

Reactive Dead Code Analysis Plan (Skip Runtime Alignment)

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Abstract

This plan replaces the batch-only dead code analysis with a fully reactive pipeline built on the Skip runtime described in `docs/reactive_ocaml.tex`. It details the preparatory refactors (pure data extraction, deterministic summaries, graph factoring), the Skip collection design, integration with the existing build (rewatch) outputs, test strategy, and troubleshooting guidance. Each milestone enumerates concrete code changes, intermediate validation steps, and acceptance criteria so implementation proceeds from small refactors to a production-ready reactive service with < 200ms latency for file changes.

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Implementation log. Each milestone has a matching entry in `docs/reactive_dead_code_log.md` summarizing the concrete code changes, validation steps, and commands that landed in the repository. Consult the log before starting a new milestone to ensure you’re building on the verified baseline.

1 Overview of Changes and Outcome

1.1 Architectural Transformation

The batch-only analyzer mutates global tables and must rescan every `.cmt` to emit diagnostics. This plan migrates it to the Skip runtime so that:

- Collection becomes fully pure: every traversal returns `Collected_types.t`, enabling deterministic caching and parallel work.
- Per-file summaries, graph state, and diagnostics persist inside a Skip heap, so warm edits reuse cached work instead of reprocessing the whole project.
- The only tracked resource is `.reanalyze/manifest.json`; its digests describe all `.cmt/.cmti` files, so Skip re-evaluates only when manifests change.
- `reanalyze --reactive` runs once per manifest update (invoked by rewatch or a watch script): declare the graph, call `Reactive.exit`, observe diagnostics, exit. This matches the lifecycle in `docs/reactive_ocaml.tex` where each process initializes, declares, exits, and then reads results.

1.2 Key Refactors (Milestones 1–3)

- Thread a collector interface through `DeadValue`, `DeadType`, `DeadException`, and `DeadOptionalArgs`; adapt batch mode via `DeadCommon_sink` so existing tooling continues to work.
- Introduce `Collected_types`, `Collector_intf`, `Pure_collector`, `Summary`, and `Summary_cache` to produce deterministic per-file artifacts with JSON goldens.
- Build `Graph_store` and `Liveness` modules that incrementally recompute SCCs only within the frontier influenced by changed summaries.
- Add scoped helpers (`Common.with_current_module`, `ModulePath.with_current`) so `Skip` maps never depend on ambient mutable refs.

1.3 Skip Integration Path (Milestone 4)

- `Rewatch` writes `.reanalyze/manifest.json` after a successful build. A supervisor reruns `reanalyze --reactive` when that file changes.
- `Reactive_service.run_once` declares the `Skip` pipeline: manifest input \rightarrow per-file summaries \rightarrow graph store \rightarrow diagnostic diffs. Individual `.cmt` files are read via regular OCaml IO inside the manifest map, relying on manifest digests for invalidation (Option A from `docs/reactive_ocaml.tex`).
- Diagnostics are pulled only after `Reactive.exit`; `Diagnostics_loop` streams them to the CLI or the LSP provider before the process exits.

1.4 Expected Outcome

- **Performance:** Cold runs match current batch latency; warm edits touch only changed summaries plus dependent SCCs (target p50 < 200 ms, p95 < 1 s).
- **Parity:** Batch mode remains the CI default, and nightly parity tests ensure reactive diagnostics are byte-identical.
- **Developer experience:** Editors receive near-real-time dead-code diagnostics via LSP, and scripts can simply call `reanalyze --reactive` after each build—no custom daemons or coordination files required.
- **Fallback:** If `Skip` mode fails, users fall back to `reanalyze -dce`; collector adapters keep batch behavior unchanged.

2 Goals and Non-Goals

- Maintain golden parity with current batch diagnostics for all analyses that depend on `DeadCommon` (dead values, optional args, exceptions).
- Recompute only the file summaries and SCC regions whose dependencies changed; target p50 latency < 200 ms and p95 < 1 s for same project edits.
- Reuse `Skip` runtime primitives (`Reactive.init`, tracked resources, `Reactive.map`, `Reactive.exit`) so the tool matches `docs/reactive_ocaml.tex` constraints.

- Preserve CLI surface area: batch mode remains default for CI; reactive mode is opt-in until parity is proven.
- Non-goals: redesigning the AST, changing warning wording, or introducing new user-facing configuration.

