Flutter Offline-First Architecture with BLoC + Hive + Sync Engine

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Architecture Overview

The system is designed as a **Flutter offline-first application** that ensures data availability and consistency across online/offline states using Hive for local persistence and a dedicated sync engine for server synchronization.

Core Architectural Principles

- **Offline-First**: App functions fully offline, with sync as enhancement
- **Eventual Consistency**: Data eventually syncs when network available
- **Conflict Resolution**: Multiple strategies for handling data conflicts
- **Separation of Concerns**: Clear layer separation for maintainability
- **Fault Tolerance**: Graceful handling of network failures and retries

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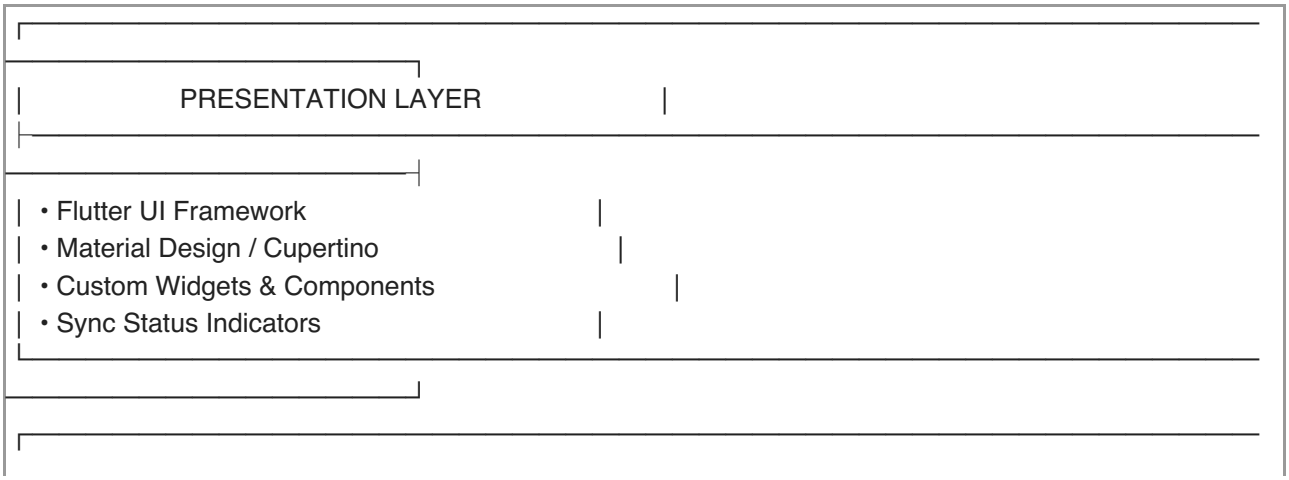
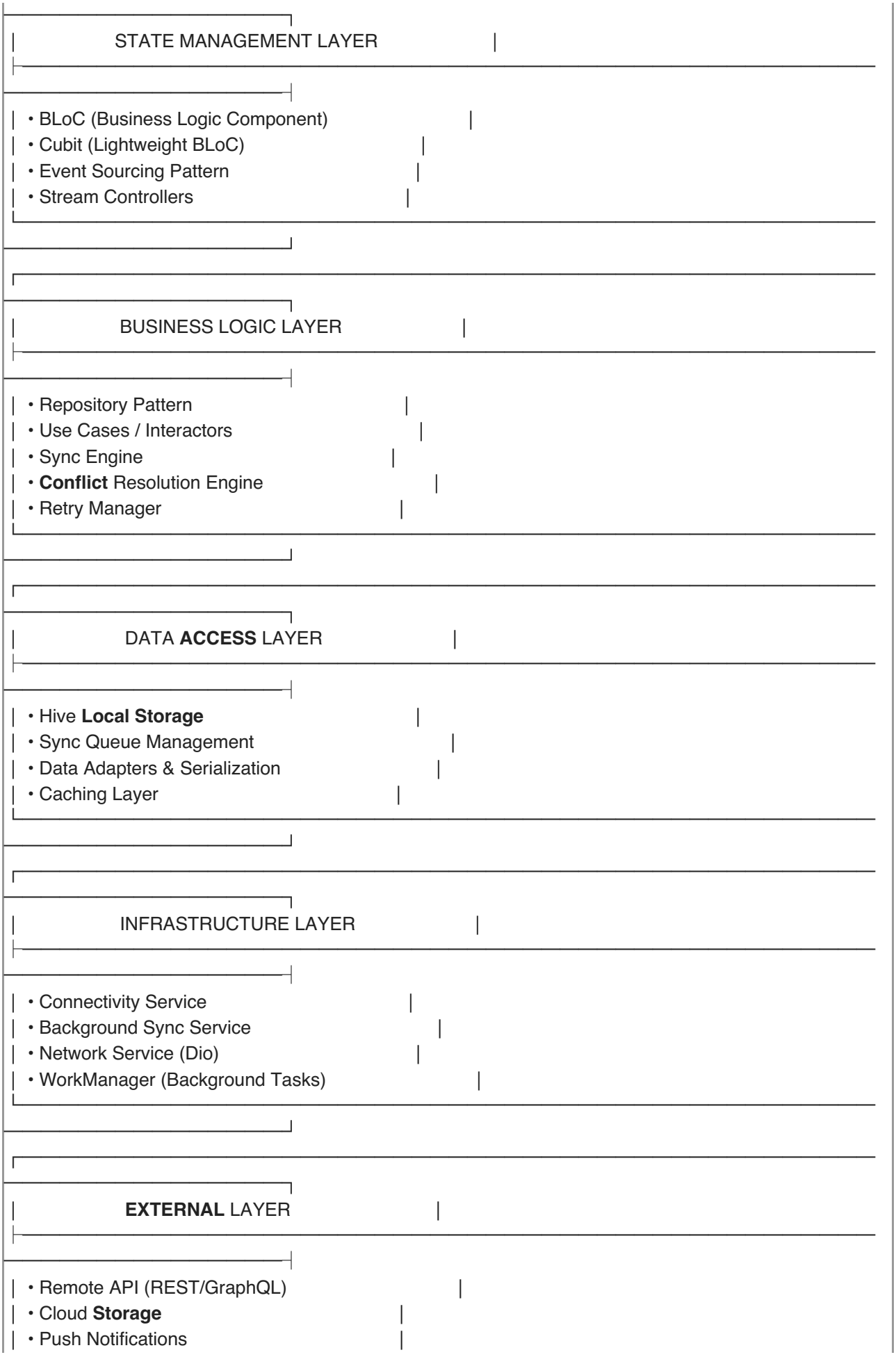
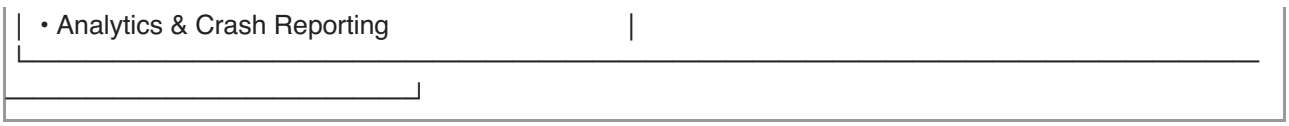
Technology Stack

