Module 6: Advanced Next.js Framework Architecture and Application

1. Introduction to Next.js and the Evolution of Modern Web Architecture

The trajectory of web development has traversed a complex arc, moving from the simplicity of static HTML files to the dynamic capabilities of server-side scripting, and subsequently to the rich interactivity of Client-Side Rendering (CSR) via Single Page Applications (SPAs). While SPAs revolutionized user experience by eliminating full page reloads, they introduced significant challenges regarding Search Engine Optimization (SEO), initial load performance, and dependency on client-side JavaScript execution. Next.js emerged as a solution to this dichotomy, offering a hybrid framework that synthesizes the interactivity of React with the performance and discoverability of server-side architecture.

Next.js is not merely a library but a comprehensive framework built on top of React. While React focuses primarily on the view layer—constructing user interfaces through component composition—Next.js provides the production infrastructure required to deploy scalable applications. This includes robust routing systems, build-time optimizations, API handling, and a flexible rendering engine that supports Server-Side Rendering (SSR), Static Site Generation (SSG), and Incremental Static Regeneration (ISR).

For university students entering the domain of full-stack JavaScript development, understanding Next.js is pivotal. It represents the industry standard for React development, shifting the paradigm from "how to render a component" to "where and when to render a component."

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2. Rendering Strategies: A Comparative Analysis of

Architectural Paradigms

The core value proposition of Next.js lies in its ability to decouple the rendering strategy from the application logic. Unlike a standard Create React App (CRA) application which enforces Client-Side Rendering, Next.js empowers developers to select the optimal rendering method for each individual page. Understanding the mechanics, advantages, and trade-offs of each strategy is essential for architecting performant applications.

2.1 The Baseline: Client-Side Rendering (CSR)

In the CSR model, the server's responsibility is minimal. It serves a basic HTML shell—often containing little more than a root and script tags—along with a JavaScript bundle. The browser downloads this bundle, parses the JavaScript, executes the React code, fetches data from APIs, and finally populates the DOM.

Operational Mechanics:
The user's experience in CSR is characterized by a "Time to First Byte" (TTFB) that is generally fast (since the server does little work), but a "First Contentful Paint" (FCP) that is delayed until the JavaScript executes. Crucially, the "Time to Interactive" (TTI) is tied to the completion of hydration.

- **Pros:** CSR allows for rich interactivity and reduces server processing cost after the initial load. It is ideal for dashboards or private applications where SEO is irrelevant.
- **Cons:** Search engine crawlers may fail to index content if they do not execute JavaScript efficiently. Users on slow devices or networks experience a "white screen" delay before content appears.[1]

2.2 Server-Side Rendering (SSR)

Server-Side Rendering, or Dynamic Rendering, inverts the CSR model. For every incoming request, the server executes the React component tree, fetches the necessary data, and generates a fully populated HTML document. This document is sent to the client, where the browser immediately renders the content.

Operational Mechanics:
React subsequently "hydrates" this static HTML. Hydration is the process of attaching event listeners and React's internal state to the existing DOM nodes, transforming the static page into an interactive application.

- **Pros:** SSR guarantees that search engines and social media bots receive fully rendered content (SEO friendly). It ensures users see content immediately upon page load, improving perceived performance.[2]
- **Cons:** The TTFB is slower because the server must complete data fetching and rendering before sending any bytes. High traffic can impose significant CPU load on the server.[1]

2.3 Static Site Generation (SSG)

SSG represents the pinnacle of performance for content that does not change frequently. In this model, HTML pages are generated at **build time**. When the application is compiled (e.g., via next build), Next.js fetches data and renders the components to static HTML files.

Operational Mechanics:
These pre-computed files are typically deployed to a Content Delivery Network (CDN). When a user requests a page, the edge server delivers the static file instantly without any server-side computation.

- **Pros:** SSG offers the fastest possible FCP and TTFB. It is highly scalable and resilient to traffic spikes since it involves serving static files. SEO is optimal.[3]
- **Cons:** Content can become stale. If data in the database changes, the site must be rebuilt and redeployed to reflect those changes. This makes SSG unsuitable for real-time applications without augmentation.[1]

2.4 Incremental Static Regeneration (ISR)

ISR is a hybrid innovation that addresses the staleness limitation of SSG. It allows developers to update static pages *after* the site has been built and deployed, without requiring a full site rebuild.