3 Baseline Architecture and Constraints

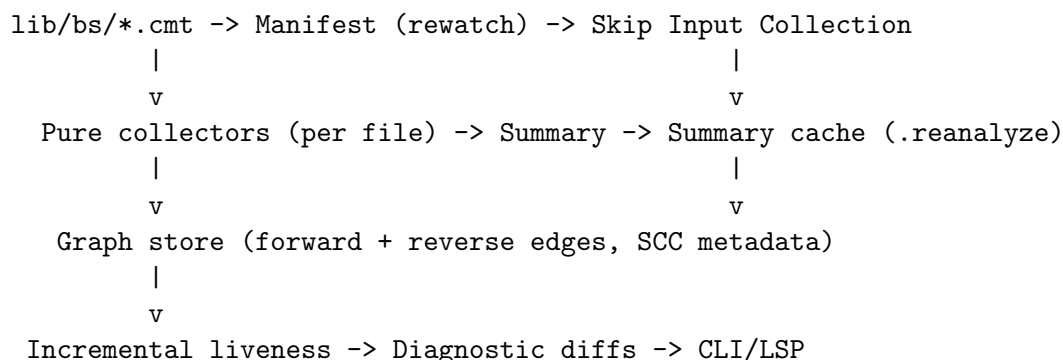
3.1 Batch Pipeline Recap

1. `Reanalyze.loadCmtFile` resolves each `.cmt/.cmti` to its source via `FindSourceFile.cmt`, sets `Common.currentSrc/currentModule/currentModuleName`, and invokes `DeadCode.processCmt`.
2. Modules under `analysis/reanalyze/src/Dead*.ml` mutate globals in `DeadCommon` (`decls`, `ValueReferences.table`, `TypeReferences.table`, `FileReferences`).
3. After all files, `DeadCommon.reportDead` resolves recursion, optional args, and emits diagnostics.

3.2 Skip Runtime Constraints (`docs/reactive_ocaml.tex`)

- Single initialization via `Reactive.init` heap size; Linux binaries must link `-no-pie -Wl,-Ttext=...` to keep pointers stable.
- Every file read occurs through trackers returned by `Reactive.input_files` or downstream maps; ad-hoc IO is prohibited.
- `Reactive.map` callbacks must be pure relative to inputs; any mutable globals (e.g., `Common.currentSrc`) must be encapsulated by helper functions that reset state per invocation.
- Graph declaration finishes with `Reactive.exit()`, after which downstream code observes derived arrays via `Reactive.get_array`.
- macOS cannot reopen heaps across fresh runs; service deletes stale `*.rheap` on start. Linux may reuse heaps if binary layout is constant.

3.3 Data Flow Diagram



4 Milestone 0: Runtime Readiness

4.1 Tasks

1. Update `analysis/bin/dune`:
 - Add conditional linking of `libskip_reactive.a`.
 - On Linux, append `-ccopt -no-pie -ccopt -Wl,-Ttext=0x8000000`; on macOS, add startup hook that deletes stale heaps before `Reactive.init`.
2. Add `analysis/bin/reactive.repl` target that simply runs `Reactive.init`; `Reactive.exit`. CI ensures Skip linkage stays healthy.
3. Capture baseline metrics (wall-clock, files processed) for `reanalyze -dce` on representative projects. Store JSON under `analysis/benchmarks/reactive_baseline.json` for later comparison.
4. Stub `--reactive` flag in `analysis/bin/main.ml` (behind experimental guard) pointing to a placeholder that exits with `'Not_implemented'`. This allows CLI plumbing to be reviewed early.

4.2 Acceptance

- Batch builds/tests pass with Skip runtime linked.
- Baseline metrics captured and committed.

5 Milestone 1: Pure Data Extraction

5.1 Overview

Goal: isolate AST traversal and data recording from `DeadCommon`'s global tables through incremental steps that keep batch behavior unchanged after each sub-step.

