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Compiler Compiler System Translation Pipeline: From Python to TypeScript with Full RealWorld Conformance

A forty-six-slice adaptive-programming case study from `nsidnev/fastapi-realworld-example-app` to an Express + TypeScript service passing 293/293 canonical Postman assertions.

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The compiler-construction substrate referenced as foundation throughout this paper is protected by US Patent 8,464,232 [1] and its multi-language runtime architecture is described in the companion technical paper [2]. The position-level argument for substrate-grounded AI-assisted construction, of which the translation pipeline reported here is a worked instance, is given in [3]. The present paper is a self-contained empirical report on the pipeline itself.

Abstract

Translating an existing application from one general-purpose programming language into another is a long-standing engineering problem with no general solution. Arbitrary source-to-source translation is intractable because the two languages live in different runtime-semantic worlds with significant non-isomorphism in their type systems, exception models, standard libraries, and reflection capabilities. We report a worked example in which a specific class of application — a data-model-shaped web backend, specifically the canonical RealWorld / Conduit Medium-clone specification implemented in Python with FastAPI — is mechanically translated into TypeScript via a multi-stage pipeline of deterministic transformations operating over a small, well-bounded family of domain-specific languages. The pipeline decomposes the Python source into ten family-specific DSLs (DataModelEntity, DataModelRelationship, RouteContract, RouteHandler, RepositoryQuery, AuthPolicy, ValidationRule, ErrorHandling, Configuration, ApplicationBootstrap), emits TypeScript fragments through ten independent per-family emitters, assembles the fragments into target modules, fills handler bodies through a registry of hand-authored translations, and wires the result through a thin TypeScript runtime adapter into an Express HTTP service. The resulting service passes 293 of 293 assertions of the canonical RealWorld Postman conformance collection — exceeding the upstream Python baseline of 280 assertions. The methodological discipline that drove the work — *Adaptive Programming*: explicit `LOCK` invariants declared at every slice opening, hand-authored golden artefacts validated by byte-equal diff before any implementation iteration — closed forty-six slices over the arc, of which forty-two landed without implementation iteration. We are explicit about scope: the authentication flow is end-to-end pipelined (register, login, JWT issuance, validation cross-call), exercising the full decompose → emit → assemble → bodies → runtime path; the non-authentication endpoints (articles, comments, profiles, tags, follow) execute against hand-wired runtime handlers that share state with the pipelined infrastructure. The full Postman collection passes against the resulting service.

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1. Introduction

A persistent practical question in software engineering is how to convert software written in one general-purpose programming language into equivalent software in another. The question arises in legacy migration, in polyglot system construction, in educational exposition, and recently in the context of AI- assisted code transformation [4]. The general form of the question is intractable: any two general-purpose languages differ along enough semantic axes — type systems, exception models, runtime libraries, reflection capabilities — that arbitrary source-to-source translation reduces to writing the program over again with a translator-in-the-loop.

A reframe is available for a useful subset of the problem. A large fraction of code that practitioners want to translate is code *organized around a data model*: schema validation, serialization, transformation, aggregation, business-rule dispatch. For such code, the data model is the load-bearing artefact; the source language is one rendering of operations on that model. If the data model can be lifted to an explicit specification, and if a target-language rendering of the same specification can be obtained mechanically, the translation question reduces to data-model recovery plus runtime adaptation — both substantially more tractable than direct source-to-source translation.

This paper describes a pipeline that performs exactly this reframe on a non-trivial benchmark and reports the empirical result. The benchmark is the RealWorld / Conduit specification [5] — a widely cited canonical Medium-clone backend specification that exists in many implementations across many languages and is validated by a canonical Postman collection of HTTP behavioural assertions. The chosen Python source is `nsidnev/fastapi-realworld-example-app` [6], a FastAPI implementation that passes 280 of the collection's assertions. The target language is TypeScript, served by Express, with JWT and bcrypt as the only runtime crypto dependencies and an in-memory store standing in for the upstream's PostgreSQL.

The pipeline lifts the Python source into ten family-specific DSLs (Section 4), mechanically emits TypeScript fragments from each (Section 5.1), assembles the fragments into target modules (Section 5.2), fills handler bodies through a registry of hand-authored translations (Section 5.3), and wires the result to Express through a thin runtime adapter (Section 5.4). The resulting service is exercised against the same Postman collection the upstream Python passes; the score is 293 of 293 assertions passing, which is the maximum the collection can report (293 exceeds the upstream Python's 280 because some assertions in the collection are conditional on prior steps succeeding and the TypeScript service unlocks branches the Python implementation does not).

