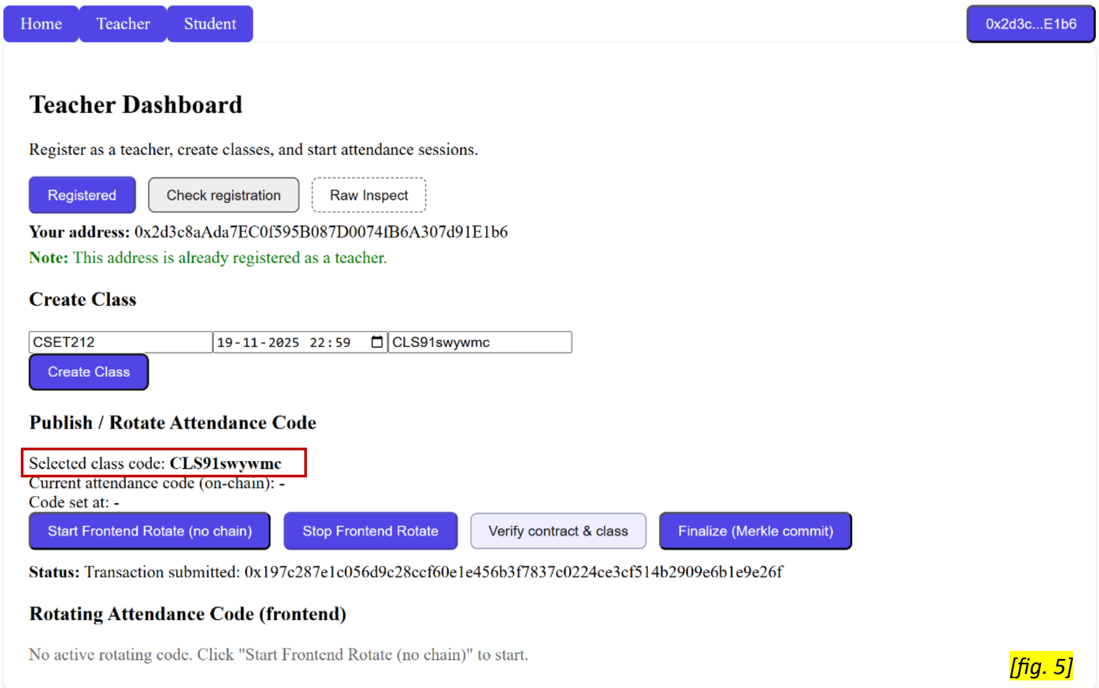
[fig. 3]

*[Click ‘Create Class’ and confirm transaction (see fig. 4)]



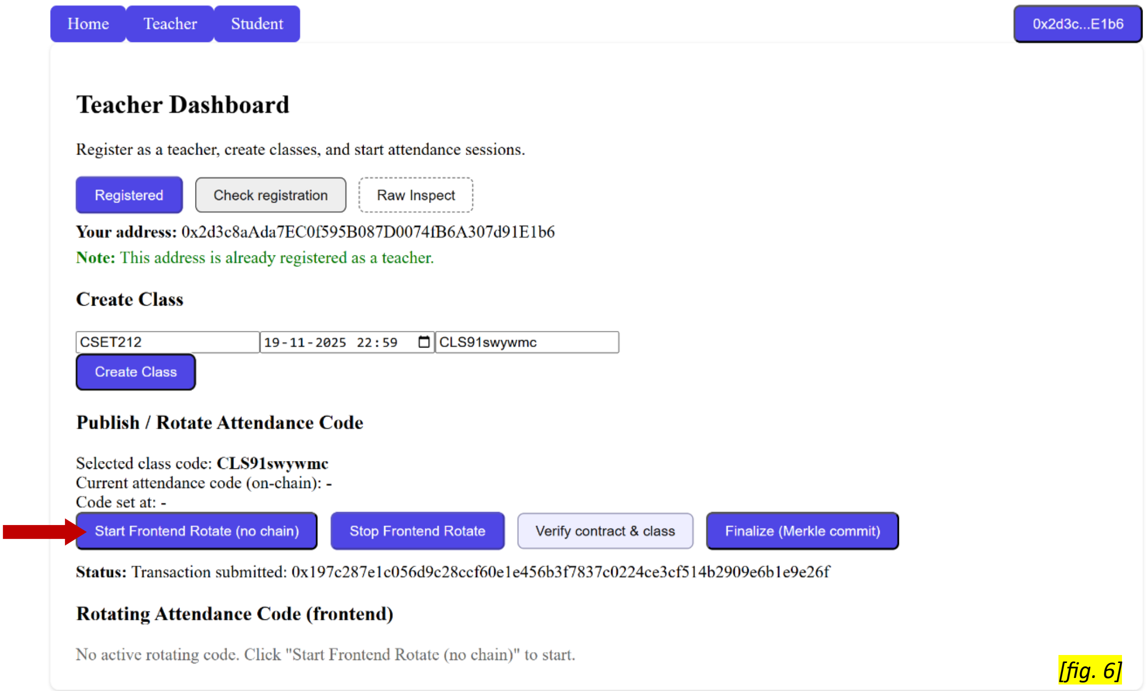
[fig. 4]