5.2 Step-by-Step Refactor

1. Step 1.1: Define collector types

```
(* Collected_types.ml *)
type optional_arg = { supplied: string list; maybe: string list }

type ref_edge_kind =
| Value
| Type
| Exception
| OptionalArgs of optional_arg

type decl = {
  name: Name.t;
  module_path: Path.t;
  loc: Location.t;
  decl_kind: Common.DeclKind.t;
}
```

```

type ref_edge = { from_: Location.t; to_: Location.t; kind: ref_edge_kind }

type file_edge = { from_file: string; to_file: string }

type t = {
  decls: decl list;
  refs: ref_edge list;
  file_edges: file_edge list;
}

type collector = t -> t

let empty = { decls = []; refs = []; file_edges = [] }

```

Document schema and invariants (e.g., loc must be non-ghost).

2. Step 1.2: Create collector interface

```

module type COLLECTOR = sig
  type t
  val empty : t
  val add_decl : t -> decl -> t
  val add_ref : t -> ref_edge -> t
  val add_file_edge : t -> file_edge -> t
end

```

Provide two implementations:

- Collected_collector storing data in Collected_types.t.
- DeadCommon_sink writing into DeadCommon by delegating to existing functions. This keeps batch mode working while the refactor proceeds.

3. Step 1.3: Thread collector through DeadValue

- Introduce DeadValue.collectValueBinding ~collector and collectExpr ~collector that perform the existing logic but call Collector.add_decl/add_ref instead of mutating globals directly.
- Example snippet:

```

let collectValueBinding ~collector super self vb =
  let collector = ref collector in
  (* existing pattern matching ... *)
  (match vb.vb_pat.pat_desc with
  | Tpat_var (id, { loc = { loc_start; loc_ghost } as loc }) when not loc_ghost ->
    let decl = { name; module_path; loc = vb.vb_loc; decl_kind = ... } in
    collector := C.add_decl !collector decl
  | _ -> ());
  collector := super.Tast_mapper.value_binding self vb;
  !collector

```

- Build DeadValue.traverse_structure ~collector structure returning the updated collector. The function creates a ref cell for the collector and assigns call-back closures inside Tast_mapper to update the ref.

- Repeat for `DeadType`, `DeadException`, and `DeadOptionalArgs`: each module gains a `~collector` parameter. Until the pure pipeline lands, pass `DeadCommon_sink.collector` from `DeadCode.processCmt`.

4. Step 1.4: Common state helpers

- Add `Common.with_current_module ~src ~module_name (fun () -> ...)` wrapping assignments to `currentSrc/currentModule/currentModuleName`. Both batch and reactive traversals call this helper so state is set consistently.
- Update `Reanalyze.loadCmtFile` to invoke `Common.with_current_module` around `DeadCode.processCmt`.
- Add `ModulePath.with_current : (unit -> 'a) -> 'a` resetting `ModulePath.current` during traversal, ensuring collector runs are isolated.

5. Step 1.5: Unit tests

- Add `tests/reanalyze_tests/typedtree_helpers.ml` to fabricate small typedtrees via the OCaml compiler-libs (e.g., parse a snippet and type-check it in-memory).
- Write tests such as:

```
let test_value_decl_collection () =
  let typedtree = Helpers.structure_of_string "let foo x = x" in
  let collected = DeadValue.traverse_structure ~collector:Collected_collector.empty
    typedtree in
  Alcotest.(check int) "decl count" 1 (List.length collected.decls)
```

- Cover optional args, exception usage, type references, and file edges by constructing appropriate typedtrees.

6. Step 1.6: Parity verification

- After each sub-step (value collection, type collection, exceptions), run `reanalyze -dce` on fixtures to ensure diagnostics match.
- Add a CI lane that compares JSON outputs before/after refactor using `git diff --no-index`. Fail if any change appears.

5.3 Acceptance

- `DeadValue`, `DeadType`, `DeadException`, `DeadOptionalArgs` can return `Collected_types.t` without mutating `DeadCommon` when passed `Collected_collector`.
- Batch diagnostics remain unchanged.
- Unit tests cover representative constructs.