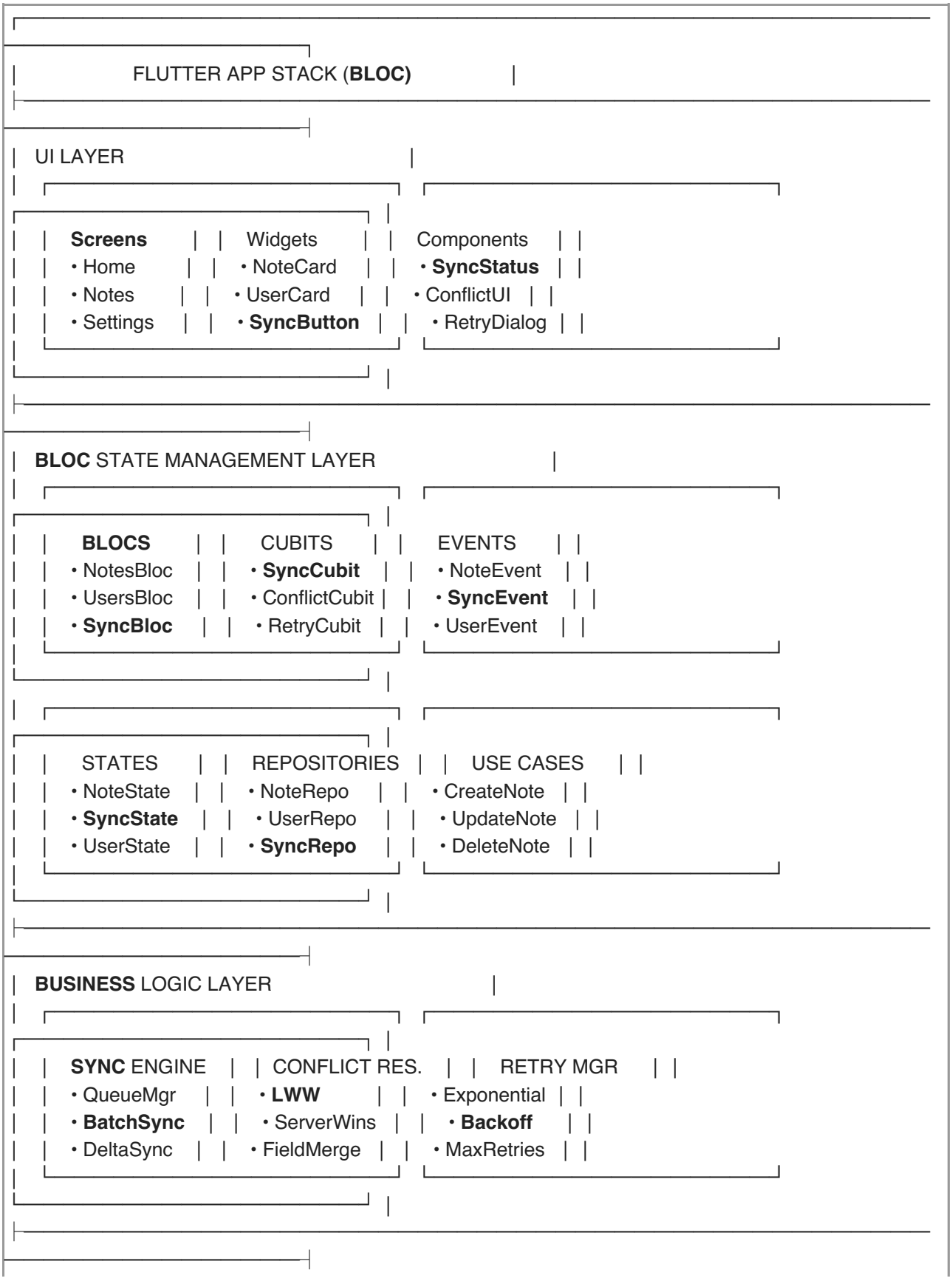
Complete Technology Stack with BLoC

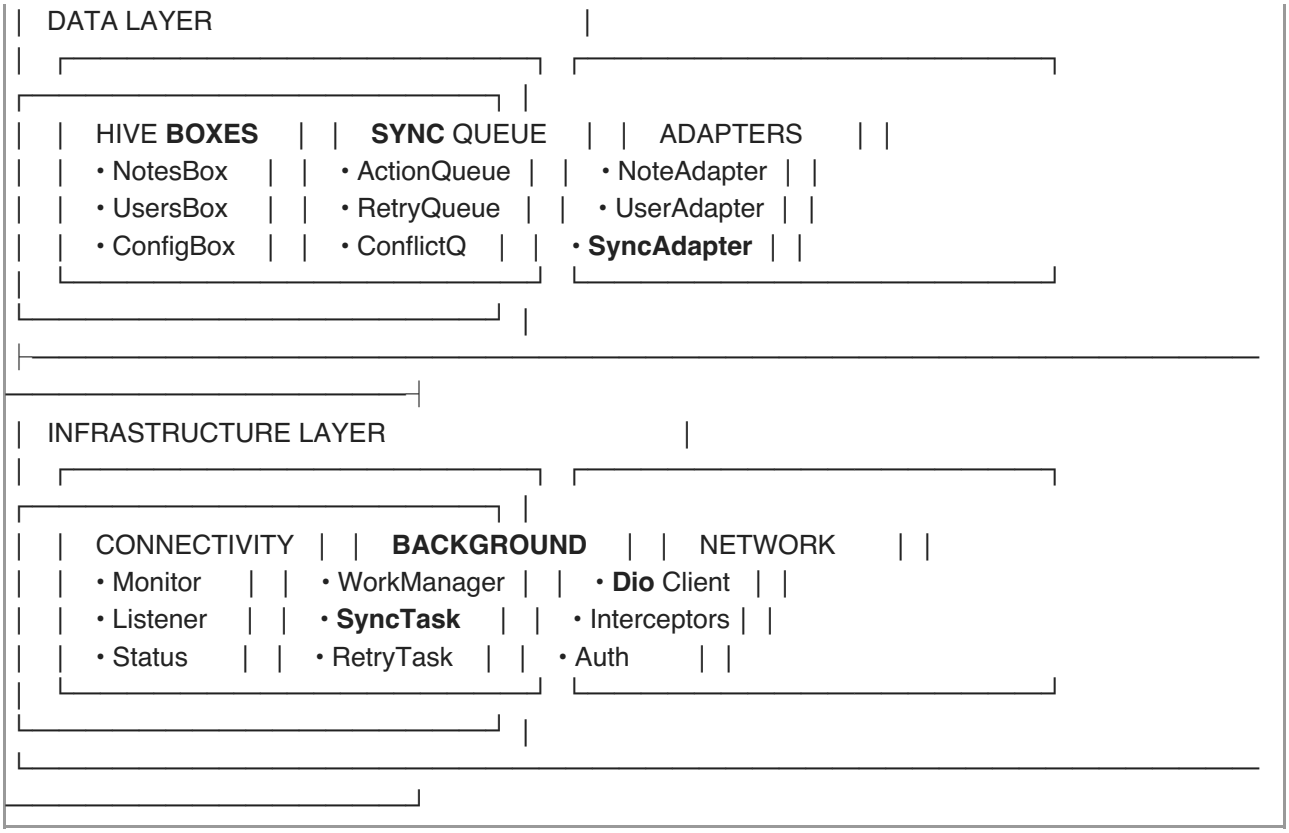



STATE MANAGEMENT LAYER
• BLoC (Business Logic Component)
• Cubit (Lightweight BLoC)
• Event Sourcing Pattern
• Stream Controllers
BUSINESS LOGIC LAYER
• Repository Pattern
• Use Cases / Interactors
• Sync Engine
• **Conflict** Resolution Engine
• Retry Manager
DATA **ACCESS** LAYER
• Hive **Local Storage**
• Sync Queue Management
• Data Adapters & Serialization
• Caching Layer
INFRASTRUCTURE LAYER
• Connectivity Service
• Background Sync Service
• Network Service (Dio)
• WorkManager (Background Tasks)
EXTERNAL LAYER
• Remote API (REST/GraphQL)
• Cloud **Storage**
• Push Notifications



Detailed BLoC Layer Breakdown





System Components

1. Model Layer

```
// Base sync metadata
class SyncMeta {
  final DateTime lastUpdated;
  final bool isSynced;
  final String? conflictFlag;
  final int retryCount;
  final DateTime? lastSyncAttempt;
}

// Entity with sync metadata
abstract class SyncableEntity {
  String get id;
  SyncMeta get syncMeta;
  Map<String, dynamic> toSyncPayload();
  void updateSyncMeta(SyncMeta meta);
}
```

2. Hive Storage Structure

```dart
// Main entity boxes
class NoteBox {
  static const String name = 'notes';
  // Stores actual Note entities
}

class UserBox {
  static const String name = 'users';
  // Stores actual User entities
}

// Sync queue box
class SyncQueueBox {
  static const String name = 'sync_queue';
  // Stores SyncAction entities
}

// Sync action types
enum SyncActionType { create, update, delete }

class SyncAction {
  final String id;
  final SyncActionType type;
  final String entityType;
  final String entityId;
  final Map<String, dynamic> payload;
  final DateTime timestamp;
  final int retryCount;
  final SyncStatus status;
}
```