*[A unique class code is displayed for this particular class (see fig. 5)]



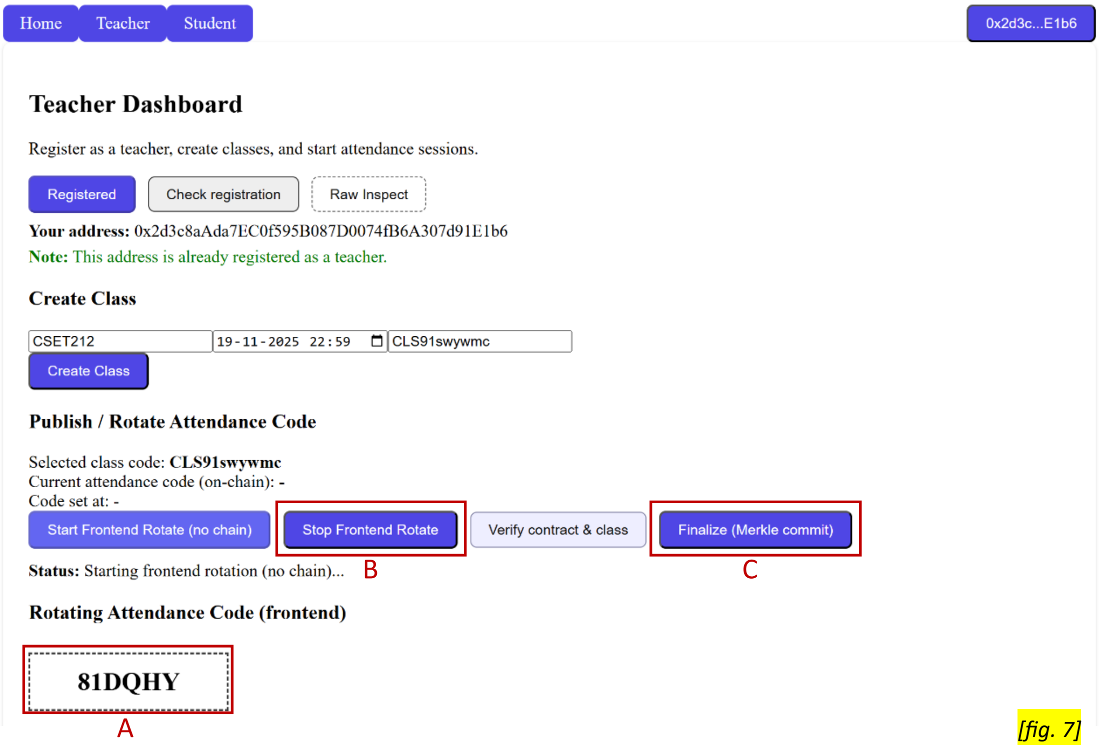
[fig. 5]

3.Start off-chain rotation (see fig. 6);(local ephemeral code updates for marking).