6 Milestone 2: Deterministic File Summaries

6.1 Schema

```

{
  "version": 1,
  "source_file": "src/Foo.res",
  "digest": "b2d7...",
  "decls": [
    {
      "name": "Foo.make",
      "kind": "Value",
      "module_path": ["Foo"],
      "loc": { "line": 12, "column": 4 },
      "toplevel": true,
      "optional_args": ["callback"],
      "side_effects": true
    }
  ],
  "refs": [
    {
      "from": { "line": 18, "column": 6 },
      "to": { "line": 12, "column": 4 },
      "kind": "Value"
    },
    {
      "from": { "line": 25, "column": 8 },
      "to": { "line": 25, "column": 8 },
      "kind": "OptionalArgs",
      "optional": { "supplied": ["callback"], "maybe": [] }
    }
  ],
  "file_edges": [ { "from": "src/Foo.res", "to": "src/Bar.res" } ]
}

```

- **Version field** follows semantic versioning (major only). Increment when schema changes; maintain backward compatibility by upgrading readers.
- Store canonical JSON (sorted keys) and compute digest using `Digestif.blake2b` over the canonical bytes.
- Add `Summary.version = 1` constant; bump to 2 if new fields become mandatory.

6.2 Implementation Tasks

1. Implement `Summary.of_collected` covering:
 - Conversion of `Collected_types.decl` to summary decls, including flags like `toplevel`, `optional_args`, `side_effects`.
 - Flattening `ref_edge_kind` into JSON-friendly shapes.
 - Deduplicating `file_edges` by sorting and calling `List.sort_uniq`.
2. Implement `Summary.to_json/from_json` with explicit error messages (raise `Summary.Invalid_format of string`). Provide property tests to ensure round-trips succeed.
3. Create `Summary_cache`:
 - Cache path: `.reanalyze/summaries/<digest>.json`.

- Write atomically by writing to temp file then `Unix.rename`.
 - Provide `read_or_recompute ~project_root summary` helper.
4. Update `DeadCode.processCmt`: after obtaining `collected`, call `Summary.of_collected`. Feed the result into `DeadCommon_sink` (for batch) and optionally write to cache when `Common.Cli.cache_summaries` is set. This validates the new path without altering output.
 5. Extend unit tests: compare generated JSON to checked-in golden files located under `tests/reactive_goldens/<file>.summary.json`. Provide helper to regenerate goldens via `dune exec tests/bin/update_summaries.exe`.

6.3 Acceptance

- Schema documented and versioned.
- Cache read/write validated by tests (including error cases like corrupt JSON).
- Batch diagnostics still match goldens.

7 Milestone 3: Graph Store and Incremental Liveness

7.1 Graph Store Design

1. Data structures

- `decl_id = <source file>##<line>##<column>##<kind>##<name>`.
- Hashtables: `forward_edges : decl_id -> decl_id list`, `reverse_edges : decl_id -> decl_id list`, `file_to_decls : string -> decl_id list`, `decl_info : decl_id -> summary_decl`.
- SCC cache: `decl_to_scc : decl_id -> int`, `scc_states : int -> { members; live; digest }`.

2. Frontier computation

```
let frontier graph changed_files =
  let seed_decls = List.concat_map (fun file -> Hashtbl.find file_to_decls file) changed_files
  in
  let rec bfs acc queue =
    match queue with
    | [] -> acc
    | id :: rest when DeclSet.mem id acc -> bfs acc rest
    | id :: rest ->
      let acc = DeclSet.add id acc in
      let revs = Hashtbl.find_opt reverse_edges id |> Option.value ~default:[] in
      bfs acc (revs @ rest)
  in
  bfs DeclSet.empty seed_decls |> DeclSet.elements
```

This yields all declarations whose liveness can change due to the modified files.

3. Incremental Tarjan

- Run Tarjan only on the subgraph induced by `frontier`. Non-frontier SCCs keep their cached `scc_state`.
- For each SCC, compute a hash of (members, outgoing edges, summary digests). If unchanged, reuse previous liveness result.
- `Liveness.solve_scc`: reuse logic from `DeadCommon.resolveRecursiveRefs` by parameterizing over callbacks to fetch references.

7.2 Pseudocode

```
let recompute_liveness graph changed_files =
  let frontier = frontier graph changed_files in
  let subgraph = induce graph frontier in
  let sccs = Tarjan.compute subgraph in
  List.iter (fun scc ->
    let key = hash_scc scc in
    match Hashtbl.find_opt graph.scc_cache key with
    | Some old when old.members = scc.members && old.out_edges = scc.out_edges -> ()
    | _ ->
      let result = Liveness.solve_scc scc in
      Hashtbl.replace graph.scc_cache key result;
      emit_diffs scc.members result)
```

7.3 Acceptance

- Frontier computation + SCC recompute documented and implemented.
- Unit tests cover cases where SCCs shrink/grow, optional-arg edges toggle liveness, and exception references propagate.