Operational Mechanics:
Developers define a revalidate period (e.g., 60 seconds).

1. **Initial Request:** User A requests the page. Next.js serves the cached (potentially stale)

static file immediately.
2. **Revalidation Trigger:** If the request occurs after the revalidation period has elapsed, Next.js triggers a background regeneration of the page.
3. **Background Build:** The server re-fetches data and re-renders the page in the background. User A still sees the old version.
4. **Cache Update:** Once regeneration succeeds, Next.js invalidates the old cache and replaces it with the new version.
5. **Subsequent Requests:** User B requests the page and receives the fresh version.[3]

Table 1: Comparative Analysis of Rendering Strategies

Feature	CSR	SSR	SSG	ISR
Render Timing	Runtime (Browser)	Runtime (Server)	Build Time	Build Time + Background
Data Source	Client API Call	Server Request	Build Process	Build + Revalidation
SEO Quality	Low	High	High	High
Server Load	Minimal	High	Negligible	Low
Best For	Dashboards, Private Apps	Personalized Data	Blogs, Docs	E-commerce, News

[2]

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3. Project Configuration and Folder Structure

Next.js adopts a philosophy of "convention over configuration," providing a standardized project structure that streamlines development and onboarding. The specific structure depends on whether the project utilizes the legacy Pages Router or the modern App Router.

3.1 Root Directory and Configuration

Regardless of the router used, the root directory houses essential configuration files:

- **next.config.js**: The central configuration file for the Next.js server and build process. It handles environment variables, redirects, rewrites, and compiler options (e.g., disabling strict mode or configuring image domains).
- **package.json**: Defines dependencies and scripts (dev, build, start, lint).
- **public/**: A reserved directory for static assets. Files placed here are served from the root URL (e.g., /public/favicon.ico maps to example.com/favicon.ico). This folder is not processed by Webpack.[8]
- **.env.local**: Stores environment variables for local development.

3.2 The src Convention

Many developers opt to place their application code inside a src/ directory to separate it from configuration files. Next.js supports this natively. Using src/ keeps the project root clean and prevents configuration files from cluttering the view of application logic.[8]

3.3 Pages Router Structure (Legacy)

In the Pages Router, the directory structure dictates the architecture:

- **pages/**: The core directory where routing occurs. Every file here is a route.
- **pages/api/**: Reserved for API routes (serverless functions).
- **pages/_app.js**: A custom component that initializes pages. It is used to keep state when navigating, set up global styles, or wrap the application in context providers.[8]
- **pages/_document.js**: Allows customization of the <html> and <body> tags. This runs only on the server.

3.4 App Router Structure (Modern)

Introduced in Next.js 13, the App Router (app/ directory) co-locates application logic and routing:

- **app/**: Contains the route hierarchy.
- **Colocation**: Unlike pages/, files in app/ are **not** routes by default. Only special files (e.g., page.tsx, route.ts) are publicly accessible. This allows developers to place components, styles, and tests directly inside the route folders they belong to.[9]
- **layout.tsx**: Defines UI that is shared across a route segment and its children. A root layout.tsx is required to define the <html> and <body> tags.[9]

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4. File-Based Routing Systems

Next.js eliminates the need for a centralized router configuration file (like react-router's switch statements) by using the filesystem as the API.

4.1 Pages Directory Routing

In the pages directory, the file path corresponds directly to the URL.

- **Index Routes**: pages/index.js serves /. pages/blog/index.js serves /blog.
- **Nested Routes**: pages/dashboard/settings.js serves /dashboard/settings.

Dynamic Routes:
Next.js uses bracket notation to define dynamic segments.

- **Basic Dynamic Route**: pages/posts/[id].js matches /posts/1, /posts/abc. The value of id is retrieved via the router query.[4]
- **Catch-All Routes**: pages/docs/[...slug].js matches /docs/a, /docs/a/b, /docs/a/b/c. The slug parameter returns an array (e.g., ['a', 'b']).
- **Optional Catch-All**: pages/docs/[[...slug]].js matches the catch-all paths *plus* the root /docs path (where slug is undefined or empty).