[fig. 6]

*[This 6-digit alpha-numerical code (see fig. 7: A) is projected on the class/session screen]

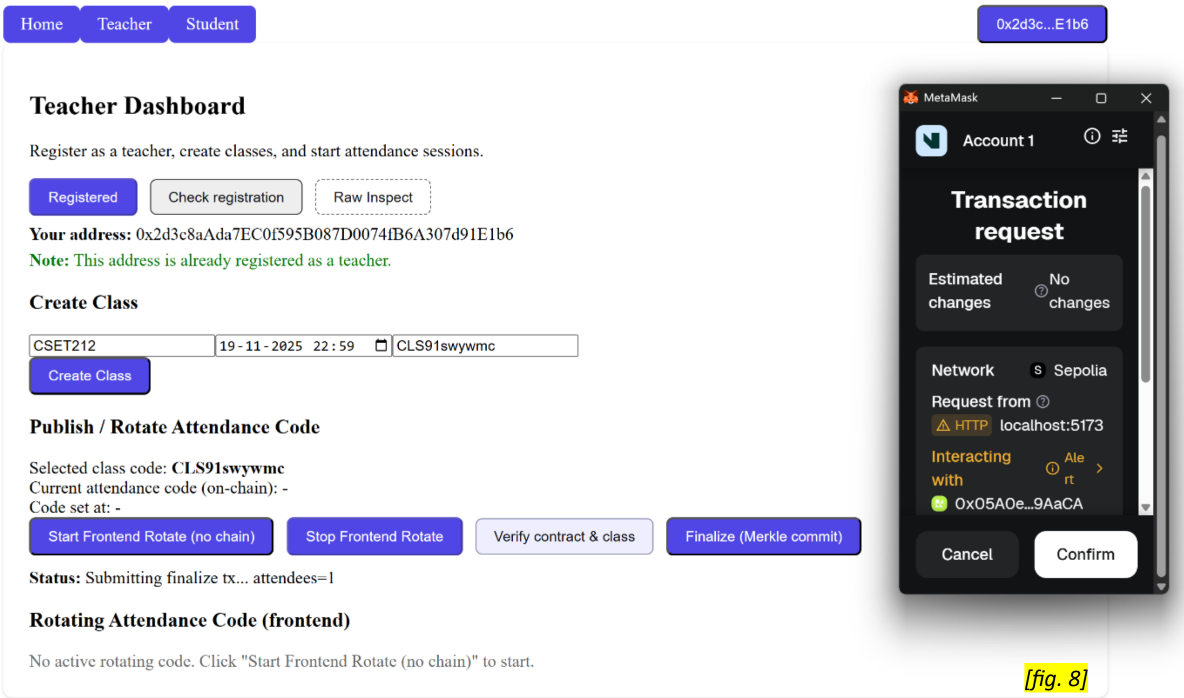


[fig. 7]

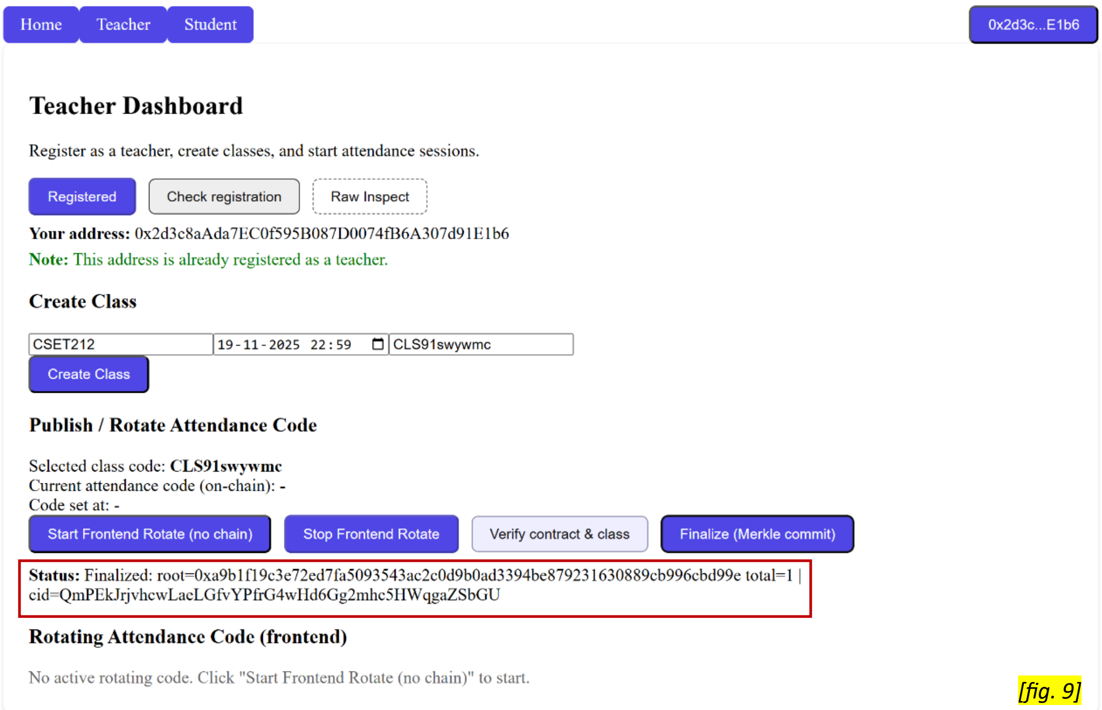
*[All present attendees will see the rotating Attendance code being projected and mark their attendance on the student page (student page workflow discussed below)]