8 Milestone 4: Skip Reactive Service Core

8.1 CMT Discovery and Input Declaration

Discovery Phase Skip runtime requires ALL input files to be declared upfront via `Reactive.input_files` (per `docs/reactive_ocaml.tex`, line 91: “Declare the set of input files. Skip records and sorts them; cached runs require the same set”). Ad-hoc file IO inside maps violates tracker discipline (line 171: “ad-hoc I/O violates dependency tracking”).

1. At service startup, discover all `.cmt/.cmti` files under `lib/bs`:

```
(* Cmt_discovery.ml *)
let discover_cmt_files ~project_root =
  let lib_bs = Filename.concat project_root "lib/bs" in
  let rec walk acc dir =
    if Sys.is_directory dir then
      Sys.readdir dir
      |> Array.fold_left (fun acc entry ->
        walk acc (Filename.concat dir entry)) acc
    else if Filename.check_suffix dir ".cmt" || Filename.check_suffix dir ".cmti" then
      dir :: acc
    else acc
  in
```

```
walk [] lib_bs |> Array.of_list
```

2. Discovery happens ONCE at startup before `Reactive.input_files`. If new CMT files appear, service must restart (input file list is fixed per `docs/reactive_ocaml.tex`).
3. For restart coordination, rewatch writes `.reanalyze/build.stamp` with monotonic build ID. Reactive service watches this (outside Skip) and exits on change, triggering supervisor restart.

8.2 Rewatch Integration

1. Add `rewatch/src/build/notify.rs`:

```
pub fn notify_reanalyze(state: &BuildState) -> anyhow::Result<()> {
    let stamp_path = state.project_context.root_dir.join(".reanalyze/build.stamp");
    let build_id = state.build_id.to_string();
    std::fs::create_dir_all(stamp_path.parent().unwrap())?;
    std::fs::write(&stamp_path, build_id)?;
    Ok(())
}
```

2. Invoke after successful build in `rewatch/src/build/compile.rs`:

```
if run_successful {
    if let Err(e) = notify::notify_reanalyze(&command_state.build_state) {
        log::warn!("Failed to notify reanalyze: {e:?}");
    }
}
```

3. Reactive service polls `build.stamp` in background thread; when content changes, exits gracefully (code 0), signaling supervisor restart with fresh CMT discovery.

8.3 Skip Graph Implementation

Tracker Discipline Critical constraint from `docs/reactive_ocaml.tex` (line 171):

“Every file read must pass through the tracker array supplied by `input_files`; ad-hoc I/O violates dependency tracking and will compromise the reactive guarantees.”

Implementation:

1. Declare ALL discovered CMT files as inputs:

```
let all_cmt_files = Cmt_discovery.discover_cmt_files ~project_root in
let cmt_inputs = Reactive.input_files all_cmt_files in
```

2. Each CMT becomes a key. Skip invokes map once per key, passing: (1) **key**: CMT path, (2) **trackers**: array with ONE tracker for this file.
3. Read CMT using ONLY the tracker (per `docs/reactive_ocaml.tex` line 93):

```
let cmt_bytes = Reactive.read_file key trackers.(0) in
```

Skip tracks content hash and invalidates when file changes.