The contributions of this paper are: (1) a description of the ten-family DSL taxonomy that decomposes the data-model-shaped fraction of a typical web-backend codebase; (2) a description of the three-loop pipeline architecture in which sub-projects are decoupled through byte-identical golden artefacts; (3) a description of the *Adaptive Programming* methodology — explicit `LOCK` invariants and golden-first testing — that drove the forty-six-slice arc, with empirical evidence that the methodology landed forty-two of the forty-six slices on first implementation pass; (4) an honest account of five distinct failure modes encountered during the arc and how each was diagnosed and resolved; and (5) the empirical conformance result — 293/293 Postman assertions — against the canonical RealWorld validation collection.

We are explicit throughout about what the result does and does not claim. The Postman collection is a behavioural conformance oracle: it exercises the HTTP surface of the implementation. A service passing all 293 assertions is behaviourally indistinguishable from a conformant reference implementation within the contract of the collection. The pipeline produces the authentication endpoints (register, login) through the full decompose → emit → assemble → bodies → runtime path; the non-authentication endpoints (articles, comments, profiles, tags, follow) execute against hand-wired runtime handlers sharing the pipelined infrastructure's data structures. Section 13 makes this scoping explicit; Section 14 discusses the straightforward extension to pipeline coverage of the remaining endpoints.

The substrate the pipeline rests on is the CCS compiler- compiler reported in [2] — specifically, the per-family grammars that the pipeline consumes are CCS-generated and the binary forms of substrate artefacts (`.fgr`, `.bfgr`) are CCS serializations. The present paper does not re-describe that substrate; the reader interested in the substrate's parsing model, runtime/binary forms, and round-trip oracle should consult [2]. The present paper takes the substrate as given and reports the application-level pipeline built on top of it.

The remainder of the paper is organized as follows. Section 2 reviews related work in cross-language source translation, language workbenches, DSL-based code generation, and AI-assisted programming. Section 3 summarizes the substrate the pipeline rests on, with pointers to [2] for detail. Section 4 describes the ten-family DSL taxonomy. Section 5 describes the three-loop pipeline architecture. Section 6 describes the Adaptive Programming methodology. Section 7 walks the forty-six-slice execution arc. Section 8 documents five bugs and what they teach. Section 9 reports the empirical Postman result. Section 10 walks the implementation in concrete detail through one end-to-end use case and the decomposer and assembler stages. Section 11 discusses implications for cross-language translation generally. Section 12 considers what generalises beyond the worked example. Section 13 names limitations and threats to validity. Section 14 outlines future work.

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2. Related Work

The pipeline reported here sits in a space several prior lines of work partially address but none fully occupies.

Source-to-source translators. Tools including js2py [7], 2to3 [8], and the broader transpiler family operate on syntactic correspondences between languages with substantial structural overlap. They succeed where the two languages share idioms and runtime models; they fail where the source program exercises language-specific features the target does not match. The pipeline reported here addresses a different problem shape: not syntactic correspondence between languages, but data-model correspondence between *applications* of the same shape (web backends organized around entities, routes, and repositories).

LLM-based code translation. Recent work has explored the use of large language models for cross-language code translation end-to-end [4, 9]. The reported throughput is high but quality depends heavily on the source-target pair and on the available test infrastructure. The substrate-grounded pipeline reported here positions LLM assistance differently: not as end-to-end translator, but as one of several mechanical stages whose output is gated by deterministic oracles (the assembler's byte-equal golden, the bodies stage's `tsc` gate, the runtime stage's Postman collection). The LLM does not control the contract between stages; the substrate does.

Language workbenches and DSL-based code generation. Systems including JetBrains MPS, Xtext, and Spoofax [10] support defining domain-specific languages with associated tooling and generating code from them. The pipeline reported here is in this lineage: every family of the ten-family taxonomy has a formal grammar, a parser, and a fragment emitter. The specifically novel architectural choice is the *decoupling through byte-identical golden artefacts* (Section 5.5): each sub-project reads the previous sub-project's golden directory as input rather than calling it as a library, so each stage is independently regenerable, swappable, and debuggable. This is a familiar pattern in the language workbench tradition but is deployed here at the *pipeline* level rather than at the intra-tool level.

Model-driven engineering (MDE). The MDE tradition [11] promotes models to first-class artefacts and generates implementations from them. The recurring obstacles have been tooling burden, generated-artefact rigidity, and the gap between modeling language and idiomatic working code. The pipeline reported here is recognisably in this tradition, with the data-model lift to ten family DSLs as the modeling step. The contribution to MDE-style work is the explicit *behavioural conformance oracle* — the canonical RealWorld Postman collection — that grounds the generated-artefact-rigidity question empirically. Generated artefact is "rigid enough" when it passes a behavioural conformance test the source also passes.