*[After all attendees have marked their attendances, teacher can 'Stop Frontend Rotate' (see fig. 7: B)]

4.Finalize: triggers server finalize endpoint; obtains CID/root; simulates contract; prompts MetaMask (see fig. 8); on success displays root + total + CID link (see fig. 9).



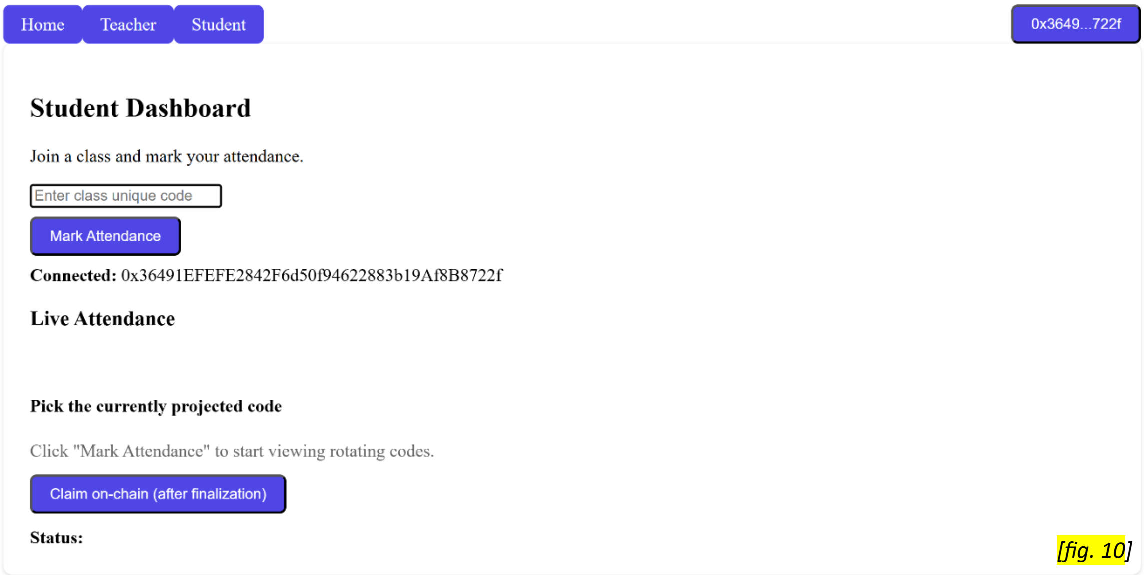
[fig. 8]



[fig. 9]