Reactive Pipeline

```
(* Reactive_service.ml *)
let run project_root =
  let heap_path = Filename.concat project_root "reanalyze.rheap" in
  Reactive.init heap_path (1024 * 1024 * 1024);

  (* Discover all CMT files upfront *)
  let all_cmt_files = Cmt_discovery.discover_cmt_files ~project_root in
  Log_.info "Tracking %d CMT files" (Array.length all_cmt_files);

  (* Declare ALL as tracked inputs - mandatory per reactive_ocaml.tex *)
  let cmt_inputs = Reactive.input_files all_cmt_files in

  (* Stage 1: Parse CMT -> Summary (one invocation per CMT file) *)
  let summaries =
    Reactive.map cmt_inputs (fun cmt_path trackers ->
      (* MUST use tracker - no ad-hoc IO per reactive_ocaml.tex:171 *)
      let cmt_bytes = Reactive.read_file cmt_path trackers.(0) in
      match Cmt_format.read_cmt_bytes cmt_bytes with
      | exception exn ->
        Diagnostics.report_cmt_error cmt_path exn;
        [||]
      | cmt_infos ->
        match FindSourceFile.cmt cmt_infos.cmt_annots with
        | None -> Diagnostics.report_no_source cmt_path; [||]
        | Some source_file ->
          let collected =
            Common.with_current_module ~src:source_file
              ~module_name:(Paths.getModuleName source_file |> Name.create)
              (fun () -> ModulePath.with_current (fun () ->
                Pure_collectors.from_cmt cmt_infos))
          in
          let summary = Summary.of_collected collected in
          Summary_cache.write ~project_root summary;
          [| (source_file, summary) |])
    ) in

  (* Stage 2: Aggregate to build unified graph *)
  (* Use special "__all__" key to collect summaries from all files *)
  let graph_inputs =
    Reactive.map summaries (fun source_file summary_arr ->
      [| ("__all__", summary_arr) |])
  in

  let graph =
    Reactive.map graph_inputs (fun key summary_arrays ->
      if key <> "__all__" then [||] else
      let graph = Graph_store.create () in
      Array.iter (fun arr ->
        Array.iter (fun (src, summary) ->
          Graph_store.add_summary graph ~source_file:src summary
        ) arr
      ) summary_arrays;
      [| (key, graph) |])
  in

  (* Stage 3: Compute liveness *)
  let diagnostics =
    Reactive.map graph (fun key graph_arr ->
```

```

    if key <> "__all__" then [[]] else
    let graph = snd graph_arr.(0) in
    let changed = Graph_store.get_dirty_files graph in
    let diffs = Liveness.recompute graph changed in
    [| (key, diffs) |])
in

Reactive.exit ();
Diagnostics_loop.run diagnostics

```

Key Design Decisions

1. **Per-CMT tracking:** Every CMT gets own tracker. File change re-runs only that key's map invocation.
2. **Aggregation key:** "_all_" collects summaries to build unified graph. Valid pattern per docs/reactive_ocaml.tex line 167 (multi-file fan-out).
3. **Zero ad-hoc IO:** ALL CMT reads use `Reactive.read_file` with trackers. `FindSourceFile.cmt` reads from already-loaded `cmt_infos` (no file IO).
4. **Summary cache:** Written for debugging but NOT used for invalidation. Skip's content hashing provides caching.

8.4 Error Handling

- **Corrupt CMT:** Catch exception from `Cmt_format.read_cmt_bytes`, emit diagnostic, return empty. Skip caches error; if fixed, hash changes and map re-runs.
- **Missing source:** `FindSourceFile.cmt` returns `None`. Emit diagnostic, return empty.
- **Collector failure:** Wrap `Pure_collectors.from_cmt` in try-catch, convert to diagnostic. Graph treats missing summaries as files with no declarations.
- **Service restart:** Fatal errors exit non-zero. Supervisor restarts service, which rediscovers CMT files.

8.5 Acceptance

- **Tracker discipline verified:** Every CMT read through `Reactive.read_file` with assigned tracker. Zero ad-hoc IO. Validated by inspecting Skip dependency graph showing all CMT files as tracked resources.
- **Content-based invalidation:** Single `.res` change (CMT rebuild) causes Skip to re-run ONLY that file's map, then propagate through graph/liveness.
- **Restart protocol:** Adding/removing modules requires service restart via `build.stamp` detection.
- **Performance:** Warm edits complete in <200ms p50, reusing cached summaries for unchanged files.

9 Milestone 5: Integration (CLI, Watcher, LSP)

9.1 Build Coordination

- Rewatch writes `.reanalyze/build.stamp` after successful builds (Milestone 4). The reactive service detects this change and restarts to discover new/removed CMT files.
- Per `docs/reactive_ocaml.tex` Section “Process Discipline” (line 183): process stays single-threaded and declares graph once. The service runs continuously, watching `build.stamp` in a background thread (outside Skip). When stamp changes, exits gracefully for supervisor restart.
- Supervisor (systemd/launchd/manual script) automatically restarts the service, which rediscovers CMT files and rebuilds the Skip graph with fresh inputs.