4.2 App Directory Routing

The App Router builds upon filesystem routing but introduces a folder-based hierarchy where leaf nodes define the UI.

- **Route Segments**: Each folder represents a route segment.
- **page.js**: The unique file that makes a segment publicly accessible. app/dashboard/page.js maps to /dashboard.
- **Route Groups**: Folders wrapped in parentheses (group) are omitted from the URL path. app/(marketing)/about/page.js maps to /about, not /(marketing)/about. This allows for organizational grouping without affecting URLs.
- **Parallel Routes**: Defined with @folder, allowing multiple pages to render in the same layout simultaneously (e.g., dashboards with split views).

4.3 Navigation: Link and useRouter

Client-side navigation prevents full page reloads, preserving the application state and speeding up interactions.

The <Link> Component:
This is the primary method for navigation. It extends the HTML <a> tag.

- **Prefetching**: In production, when a <Link> enters the user's viewport, Next.js automatically prefetches the code and data for that linked route. This makes the transition near-instantaneous upon click.
- **Usage**:
```
import Link from 'next/link';
<Link href="/about">About Us</Link>
```

Programmatic Navigation (useRouter):
Hooks allow navigation via JavaScript logic (e.g., after form submission).

- **Pages Router**: Imported from next/router.
```
import { useRouter } from 'next/router';
const router = useRouter();
router.push('/dashboard');
```

- **App Router**: The API has changed. useRouter is imported from next/navigation and is used strictly for navigation actions (push, replace). Accessing URL parameters is split into separate hooks: usePathname and useSearchParams.[13]
```
// App Router
import { useRouter, usePathname } from 'next/navigation';
const router = useRouter();
// router.events is NOT supported in App Router
```

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5. Data Fetching in the Pages Router

The Pages Router utilizes specific data-fetching functions exported from page files to determine the rendering strategy. These functions run exclusively on the server.

5.1 Static Generation: getStaticProps

getStaticProps signals to Next.js that the page should be pre-rendered at build time. It receives a context object containing route parameters and returns an object containing props.

Key Characteristics:

- **Server-Side Only**: Code inside getStaticProps is stripped from the client bundle. This allows direct database queries using server-side secrets.[15]
- **Context**: Provides access to params (for dynamic routes) and preview (for CMS preview mode).
- **Returns**:
  - props: The data passed to the React component.
  - revalidate: Time in seconds for ISR.
  - notFound: Boolean to trigger a 404 page.
  - redirect: Object to redirect the user to another route.[16]

Example:

```
export async function getStaticProps() {
  const res = await fetch('https://api.example.com/posts');
  const posts = await res.json();
  return { props: { posts } };
}
```

5.2 Dynamic Paths: getStaticPaths

When using getStaticProps on a dynamic route (e.g., [id].js), Next.js must know which paths to generate at build time. getStaticPaths defines this list.

The fallback Property:

This property controls how the system handles paths not returned in the list.

- fallback: false: Returns a 404 for any unknown path. Useful for small, finite datasets.[17]
- fallback: true: Returns a fallback version of the page (loading state) immediately while the server generates the full page in the background. Once generated, the page is swapped in. Useful for large archives where building every page is infeasible.
- fallback: 'blocking': The browser waits (hangs) while the server generates the page (SSR behavior for the first request), then serves the static HTML. No loading state is shown.[17]

5.3 Server-Side Rendering: getServerSideProps

getServerSideProps commands Next.js to render the page on every request. It provides access to the request object (req) and response object (res), allowing for logic based on cookies, headers, or authentication tokens.

Comparisons:
Unlike getStaticProps, getServerSideProps creates a Time to First Byte (TTFB) dependency on the data source. It should only be used when data must be perfectly fresh or is personalized to the user.19

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6. Incremental Static Regeneration (ISR)

ISR is a critical architectural feature that allows Next.js to scale static generation to millions of pages. It decouples the build process from the content update process.