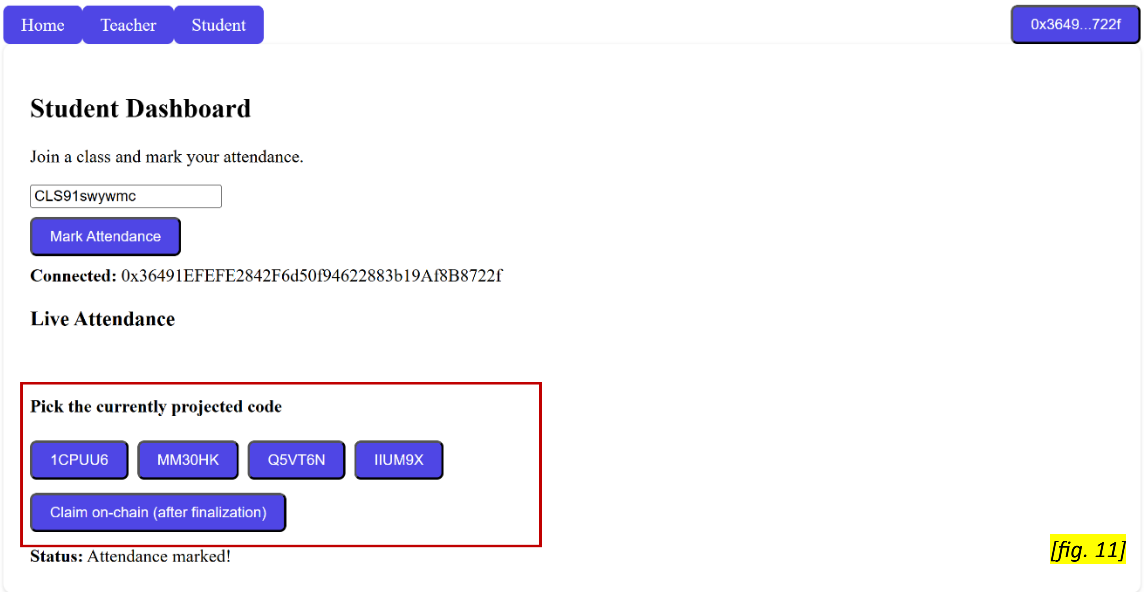
Student workflow:

1.Enter class code after the teacher has created a class; mark attendance (see fig. 10); (server collects address).



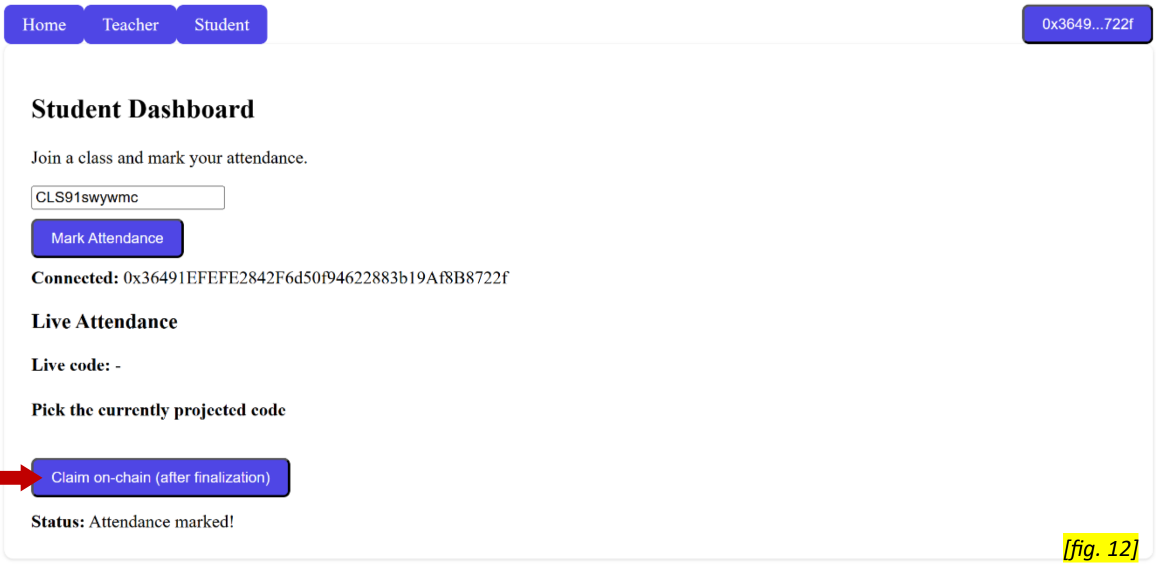
[fig. 10]

*[Choose the correct code among the four (the one being projected in that instant by the teacher); (see fig. 11)]