9.2 CLI Mode

1. `analysis/bin/main.ml`:

```
if Common.Cli.reactive then
  Reactive_service.run_forever ()
else
  Reanalyze.cli ()
```

2. `Reactive_service.run_forever`:

- Initialize heap via `Reactive.init`
- Discover and declare all CMT files via `Reactive.input_files`
- Declare reactive graph (summaries -i graph -i diagnostics)
- Call `Reactive.exit()`
- Enter monitoring loop:
 - a. Read diagnostics via `Reactive.get_array`
 - b. Print/publish diagnostics
 - c. Sleep/poll `build.stamp` in background thread
 - d. On stamp change, exit gracefully (code 0) for supervisor restart

3. Provide `--reactive-heap=<bytes>` flag. Heap persists across restarts on Linux (per `docs/reactive_ocaml.tex` line 189), deleted on startup on macOS (line 188).

4. Streaming output: Print diagnostics in same format as batch mode (file, location, message).

9.3 LSP Integration

- Implement `analysis/lsp/Reactive_provider.ml` targeting LSP 3.17. Diagnostics use `textDocument/publishDiagnostics` with payload:

```
{
  "jsonrpc": "2.0",
  "method": "textDocument/publishDiagnostics",
  "params": {
    "uri": "file:///abs/path/Foo.res",
```

```

    "version": 42,
    "diagnostics": [
      {
        "range": { "start": {"line": 9, "character": 2}, "end": {"line": 9, "character": 5} },
        "severity": 2,
        "source": "reanalyze",
        "message": "foo is never used"
      }
    ]
  }
}

```

- Maintain `file -> Diagnostic.t` list; when diffs arrive, recompute per-file arrays and emit the JSON payload above. Multiple clients are supported by broadcasting via the existing session manager. Add a 50ms debounce.

9.4 Acceptance

- CLI watch mode mirrors batch output after each build.
- LSP clients receive timely diagnostics with proper versioning.

10 Milestone 6: Validation and Rollout

10.1 Parity Harness

- Implement `tests/reactive_parity.ml`:

```

let run_batch project =
  Reanalyze_cli.run ~project ~mode:'Batch
let run_reactive project =
  Reactive_runner.run_once ~project:(project)
let assert_parity project =
  let batch = run_batch project in
  let reactive = run_reactive project in
  Alcotest.(check diagnostics) (project ^ " parity") batch reactive

```

- Diagnostics comparison normalizes ordering and formatting (sort by file/line, compare message text).
- Run parity harness nightly on: core repo, partner repo A, partner repo B. Report failures in CI dashboard.

10.2 Performance Benchmarks

- Benchmark script runs both pipelines on 10/100/1000-file fixtures, measuring: manifest read, summary generation, graph recompute, diagnostic emission. Record p50/p95.
- Compare against baseline metrics; fail if p50 or p95 regress more than 10%.

10.3 Rollout

1. **Phase 1:** internal opt-in via VS Code flag.
2. **Phase 2:** enable reactive mode by default for ReScript repo devs; keep batch fallback flag.
3. **Phase 3:** public beta announced in release notes; encourage feedback via GitHub issues. Automatic rollback if parity job fails.

11 Troubleshooting Guide

- **Heap exhaustion:** expose CLI flag to grow heap; log heap usage when exceeding 80%. Document that macOS removes heaps on restart.
- **Manifest corruption:** instruct users to delete `.reanalyze/manifest.json` and rerun `make`. Provide CLI flag `--reanalyze-force-cold` to ignore cache.
- **Tracker violations:** add instrumentation to detect direct file IO during reactive runs (wrap `open_in` and warn if called inside `map`).
- **Cross-platform linking:** include section in README describing required linker flags and how to install Skip runtime dependencies.

12 Summary

| Milestone | Key Deliverables |
|---|--|
| M0 Readiness | Skip linkage, baseline metrics |
| M1 Pure collection | Collector interfaces, refactored <code>Dead*</code> , unit tests |
| M2 Summaries | <code>Summary.ml</code> , cache, goldens |
| M3 Graph + liveness | <code>Graph_store</code> , frontier + SCC cache |
| M4 Skip service | Reactive pipeline, manifest writer, error handling |
| M5 CLI/LSP | <code>--reactive</code> mode, watcher, LSP provider |
| M6 Rollout | Parity harness, perf benchmarks, troubleshooting |
| Reactive dead code analysis built on Skip runtime | |