3. Repository Layer

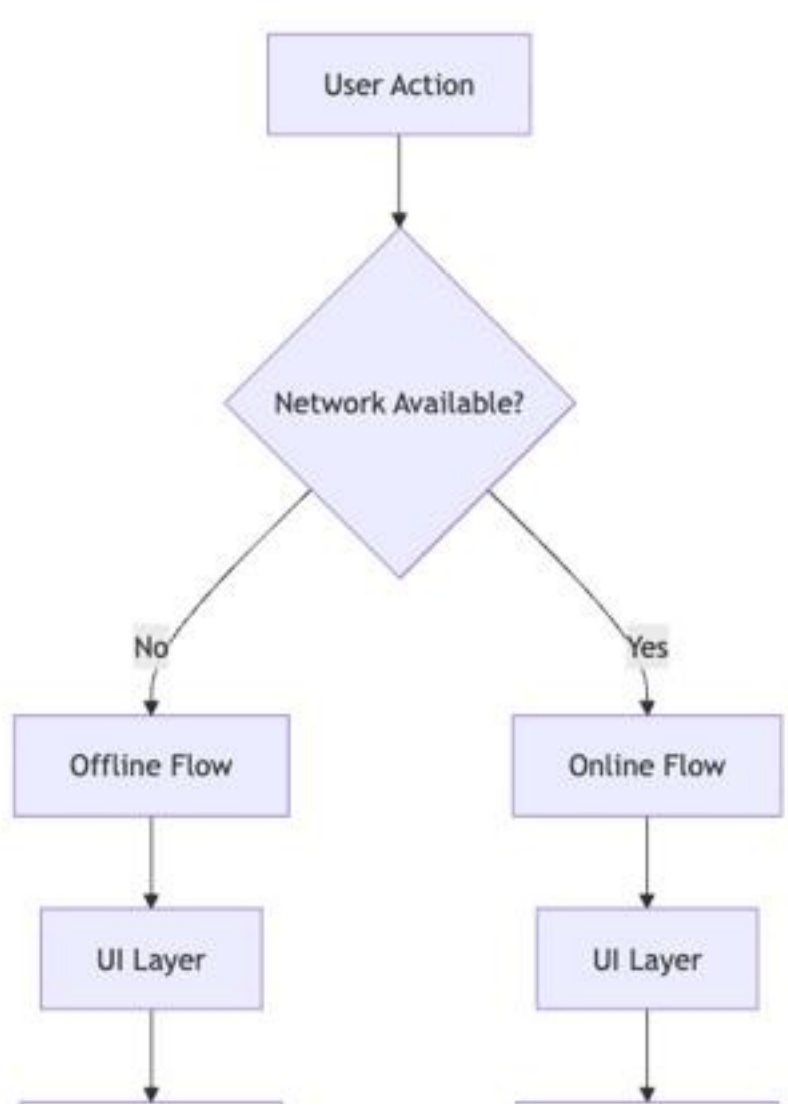
```dart
abstract class BaseRepository<T extends SyncableEntity> {
  Future<void> create(T entity);
  Future<void> update(T entity);
  Future<void> delete(String id);
  Stream<List<T>> watchAll();
  Stream<T?> watchById(String id);

  // Sync-specific methods
  Future<void> markAsSynced(String id);
  Future<void> markAsConflict(String id, String conflictReason);
  Future<List<T>> getUnsyncedEntities();
}
```

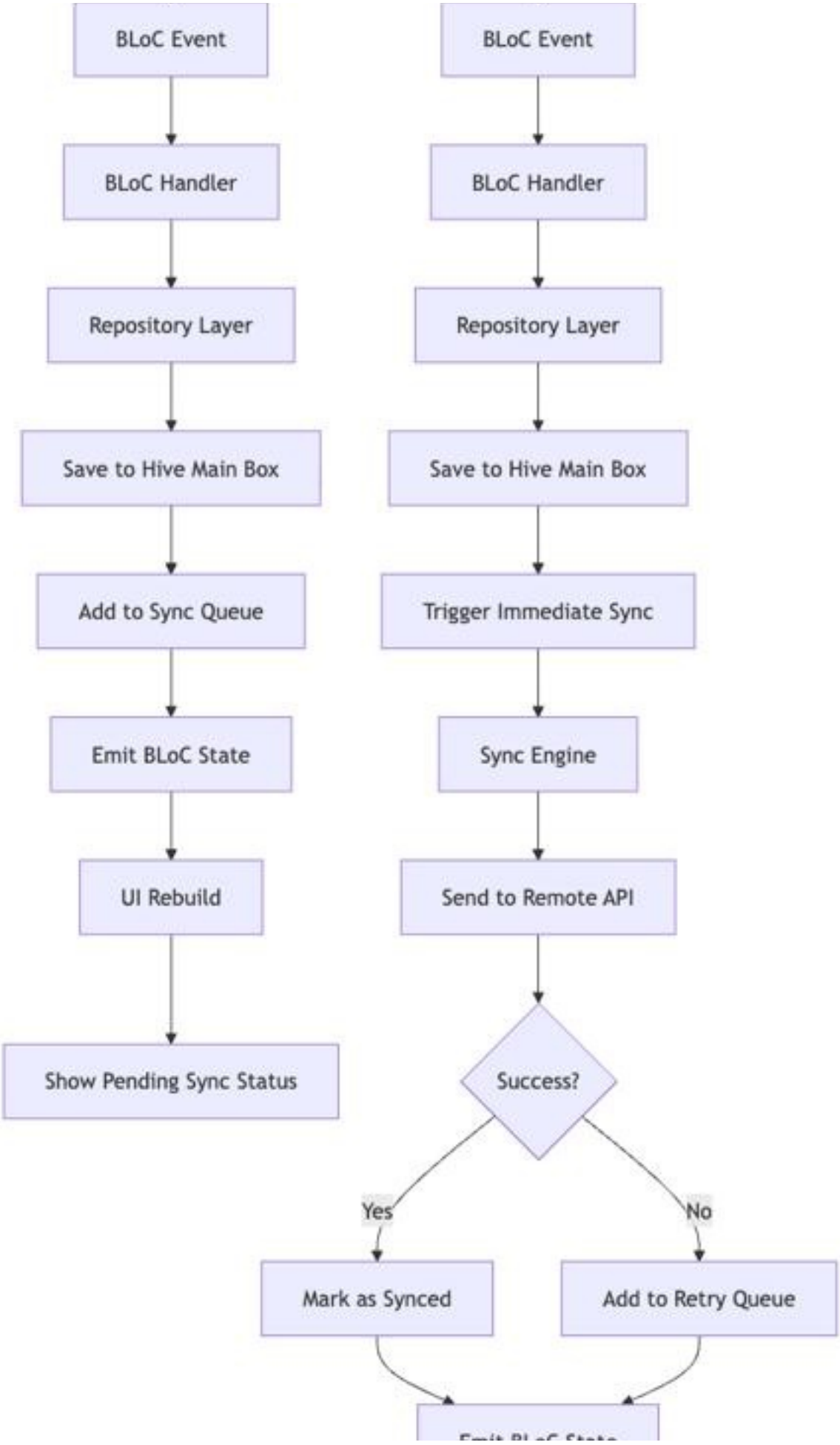
4. Sync Engine Architecture

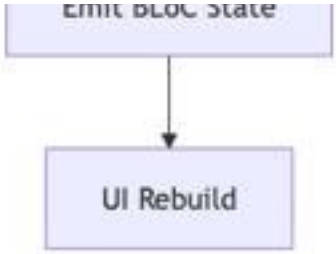
```dart
class SyncEngine {
  final ConnectivityService _connectivity;
  final SyncQueueService _syncQueue;
  final ConflictResolver _conflictResolver;
  final RetryManager _retryManager;

  // Core sync methods
  Future<void> startSync();
  Future<void> stopSync();
  Future<void> processSyncQueue();
  Future<void> syncEntity(SyncAction action);

  // Conflict resolution
  Future<SyncResult> resolveConflict(SyncAction action, ServerResponse response);
}
```