Adaptive programming and AI-assisted methodology. A position paper [3] argues that the substrate-grounded AI- assisted construction methodology — explicit specifications validated by mechanical oracles, AI assistance at the specification layer rather than the code surface — supports construction throughput substantially above the conventional engineer-with-editor baseline. The pipeline reported here is the most extensive single instance of that methodology so far exercised, in the sense that its forty-six-slice execution arc was driven entirely by the LOCK-chain discipline [3, Section 4] and validated entirely by mechanical oracles. The present paper reports the empirical work; the position paper [3] addresses the methodology's broader implications.

Self-hosting compiler-compilers. The CCS substrate [2] is self-hosting: its own meta-grammar is processed by its own parser, and the canonical binary form round-trips byte-identically with the textual source. The substrate's self-validation regime is the foundation on which the present pipeline's family-grammar artefacts rest. The reader interested in the substrate's bootstrap property should consult [2, §6, §8].

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3. Substrate Foundation

The pipeline rests on the CCS compiler-compiler [2]. CCS accepts a context-free grammar specification in its source grammar definition language (SGDL) and produces a parser, serializer, accessor APIs, and canonical-binary encoders in multiple target languages. The architectural property of CCS load-bearing for the present pipeline is that *every family grammar is itself a CCS-generated artefact*: the ten family DSLs of Section 4 are described by ten SGDL grammars under `p2t/sgdl/F<N>/`, compiled by CCS to produce per-family parsers, decomposers, and serializers.

The pipeline's stages consume CCS-emitted artefacts in three ways. First, the per-family parsers in the decomposer stage read raw `.dsl` records and produce structured trees the emitter walks. Second, the canonical binary form (`.fgr` or `.bfgr`) is the persistence form for substrate intermediate artefacts; pipeline stages can be re-driven from binary inputs without re-running upstream stages. Third, the round-trip oracle property of CCS-generated parsers is exercised by the per-stage `tests/roundtrip.sh` harnesses: each stage's golden artefacts are validated by a byte-equal diff against the stage's output on its own canonical input.

The substrate's mechanical round-trip oracle is what makes the pipeline's *stage decoupling through golden artefacts* (Section 5.5) practical at this scale. A stage's output that round-trips correctly through CCS's parser is a stable target the next stage can be tested against; a stage's output that does not round-trip indicates a substrate-level inconsistency that the oracle catches before pipeline composition surfaces a downstream failure.

For the empirical work reported below, the substrate is taken as given. The reader interested in substrate detail — parsing model, runtime and binary forms, generator subsystem, bootstrap loop, JSON parsing benchmarks — should consult [2]. The substrate's status under US Patent 8,464,232 [1] means it is not currently available as an open-source artefact; practitioners interested in replication should pursue commercial engagement through Bet Three LLC.

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4. The Ten-Family DSL Taxonomy

Decomposing a data-model-shaped web backend into a small, well-bounded family of DSLs is the central abstraction the pipeline rests on. The decomposer projects every Python construct in the upstream into exactly one of ten families:

```
+----+--------------------------+-------------------------------+
| F# | Family name              | Captures                       |
+----+--------------------------+-------------------------------+
| F1 | DataModelEntity          | domain types (User, Article,   |
|    |                          | Tag, Comment, Profile)         |
+----+--------------------------+-------------------------------+
| F2 | DataModelRelationship    | junction tables (follow,       |
|    |                          | favorite)                       |
+----+--------------------------+-------------------------------+
| F3 | RouteContract            | HTTP method + path + request   |
|    |                          | body shape                      |
+----+--------------------------+-------------------------------+
| F4 | RouteHandler             | endpoint function signature    |
+----+--------------------------+-------------------------------+
| F5 | RepositoryQuery          | DB query method (read/list/    |
|    |                          | create/update/delete)          |
+----+--------------------------+-------------------------------+
| F7 | AuthPolicy               | bcrypt + JWT primitives        |
+----+--------------------------+-------------------------------+
| F8 | ValidationRule           | check_<X>_is_taken pattern;    |
|    |                          | cross-call validation           |
+----+--------------------------+-------------------------------+
| F10| ErrorHandling            | exception classes + envelope   |
|    |                          | + string registry              |
+----+--------------------------+-------------------------------+
| F11| Configuration            | Settings + env overrides       |
+----+--------------------------+-------------------------------+
| F12| ApplicationBootstrap     | framework-agnostic startup     |
+----+--------------------------+-------------------------------+
```

(F6 and F9 were retired during taxonomy refinement and do not appear in the final ten.)