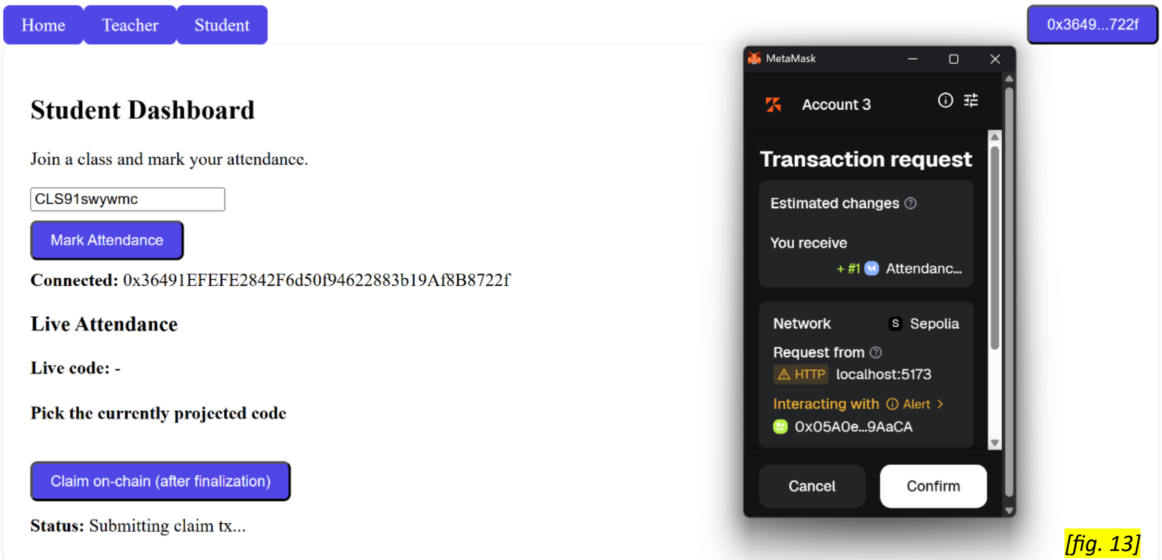


[fig. 11]

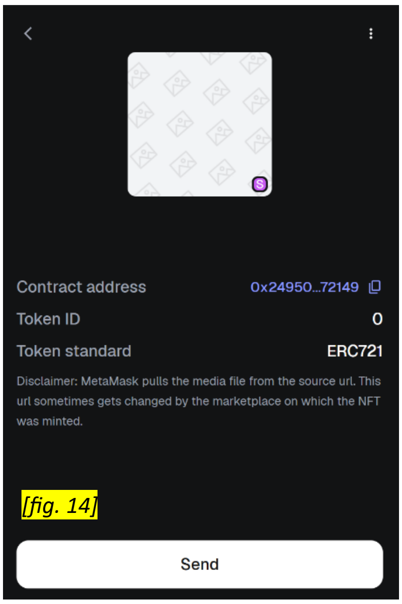
2.After finalization (on teacher's side), fetch Merkle proof from server via claim button (see fig. 12); simulate claim; confirm transaction (see fig. 13); token minted and visible in wallet (see fig. 14), and on etherscan (see fig. 15).



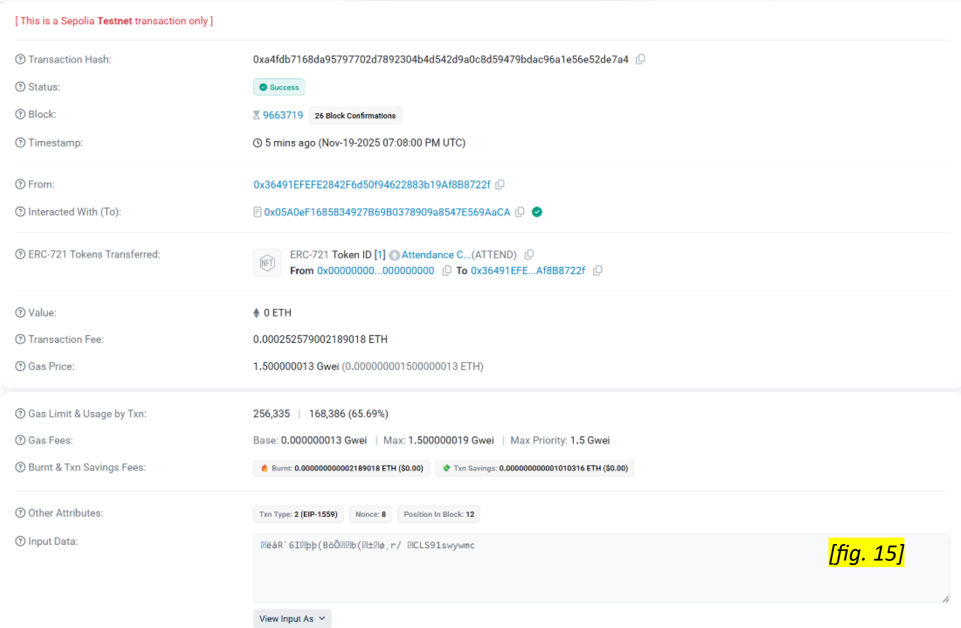
[fig. 12]