Data Flow Diagrams

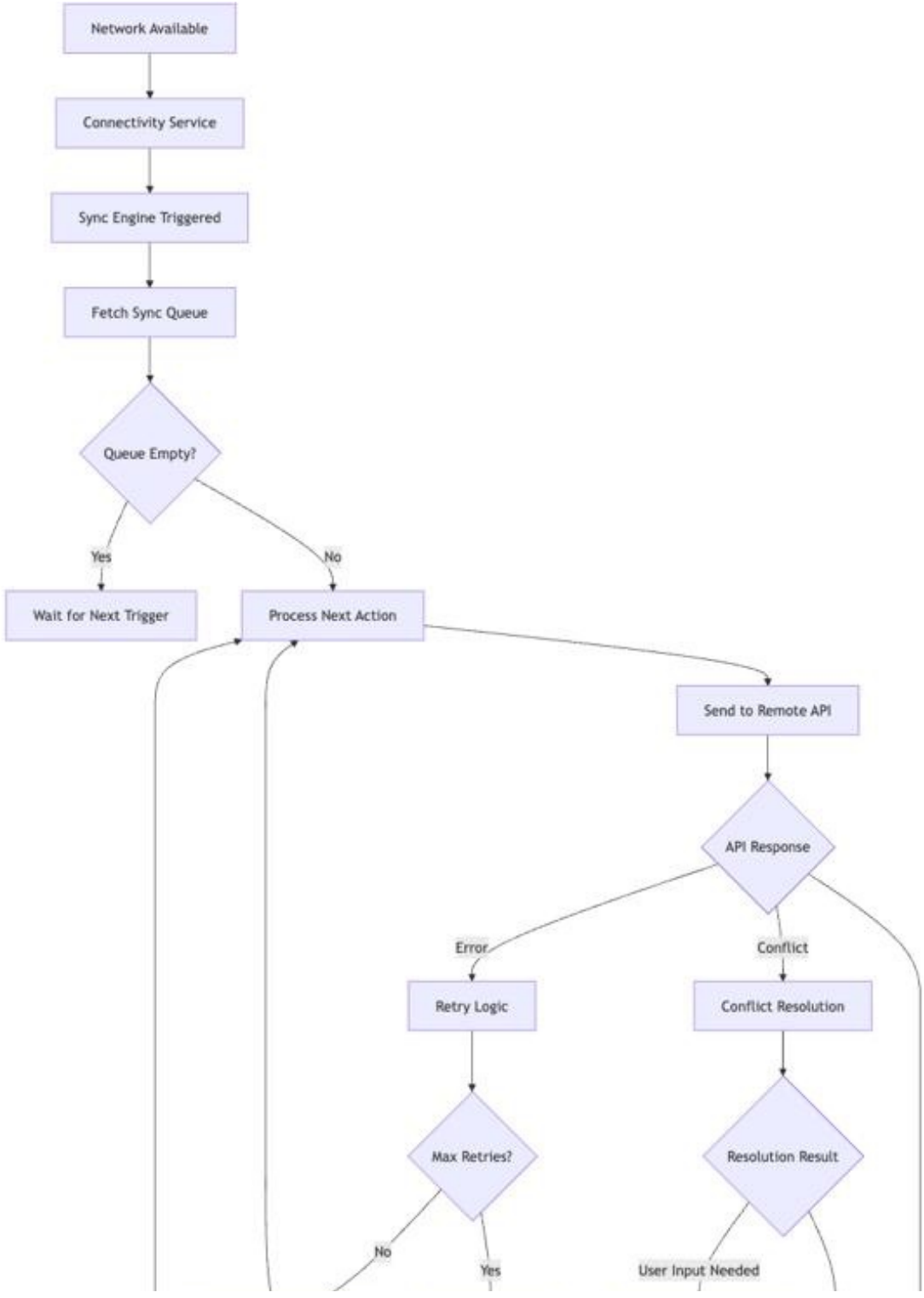
1. Offline Data Flow Diagram

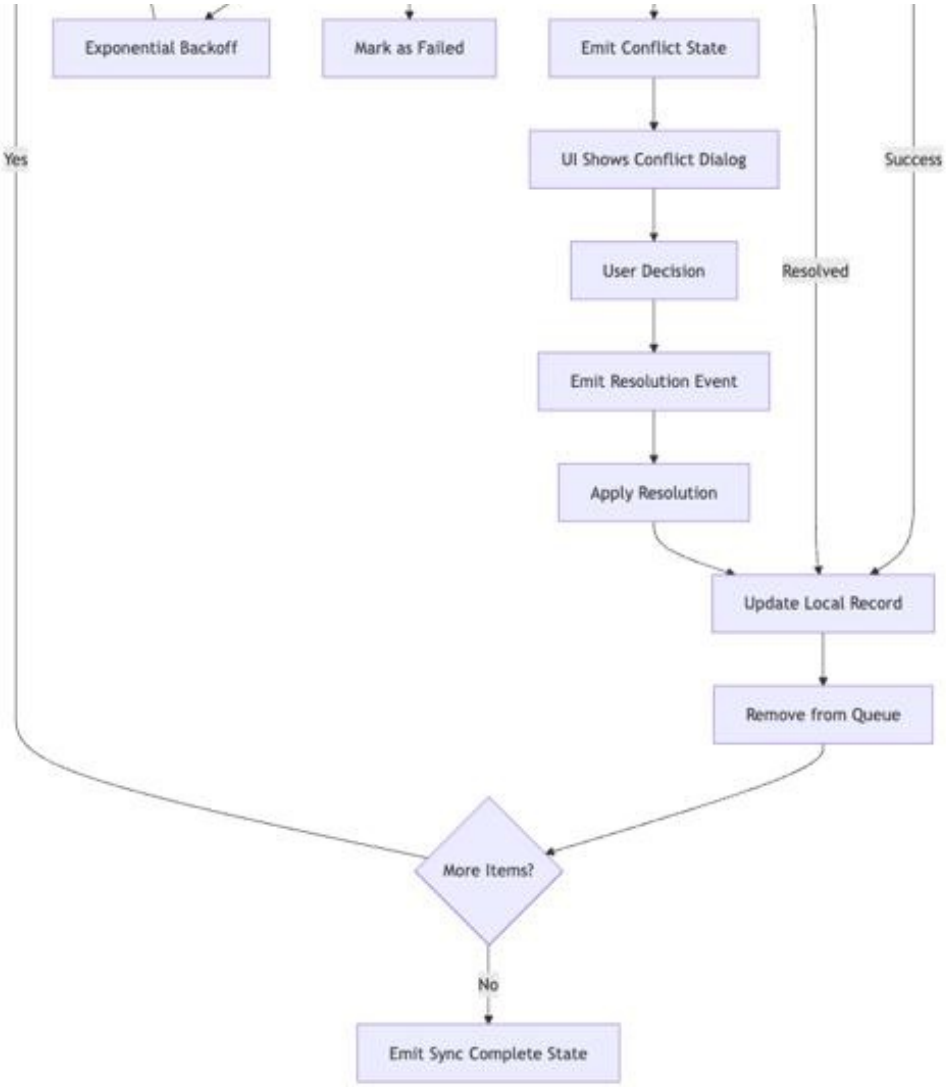



BLoC Event
BLoC Handler
Repository Layer
Save to Hive Main Box
Add to Sync Queue
Emit BLoC State
UI Rebuild
Show Pending Sync Status
BLoC Event
BLoC Handler
Repository Layer
Save to Hive Main Box
Trigger Immediate Sync
Sync Engine
Send to Remote API
Success?
Yes
No
Mark as Synced
Add to Retry Queue