6.1 Time-Based Revalidation

By adding the revalidate property to getStaticProps, developers instruct the edge cache to consider the page "fresh" for a set duration.

- **Mechanism (Stale-While-Revalidate)**:
  1. Request at T=0: Returns fresh static page.
  2. Request at T=10 (within revalidate window): Returns cached page.
  3. Request at T=65 (after window): Returns cached page (stale) *and* triggers a

background regeneration.
4. Regeneration Complete: Cache is updated.
5. Request at T=70: Returns new fresh page.[6]

6.2 On-Demand Revalidation

Time-based revalidation can imply a lag between data updates and user visibility. On-Demand ISR allows an external event (e.g., a CMS webhook) to trigger a purge of the cache for a specific URL.

- **Implementation**: Using res.revalidate('/path-to-page') inside an API route allows instant updates when content changes, combining the performance of static sites with the immediacy of dynamic rendering.[20]

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7. The App Router Architecture (Next.js 13+)

The App Router represents a paradigm shift, introducing React Server Components (RSC) to the mainstream. This architecture addresses the "waterfall" problem of data fetching and reduces the JavaScript payload sent to the client.

7.1 Server Components vs. Client Components

The distinction between Server and Client Components is the foundational concept of the App Router.

Server Components (Default):

- **Execution**: Render exclusively on the server.
- **Capabilities**: Can access the database, filesystem, and private environment variables directly.
- **Restrictions**: Cannot use hooks (useState, useEffect) or event listeners (onClick).
- **Output**: They render into a special JSON format (RSC Payload) which the client uses to reconstruct the DOM, without executing JavaScript logic for those components.[22]

Client Components:

- **Declaration**: Marked with 'use client' at the top of the file.
- **Execution**: Prerendered on the server (for initial HTML) and then hydrated on the client.
- **Role**: Handle interactivity and browser APIs (window, localStorage).
- **Boundary**: A Client Component defines a boundary. Any component imported into a Client Component becomes part of the client bundle.[22]

Composition Patterns:
To maximize performance, "leaf" components (like buttons or inputs) should be Client Components, while layout and data-fetching components should remain Server Components. Server Components can be passed as children to Client Components, preserving their server-only nature even when wrapped in interactive elements.24

7.2 Data Fetching in the App Router

The App Router unifies data fetching around the extended fetch API, replacing getStaticProps and getServerSideProps.

Caching Levels:

- **force-cache (Default)**: fetch('...', { cache: 'force-cache' }). Equivalent to getStaticProps. Data is cached indefinitely until revalidated.
- **no-store**: fetch('...', { cache: 'no-store' }). Equivalent to getServerSideProps. Data is fetched on every request.
- **Revalidation**: fetch('...', { next: { revalidate: 3600 } }). Equivalent to ISR.
- **Tags**: fetch('...', { next: { tags: ['collection'] } }). Allows identifying data dependencies to invalidate specific cache keys on demand via revalidateTag.

generateStaticParams:
This function replaces getStaticPaths. It runs at build time in the App Router to define dynamic routes that should be statically generated. It is optimized to run in parallel with page generation.

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8. API Development in Next.js

Next.js serves as a full-stack framework, enabling the creation of RESTful endpoints

alongside frontend code.

8.1 API Routes (Pages Router)

Located in pages/api/, these files export a default function handler.

- **Request/Response**: Uses Node.js-like objects (req, res).
- **Usage**: Ideal for masking third-party APIs, accessing databases, or handling form submissions.

```
// pages/api/user.js
export default function handler(req, res) {
 if (req.method === 'POST') {
  // create user logic
  res.status(200).json({ id: 1 });
 }
}
```

8.2 Route Handlers (App Router)

Located in app/api/.../route.ts, these use standard Web APIs (Request, Response).

- **Method Exports**: Named exports (GET, POST, DELETE) replace the switch-statement style of the Pages router.
- **Static by Default**: GET requests are cached by default unless they use dynamic functions (cookies, headers) or opt-out.[30]

```
// app/api/items/route.ts
import { NextResponse } from 'next/server';

export async function GET() {
 const data = await fetchDocs();
 return NextResponse.json(data);
}
```

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9. Optimization Engines

Next.js automates complex performance optimizations that typically require manual configuration in other frameworks.