[fig. 13]

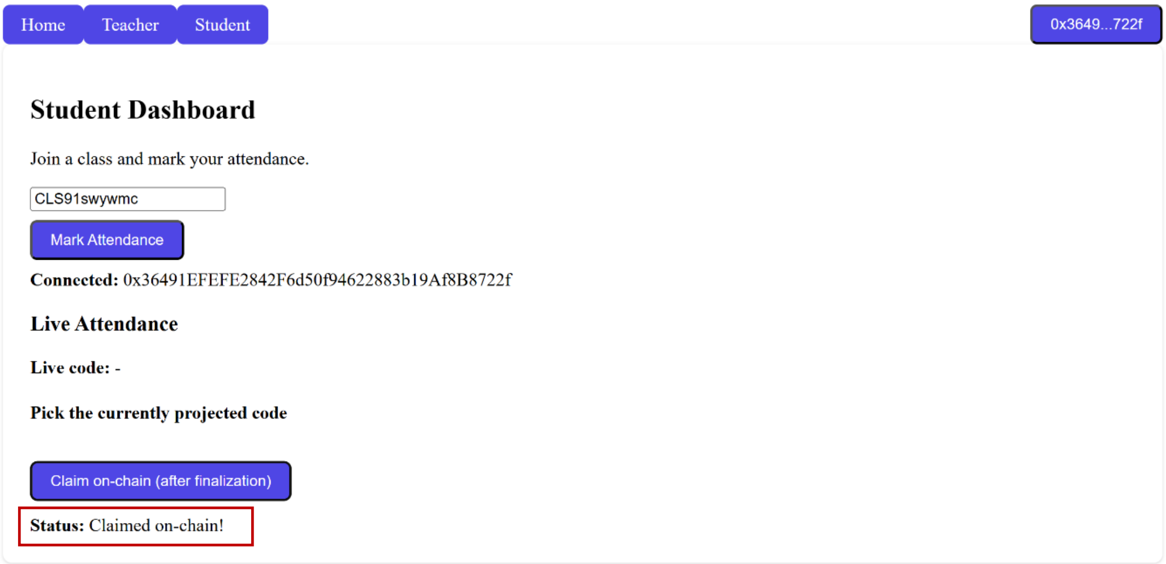


[fig. 14]



[fig. 15]

3.Displayed status message.



6. Results and Discussion

Functional Outcomes

- Successful class creation, single-attendee and multi-attendee finalization (root correctness confirmed manually).
- Accurate Merkle proof acceptance with empty proof for single-leaf sessions.
- AttendanceToken minted only through authorized system; transfer attempts blocked (soulbound behavior).
- Etherscan transaction displays decoded input (root, total, contentHash, CID); event log retrievable.

Verification Robustness

- Recomputed roots from IPFS JSON matched on-chain roots—demonstrating integrity of off-chain record binding.
- “Invalid proof” surfaced correctly during mismatch (e.g., stale contract address or wrong salt) enabling rapid debugging.

Performance

- Gas usage per finalization within a modest range; dominated by storage writes (root, counts, hashes).
- Claim operations low-cost (Merkle verification over short proof arrays; O(log n) scaling).

Problem Fit

The application satisfies the initial need for immutable attendance verification: teacher cannot retrospectively alter an already committed root without creating a new transaction; any tampering with the IPFS JSON invalidates contentHash and Merkle root consistency.

Limitations Observed

- Reliance on centralized server for ordering leaves (although detectable via root mismatch).
- Lack of automated batch testing across many attendees.

7. Conclusion and Recommendations

Conclusion

The DApp demonstrates a practical, gas-efficient pattern for decentralized attendance verification using Merkle commitments and off-chain storage. The system effectively minimizes on-chain data while preserving auditability and enabling self-sovereign token claims for participants. The integration of IPFS CIDs enhances transparency, allowing independent reconstruction and validation of attendance sets.

8. References

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