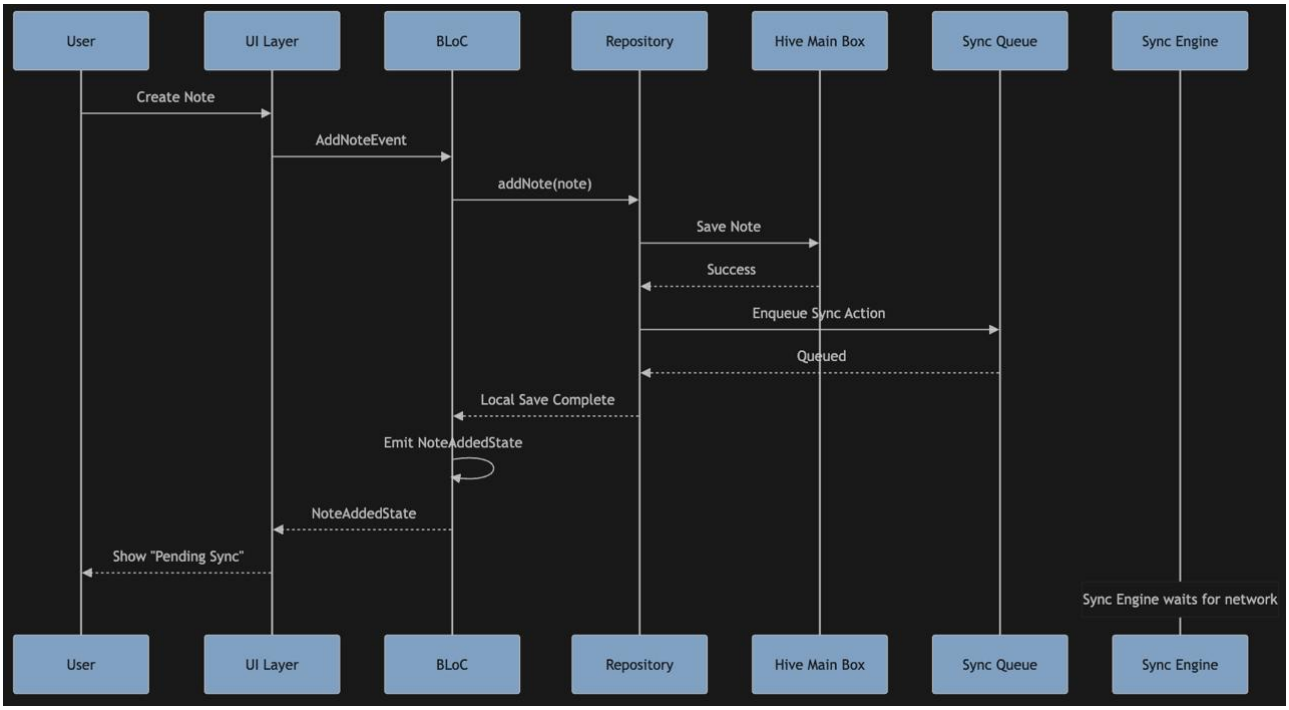


2. Online Data Flow Diagram

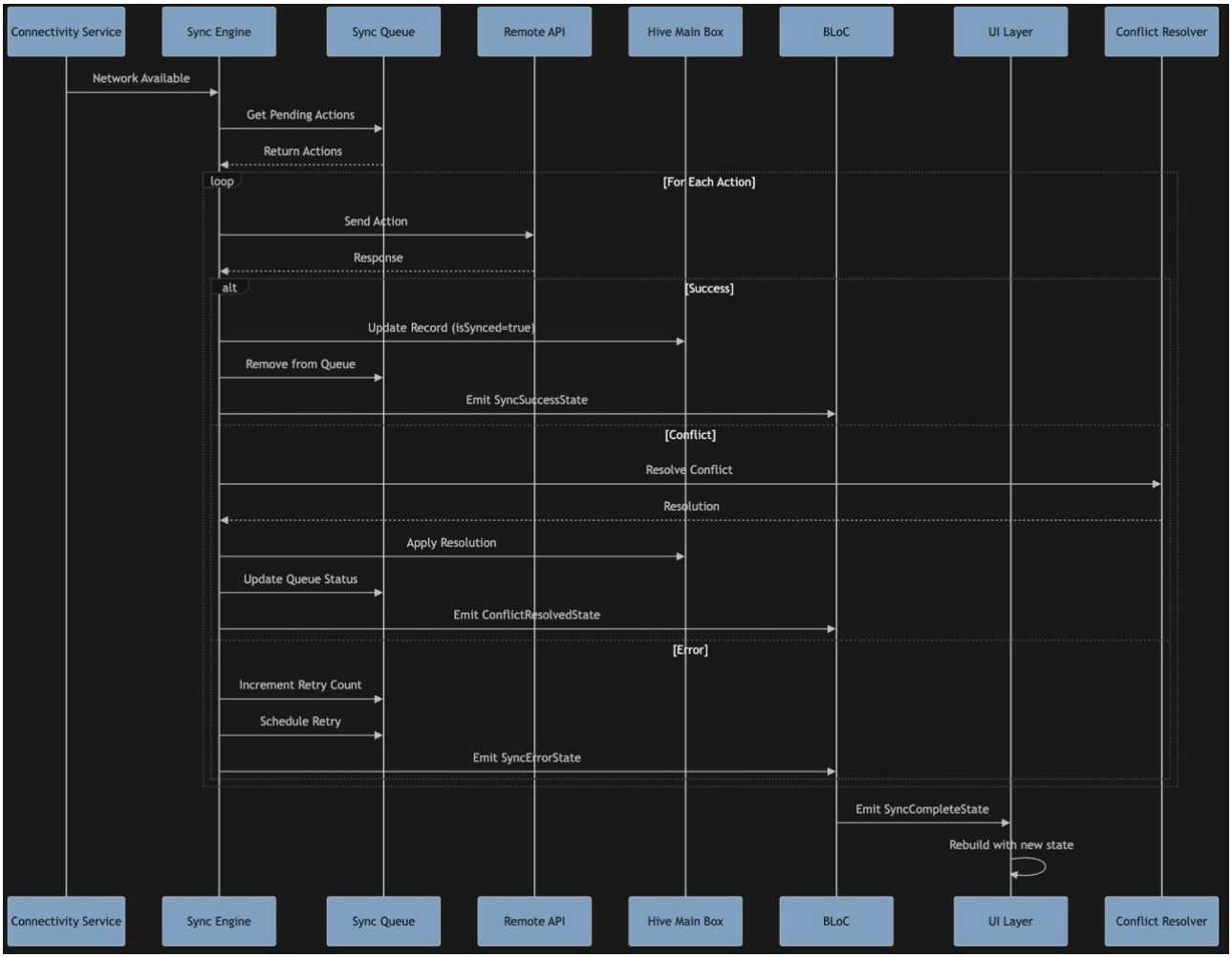




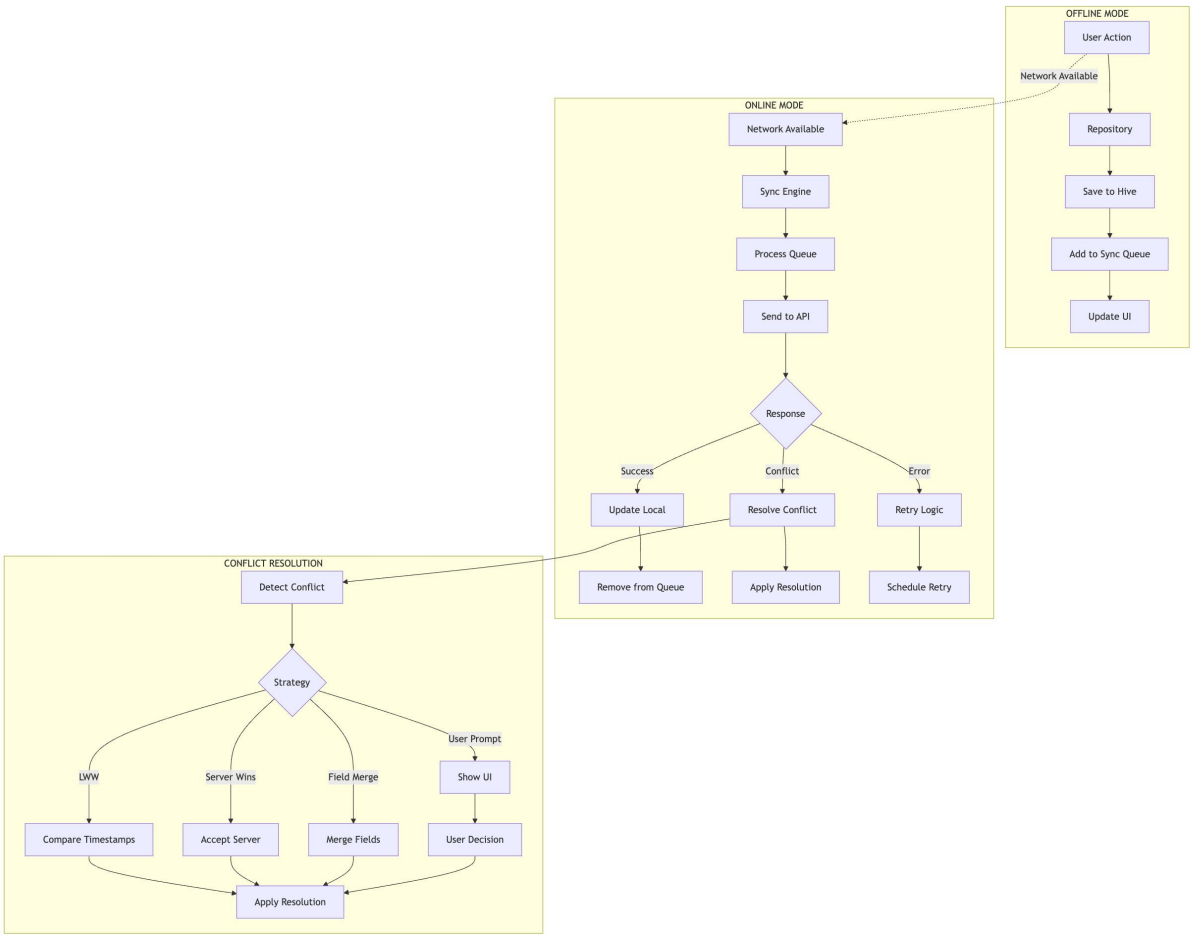
3. Offline Sequence Diagram



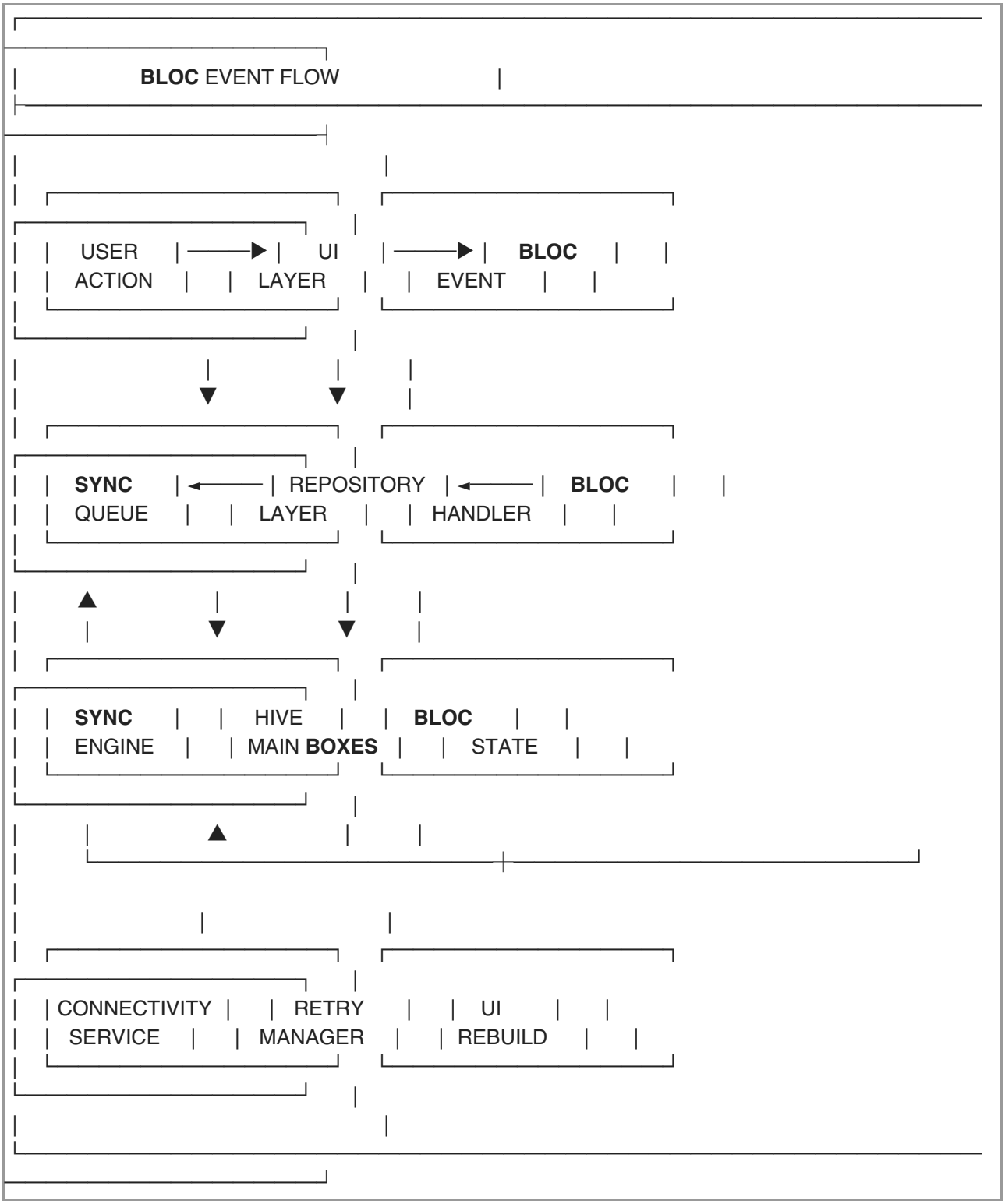
4. Online Sequence Diagram



5. End-to-End Flow Diagram



3. BLoC Event Flow Architecture



BLoC State Management

1. BLoC Structure

```
// Events
abstract class NoteEvent {}

class AddNoteEvent extends NoteEvent {
```

```
  final Note note;
  AddNoteEvent(this.note);
}

class UpdateNoteEvent extends NoteEvent {
  final Note note;
  UpdateNoteEvent(this.note);
}

class DeleteNoteEvent extends NoteEvent {
  final String noteId;
  DeleteNoteEvent(this.noteId);
}

class SyncNotesEvent extends NoteEvent {}

// States
abstract class NoteState {}

class NoteInitial extends NoteState {}

class NoteLoading extends NoteState {}

class NoteLoaded extends NoteState {
  final List<Note> notes;
  final SyncStatus syncStatus;
  NoteLoaded(this.notes, this.syncStatus);
}

class NoteAdded extends NoteState {
  final Note note;
  final bool isSynced;
  NoteAdded(this.note, this.isSynced);
}

class NoteUpdated extends NoteState {
  final Note note;
  final bool isSynced;
  NoteUpdated(this.note, this.isSynced);
}

class NoteDeleted extends NoteState {
  final String noteId;
  NoteDeleted(this.noteId);
}

class NoteSyncInProgress extends NoteState {
  final List<Note> notes;
  NoteSyncInProgress(this.notes);
}

class NoteSyncComplete extends NoteState {
```

```
  final List<Note> notes;
  NoteSyncComplete(this.notes);
}

class NoteSyncError extends NoteState {
  final String error;
  final List<Note> notes;
  NoteSyncError(this.error, this.notes);
}

class NoteConflictDetected extends NoteState {
  final Note localNote;
  final Note serverNote;
  final String conflictReason;
  NoteConflictDetected(this.localNote, this.serverNote, this.conflictReason);
}
```