9.1 Image Optimization (next/image)

The <Image> component prevents Core Web Vitals regressions.

- **Layout Shift**: By requiring width/height data, it reserves space in the DOM, preventing Cumulative Layout Shift (CLS).
- **Modern Formats**: Automatically converts JPEGs/PNGs to WebP or AVIF.
- **Lazy Loading**: Defers loading of off-screen images.
- **Remote Patterns**: Security configuration in next.config.js restricts which external domains can be optimized.[32]

9.2 Script Optimization (next/script)

Scripts are often the bottleneck of page performance. The <Script> component allows prioritizing third-party code (analytics, chatbots).

- **Strategies**: beforeInteractive (critical scripts), afterInteractive (default), lazyOnload (low priority), and worker (offloads to a Web Worker via Partytown).[34]

9.3 Font Optimization (next/font)

This system eliminates layout shifts caused by fonts loading (Flash of Unstyled Text).

- **Self-Hosting**: Automatically downloads Google Fonts at build time and serves them from the same domain, removing external DNS lookups.
- **Zero Layout Shift**: Uses CSS size-adjust to match the fallback font metrics to the web font, ensuring the text takes up the same space before and after the font loads.[36]

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10. Metadata and SEO

Managing the document head is vital for search visibility.

- **Head Component (Pages)**: A React component allowing modification of <head>. Tags are deduplicated automatically.
- **Metadata API (App)**: A strictly typed API for defining SEO tags. Metadata can be exported from a layout.js or page.js.
  - **Static**: export const metadata = { title: '...' }.
  - **Dynamic**: export async function generateMetadata({ params }) {... }.
  - **Inheritance**: Metadata in leaf segments overrides or merges with metadata in root layouts.

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11. Environment Configuration and Deployment

11.1 Environment Variables

Next.js supports multiple .env files (.env.local, .env.production).

- **Server vs. Client**: Variables are server-only by default. To expose a variable to the browser, it *must* be prefixed with NEXT_PUBLIC_ (e.g., NEXT_PUBLIC_API_URL).
- **Inlining**: During the build, NEXT_PUBLIC_ variables are replaced with their string values in the JavaScript bundle.[41]

11.2 Styling

- **CSS Modules**: Scopes CSS to the component by generating unique class names, preventing style conflicts.
- **Global Styles**: Imported only in _app.js or root layout.tsx.
- **Tailwind CSS**: First-class support via PostCSS configuration.[43]

11.3 Deployment to Vercel

Vercel provides a zero-configuration deployment workflow for Next.js.

- **Git Integration**: Connects to GitHub/GitLab. Pushes to main deploy to production; other branches create preview URLs.
- **Infrastructure**: Automatically provisions Serverless Functions for API routes and SSR

pages, and Edge Functions for middleware.
- **Edge Network**: Caches static assets and ISR pages globally.

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12. Student Exercises

These exercises are designed to reinforce the concepts covered in the module, ranging from basic routing to advanced optimization.

Exercise 1: Dynamic Blog System (Routing & SSG)

Objective: Create a blog using the Pages Router where content is generated statically.

1. Create a data.json file with an array of 5 blog posts (id, title, content).
2. Create an index.js page that fetches this data and lists the blog titles.
3. Create a dynamic route pages/blog/[id].js.
4. Implement getStaticPaths to generate paths for all 5 posts.
5. Implement getStaticProps to fetch the specific post data based on the id param.
6. **Challenge:** Set fallback: true in getStaticPaths and add a new item to data.json manually. Try to access its URL without restarting the server to observe fallback behavior.

Exercise 2: Dashboard with Hybrid Rendering (App Router)

Objective: Build a dashboard using the App Router that mixes server and client components.

1. Create a layout app/dashboard/layout.tsx with a static sidebar navigation.
2. Create a page app/dashboard/page.tsx that fetches "User Profile" data from a mock API (use setTimeout to simulate delay). This should be a **Server Component**.
3. Create a "Settings" toggle component that uses useState to switch between dark/light mode for the dashboard panel. This must be a **Client Component** ('use client').
4. Embed the Client Component inside the Server Component page.

Exercise 3: API Route & Middleware

Objective: Secure an API endpoint.

1. Create an API route /api/secret that returns { secret: "Next.js is cool" }.
2. Create a middleware.ts file in the root.
3. Implement logic to check for a custom header x-api-key.
4. If the header matches a secret value (stored in .env.local), allow the request. If not, rewrite the response to a 401 Unauthorized page or JSON response.

Exercise 4: Image & Font Optimization

Objective: Improve Core Web Vitals.

1. Add a large high-resolution image to your public folder.

2. Render it using the standard <img> tag and observe the layout shift (CLS) in Chrome DevTools.
3. Replace it with the next/image component, setting proper width and height. Observe the automatic placeholder and lack of layout shift.
4. Import a Google Font using next/font/google in your root layout and apply it globally to the <body>. Verify in the Network tab that no requests are sent to fonts.googleapis.com (it should be self-hosted).

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13. Small Project

To demonstrate mastery of Next.js, students should complete one of the following capstone projects. These projects integrate multiple concepts (routing, data fetching, API handling, and optimization) into a cohesive application.

AI-Powered Knowledge Base

Description: A documentation site that uses AI to answer user questions based on the content.

- **Tech Stack:** Next.js 15, Vercel AI SDK, Postgres (with pgvector for embeddings), Tailwind CSS.
- **Key Features:**
  - **RAG (Retrieval-Augmented Generation):** Store documentation chunks in a vector database.
  - **Streaming UI:** Use the Vercel AI SDK to stream the AI's response letter-by-letter to the client for a realtime feel.
  - **Server Actions:** Use React Server Actions to handle the user's prompt submission and database querying directly from the component.
  - **Hybrid Rendering:** Static documentation pages for SEO, combined with a dynamic "Ask AI" floating widget.
  - **Edge Middleware:** Implement rate limiting on the AI API route to prevent abuse.

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14. Advanced Technology: React 19 & The React Compiler

As of late 2024 and 2025, the React ecosystem has undergone a massive shift with the release of **React 19** and the **React Compiler** (formerly known as React Forget). Next.js is at the

forefront of adopting these technologies.

14.1 The Problem: Manual Memoization

Historically, React developers had to manually optimize render performance using hooks like useMemo, useCallback, and memo.

- **The Burden:** Developers had to manually track dependency arrays ([a, b]). Missing a dependency caused stale closures (bugs), while over-memoizing led to code bloat and memory overhead.
- **The "Re-render" Issue:** By default, if a parent component re-renders, all children re-render, even if their props haven't changed. preventing this required wrapping components in memo().

14.2 The Solution: React Compiler

The React Compiler is a build-time tool that automatically optimizes your React code. It understands the rules of JavaScript and React deeply enough to rewrite your code during the build process.

- **Automatic Memoization:** It automatically memoizes values and functions, effectively eliminating the need for useMemo and useCallback.
- **Fine-Grained Reactivity:** The compiler allows React to update only the specific parts of the DOM that changed, rather than re-rendering entire component sub-trees.
- **Implementation in Next.js:** Next.js 15 includes experimental support for the React Compiler. By enabling it in next.config.js, developers can simply write "naive" React code, and the compiler ensures it runs with optimal performance.

14.3 Server Actions (React 19)

React 19 stabilizes **Server Actions**, which allow you to call server-side functions directly from event handlers in Client Components.

- **No API Routes Needed:** Instead of creating a file in pages/api/submit.js and fetching it via fetch('/api/submit'), you define an async function acting on the server and pass it to the action prop of a <form>.
- **Progressive Enhancement:** Forms using Server Actions work even before JavaScript loads on the client.

```
// actions.js (Server-side logic)
'use server'
export async function createPost(formData) {
  const title = formData.get('title');
  await db.posts.create({ title });
}
```

```
// Component.js (Client-side UI)
import { createPost } from './actions';

export default function Form() {
  return (
    <form action={createPost}>
      <input name="title" />
      <button type="submit">Create</button>
    </form>
  );
}
```