2. BLoC Implementation

```
class NoteBloc extends Bloc<NoteEvent, NoteState> {
  final NoteRepository _noteRepository;
  final SyncEngine _syncEngine;
  final ConnectivityService _connectivityService;

  NoteBloc({
    required NoteRepository noteRepository,
    required SyncEngine syncEngine,
    required ConnectivityService connectivityService,
  }) : _noteRepository = noteRepository,
       _syncEngine = syncEngine,
       _connectivityService = connectivityService,
       super(NoteInitial()) {

    on<AddNoteEvent>(_onAddNote);
    on<UpdateNoteEvent>(_onUpdateNote);
    on<DeleteNoteEvent>(_onDeleteNote);
    on<SyncNotesEvent>(_onSyncNotes);

    // Listen to connectivity changes
    _connectivityService.connectivityStream.listen((isConnected) {
      if (isConnected) {
        add(SyncNotesEvent());
      }
    });
  }

  Future<void> _onAddNote(AddNoteEvent event, Emitter<NoteState> emit) async {
    try {
      emit(NoteLoading());

      // Save note locally
      await _noteRepository.addNote(event.note);
```

```
    // Check if online for immediate sync
    final isOnline = await _connectivityService.isConnected;

    if (isOnline) {
      // Trigger immediate sync
      await _syncEngine.syncEntity(event.note);
      emit(NoteAdded(event.note, true));
    } else {
      // Note will be synced when online
      emit(NoteAdded(event.note, false));
    }

    // Load updated notes
    final notes = await _noteRepository.getAllNotes();
    emit(NoteLoaded(notes, SyncStatus.idle));

  } catch (e) {
    emit(NoteSyncError(e.toString(), []));
  }
 }

 Future<void> _onSyncNotes(SyncNotesEvent event, Emitter<NoteState> emit) async {
  try {
    final notes = await _noteRepository.getAllNotes();
    emit(NoteSyncInProgress(notes));

    await _syncEngine.processSyncQueue();

    final updatedNotes = await _noteRepository.getAllNotes();
    emit(NoteSyncComplete(updatedNotes));

  } catch (e) {
    final notes = await _noteRepository.getAllNotes();
    emit(NoteSyncError(e.toString(), notes));
  }
 }
}
```

Conflict Resolution

1. Conflict Resolution Strategies

```
abstract class ConflictResolver {
 Future<ConflictResolution> resolve(ConflictContext context);
}

class LastWriteWinsResolver implements ConflictResolver {
 @override
 Future<ConflictResolution> resolve(ConflictContext context) async {
```

```
    final localTime = context.localEntity.syncMeta.lastUpdated;
    final serverTime = context.serverResponse.serverTimestamp;

    if (localTime.isAfter(serverTime)) {
      return ConflictResolution.keepLocal;
    } else {
      return ConflictResolution.acceptServer;
    }
  }
}

class ServerWinsResolver implements ConflictResolver {
  @override
  Future<ConflictResolution> resolve(ConflictContext context) async {
    return ConflictResolution.acceptServer;
  }
}

class FieldLevelMergeResolver implements ConflictResolver {
  @override
  Future<ConflictResolution> resolve(ConflictContext context) async {
    // Implement field-level merging logic
    final mergedData = _mergeFields(
      context.localEntity.toSyncPayload(),
      context.serverResponse.data,
    );

    return ConflictResolution.merge(mergedData);
  }

  Map<String, dynamic> _mergeFields(
    Map<String, dynamic> local,
    Map<String, dynamic> server,
  ) {
    // Custom merge logic based on field types
    final merged = Map<String, dynamic>.from(local);

    // Example: merge tags arrays
    if (local['tags'] is List && server['tags'] is List) {
      final localTags = List<String>.from(local['tags']);
      final serverTags = List<String>.from(server['tags']);
      merged['tags'] = [...localTags, ...serverTags].toSet().toList();
    }

    // Example: keep server timestamp for lastUpdated
    merged['lastUpdated'] = server['lastUpdated'];

    return merged;
  }
}
```

2. Conflict Resolution Context

```dart
class ConflictContext {
  final SyncableEntity localEntity;
  final ServerResponse serverResponse;
  final String conflictReason;
  final Map<String, dynamic> conflictFields;

  ConflictContext({
    required this.localEntity,
    required this.serverResponse,
    required this.conflictReason,
    required this.conflictFields,
  });
}

enum ConflictResolution {
  keepLocal,
  acceptServer,
  merge(Map<String, dynamic> mergedData),
  requireUserInput,
}

class ConflictResolutionResult {
  final ConflictResolution resolution;
  final String? reason;
  final Map<String, dynamic>? mergedData;

  ConflictResolutionResult({
    required this.resolution,
    this.reason,
    this.mergedData,
  });
}
```

Project Structure

```
lib/
├── core/
│   ├── models/
│   │   ├── sync_meta.dart
│   │   └── syncable_entity.dart
│   ├── storage/
│   │   ├── hive_service.dart
│   │   ├── sync_queue_service.dart
│   │   └── box_registry.dart
│   ├── sync/
│   │   ├── sync_engine.dart
│   │   ├── conflict_resolver.dart
│   │   └── retry_manager.dart
```

```
|   ├── connectivity/
|   |   └── connectivity_service.dart
|   └── errors/
|       ├── sync_exceptions.dart
|       └── conflict_exceptions.dart
├── features/
|   ├── notes/
|   |   ├── models/
|   |   |   └── note.dart
|   |   ├── repositories/
|   |   |   └── note_repository.dart
|   |   ├── bloc/
|   |   |   ├── note_bloc.dart
|   |   |   ├── note_event.dart
|   |   |   └── note_state.dart
|   |   ├── widgets/
|   |   |   ├── note_card.dart
|   |   |   ├── sync_status_indicator.dart
|   |   |   └── conflict_resolution_dialog.dart
|   |   └── screens/
|   |       └── notes_screen.dart
|   └── users/
|       ├── models/
|       |   └── user.dart
|       ├── repositories/
|       |   └── user_repository.dart
|       ├── bloc/
|       |   ├── user_bloc.dart
|       |   ├── user_event.dart
|       |   └── user_state.dart
|       └── screens/
|           └── users_screen.dart
├── services/
|   ├── api/
|   |   └── remote_api.dart
|   └── sync/
|       └── background_sync_service.dart
├── shared/
|   ├── widgets/
|   |   ├── loading_widget.dart
|   |   ├── error_widget.dart
|   |   └── retry_button.dart
|   └── utils/
|       ├── date_utils.dart
|       └── validation_utils.dart
└── main.dart
```

Code Examples

1. Hive Adapter Implementation

```
@HiveType(typeId: 0)
class Note extends SyncableEntity {
  @HiveField(0)
  final String id;

  @HiveField(1)
  final String title;

  @HiveField(2)
  final String content;

  @HiveField(3)
  final SyncMeta syncMeta;

  @HiveField(4)
  final List<String> tags;

  @HiveField(5)
  final DateTime createdAt;

  Note({
    required this.id,
    required this.title,
    required this.content,
    required this.syncMeta,
    this.tags = const [],
    required this.createdAt,
  });

  @override
  Map<String, dynamic> toSyncPayload() => {
    'id': id,
    'title': title,
    'content': content,
    'tags': tags,
    'createdAt': createdAt.toIso8601String(),
    'lastUpdated': syncMeta.lastUpdated.toIso8601String(),
  };

  @override
  void updateSyncMeta(SyncMeta meta) {
    // Update sync metadata
  }

  Note copyWith({
    String? id,
    String? title,
    String? content,
    SyncMeta? syncMeta,
    List<String>? tags,
    DateTime? createdAt,
```

```
  }) {
    return Note(
      id: id ?? this.id,
      title: title ?? this.title,
      content: content ?? this.content,
      syncMeta: syncMeta ?? this.syncMeta,
      tags: tags ?? this.tags,
      createdAt: createdAt ?? this.createdAt,
    );
  }
}
```

2. Repository Implementation

```
class NoteRepository implements BaseRepository<Note> {
  final HiveService _hiveService;
  final SyncQueueService _syncQueue;
  final ConnectivityService _connectivity;

  NoteRepository({
    required HiveService hiveService,
    required SyncQueueService syncQueue,
    required ConnectivityService connectivity,
  }) : _hiveService = hiveService,
       _syncQueue = syncQueue,
       _connectivity = connectivity;

  @override
  Future<void> create(Note note) async {
    // Save to Hive
    await _hiveService.notesBox.put(note.id, note);

    // Add to sync queue if offline
    if (!await _connectivity.isConnected) {
      await _syncQueue.enqueue(SyncAction(
        id: Uuid().v4(),
        type: SyncActionType.create,
        entityType: 'Note',
        entityId: note.id,
        payload: note.toSyncPayload(),
        timestamp: DateTime.now(),
        retryCount: 0,
        status: SyncStatus.pending,
      ));
    }
  }

  @override
  Future<void> update(Note note) async {
    // Update in Hive
    await _hiveService.notesBox.put(note.id, note);
```

```
  // Add to sync queue if offline
  if (!await _connectivity.isConnected) {
    await _syncQueue.enqueue(SyncAction(
      id: Uuid().v4(),
      type: SyncActionType.update,
      entityType: 'Note',
      entityId: note.id,
      payload: note.toSyncPayload(),
      timestamp: DateTime.now(),
      retryCount: 0,
      status: SyncStatus.pending,
    ));
  }
}

@override
Future<void> delete(String id) async {
  // Delete from Hive
  await _hiveService.notesBox.delete(id);

  // Add to sync queue if offline
  if (!await _connectivity.isConnected) {
    await _syncQueue.enqueue(SyncAction(
      id: Uuid().v4(),
      type: SyncActionType.delete,
      entityType: 'Note',
      entityId: id,
      payload: {'id': id},
      timestamp: DateTime.now(),
      retryCount: 0,
      status: SyncStatus.pending,
    ));
  }
}

@override
Stream<List<Note>> watchAll() {
  return _hiveService.notesBox.watch().map((box) {
    return box.values.cast<Note>().toList();
  });
}

@override
Stream<Note?> watchById(String id) {
  return _hiveService.notesBox.watch().map((box) {
    return box.get(id) as Note?;
  });
}

@override
Future<void> markAsSynced(String id) async {
  final note = _hiveService.notesBox.get(id) as Note?;
```

```
  if (note != null) {
    final updatedNote = note.copyWith(
      syncMeta: SyncMeta(
        lastUpdated: DateTime.now(),
        isSynced: true,
        conflictFlag: null,
        retryCount: 0,
        lastSyncAttempt: DateTime.now(),
      ),
    );
    await _hiveService.notesBox.put(id, updatedNote);
  }
 }

 @override
 Future<void> markAsConflict(String id, String conflictReason) async {
  final note = _hiveService.notesBox.get(id) as Note?;
  if (note != null) {
    final updatedNote = note.copyWith(
      syncMeta: SyncMeta(
        lastUpdated: note.syncMeta.lastUpdated,
        isSynced: false,
        conflictFlag: conflictReason,
        retryCount: note.syncMeta.retryCount,
        lastSyncAttempt: DateTime.now(),
      ),
    );
    await _hiveService.notesBox.put(id, updatedNote);
  }
 }

 @override
 Future<List<Note>> getUnsyncedEntities() async {
  return _hiveService.notesBox.values
      .cast<Note>()
      .where((note) => !note.syncMeta.isSynced)
      .toList();
 }
}
```

3. UI Integration with BLoC

```
class NotesScreen extends StatelessWidget {
 @override
 Widget build(BuildContext context) {
  return BlocBuilder<NoteBloc, NoteState>(
    builder: (context, state) {
      if (state is NoteLoading) {
        return Center(child: CircularProgressIndicator());
      } else if (state is NoteLoaded) {
        return NotesList(
          notes: state.notes,
```

```
          syncStatus: state.syncStatus,
        );
      } else if (state is NoteSyncError) {
        return ErrorWidget(
          error: state.error,
          onRetry: () => context.read<NoteBloc>().add(SyncNotesEvent()),
        );
      } else if (state is NoteConflictDetected) {
        return ConflictResolutionDialog(
          localNote: state.localNote,
          serverNote: state.serverNote,
          conflictReason: state.conflictReason,
          onResolve: (resolution) {
            // Handle conflict resolution
          },
        );
      }

      return Container();
    },
  );
 }
}

class NotesList extends StatelessWidget {
 final List<Note> notes;
 final SyncStatus syncStatus;

 const NotesList({
  required this.notes,
  required this.syncStatus,
 });

 @override
 Widget build(BuildContext context) {
  return Column(
    children: [
      // Sync status indicator
      SyncStatusIndicator(status: syncStatus),

      // Notes list
      Expanded(
        child: ListView.builder(
          itemCount: notes.length,
          itemBuilder: (context, index) {
            final note = notes[index];
            return NoteCard(
              note: note,
              onEdit: () => _editNote(context, note),
              onDelete: () => _deleteNote(context, note),
            );
          },
```

```
        ),
      ),
    ],
  );
 }

 void _editNote(BuildContext context, Note note) {
  // Navigate to edit screen
 }

 void _deleteNote(BuildContext context, Note note) {
  context.read<NoteBloc>().add(DeleteNoteEvent(note.id));
 }
}
```

4. Sync Status Indicator

```
class SyncStatusIndicator extends StatelessWidget {
 final SyncStatus status;

 const SyncStatusIndicator({required this.status});

 @override
 Widget build(BuildContext context) {
  return Container(
   padding: EdgeInsets.all(8.0),
   child: Row(
    children: [
     Icon(
      _getStatusIcon(),
      color: _getStatusColor(),
      size: 16,
     ),
     SizedBox(width: 8),
     Text(
      _getStatusText(),
      style: TextStyle(
       color: _getStatusColor(),
       fontSize: 12,
      ),
     ),
    ],
   ),
  );
 }

 IconData _getStatusIcon() {
  switch (status) {
   case SyncStatus.idle:
    return Icons.check_circle;
   case SyncStatus.syncing:
    return Icons.sync;
```

```
    case SyncStatus.error:
      return Icons.error;
    case SyncStatus.conflict:
      return Icons.warning;
  }
}

Color _getStatusColor() {
  switch (status) {
    case SyncStatus.idle:
      return Colors.green;
    case SyncStatus.syncing:
      return Colors.blue;
    case SyncStatus.error:
      return Colors.red;
    case SyncStatus.conflict:
      return Colors.orange;
  }
}

String _getStatusText() {
  switch (status) {
    case SyncStatus.idle:
      return 'All synced';
    case SyncStatus.syncing:
      return 'Syncing...';
    case SyncStatus.error:
      return 'Sync error';
    case SyncStatus.conflict:
      return 'Conflict detected';
  }
}
}
```

5. Dependencies (pubspec.yaml)

```
dependencies:
  flutter:
    sdk: flutter
  hive: ^2.2.3
  hive_flutter: ^1.1.0
  flutter_bloc: ^8.1.3
  connectivity_plus: ^5.0.2
  uuid: ^4.2.1
  dio: ^5.4.0
  workmanager: ^0.5.2
  equatable: ^2.0.5

dev_dependencies:
  flutter_test:
    sdk: flutter
  hive_generator: ^2.0.1
  build_runner: ^2.4.7
  bloc_test: ^9.1.5
  mockito: ^5.4.2
```

Best Practices

1. State Management

- Use BLoC for complex state management
- Use Cubit for simple state management
- Keep BLoCs focused on single features
- Use Equatable for state comparison
- Emit states in the correct order

2. Data Persistence

- Use Hive for local storage
- Implement proper data adapters
- Handle data migration gracefully
- Use transactions for batch operations
- Implement proper error handling

3. Sync Engine

- Implement exponential backoff for retries
- Use batch sync to reduce API calls
- Handle conflicts gracefully
- Provide user feedback for sync status
- Implement proper error recovery

4. Conflict Resolution

- Implement multiple resolution strategies
- Provide user choice for critical conflicts
- Log conflict resolution decisions

- Test conflict scenarios thoroughly
- Document resolution policies

5. Error Handling

- Implement comprehensive error handling
- Provide meaningful error messages
- Log errors for debugging
- Implement retry mechanisms
- Handle network failures gracefully

6. Testing

- Write unit tests for BLoCs
- Test repository implementations
- Mock external dependencies
- Test offline/online scenarios
- Test conflict resolution

7. Performance

- Use lazy loading for large datasets
- Implement pagination
- Optimize Hive queries
- Use background sync
- Monitor memory usage

8. Security

- Encrypt sensitive data
- Use secure storage
- Implement proper authentication
- Validate all inputs
- Handle sensitive data properly

This comprehensive architecture provides a robust, production-ready foundation for a Flutter offline-first application using BLoC, Hive, and a dedicated sync engine. The design ensures reliable offline functionality with proper conflict resolution and state management.