Each family has three artefacts in the substrate:

1. **A grammar** (p2t/sgdl/F<N>/meta_F<N>.sgr) — declares the DSL's surface syntax. The grammar is processed by CCS to produce per-family parser and serializer code.

2. **A decomposer extractor** (`p2t/decomposer/src/p2t_decomposer/ extract_f<N>.py`) — walks the Python AST and emits `.dsl` records matching the grammar.

3. **A per-family emitter** (`p2t/emitter/src/p2t_emitter/ emit_f<N>.py`) — reads `.dsl` and emits a TypeScript fragment.

The taxonomy is bipartite. Six families (F1, F2, F3, F4, F5, F8) are *per-fragment* — they emit one TypeScript file per source construct. The remaining four families (F7, F10, F11, F12) are *aggregator* — they emit one TypeScript file per source application, summarising the application's collection of that family's constructs.

The bipartite property is load-bearing for the assembler (Section 5.2): assembling a target module requires choosing which per-fragment emitters' outputs to splice together and which aggregator outputs to include unmodified. The assembler's `TARGETS` map encodes the splice plan for each of the sixteen TypeScript target modules.

The taxonomy is **frozen**. The decomposer cannot succeed on Python constructs that do not fit one of the ten families; an upstream construct that does not slot in triggers a *substrate fix* — a slice that extends one of the ten grammars or, in exceptional cases, introduces a new family. The forty-six-slice arc did not require any new-family substrate fix: the ten families landed at `.D` and were preserved through the entire arc.

The taxonomy was arrived at empirically rather than analytically. The first attempt enumerated thirteen candidate families; the decomposer's first pass over the upstream collapsed three pairs through observation that the productions overlapped (F6 was collapsed into F4; F9 was collapsed into F8 and F11). The final ten survived the entire `nsidnev/fastapi-realworld-example- app` upstream without further consolidation. Whether the ten families generalise beyond Conduit-shaped applications is an empirical question the present paper does not settle; Section 13 lists it as a future-work item.

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5. Pipeline Architecture

The pipeline is a three-loop, six-stage flow. The high-level shape is:

```
                   Python source (read-only upstream clone)
                                  |
                                  v
```

```
+-------------+-------------+
|       Stage 1 (.E)         |
|    Decomposer (Python AST  |
|    -> 10 .dsl + dag.json) |
+-------------+-------------+
              |
              v
+-------------+-------------+
|   Stage 2 (.F..F9)         |
|   Loop 3A — per-family     |
|   emit  (.dsl -> 25 .ts    |
|   fragments)               |
+-------------+-------------+
              |
              v
+-------------+-------------+
|   Stage 3 (.F10/.F15)      |
|   Loop 3B-det — per-target |
|   assemble  (fragments     |
|   -> 16 .ts modules)       |
+-------------+-------------+
              |
              v
+-------------+-------------+
|   Stage 4 (.F11..F14)      |
|   Loop 3B-bodies — body    |
|   fill (stubs -> filled    |
|   bodies)                  |
+-------------+-------------+
              |
              v
+-------------+-------------+
|   Stage 5 (.F16..F17)      |
|   Static fixtures + tsc    |
|   gate (16/16 strict-clean)|
+-------------+-------------+
              |
              v
+-------------+-------------+
|   Stage 6 (.F18..G3)       |
|   Runtime adapter + Express|
|   + Postman conformance    |
+-------------+-------------+
```

Each stage is a stand-alone sub-project with its own `tests/roundtrip.sh` oracle, package layout, and committed golden artefacts. Stages compose by **reading the previous stage's golden directory as input —** never by direct in-process call. The next subsections describe each stage in detail.

5.1 Decomposer (Stage 1)

The decomposer reads the upstream's Python source via the `ast` module, identifies the constructs each per-family extractor recognises, and emits one `.dsl` file per family. The output is ten `.dsl` files and one `dag.json` recording the cross-family references the assembler needs to resolve at Stage 3.

The decomposer's correctness oracle is byte-identical comparison against ten committed `.dsl` golden artefacts. The oracle is mechanical: `diff -r decomposer/tests/golden/ <actual>` is the pass criterion. The decomposer landed at `.E` over twelve slices (`.E..E11`); each slice extended the AST walker to handle one additional family or one additional source-construct shape.

5.2 Per-family emitter (Stage 2)

The emitter reads the ten `.dsl` files and runs ten per-family emitters. Each emitter parses its family's `.dsl` records through a generic s-expression tokeniser-and-nester (`sexpr.py`) followed by a family-specific structural walker (`parse_f<N>.py`) and emits TypeScript through a family-specific template (`emit_f<N>.py`).

The bipartite family taxonomy (Section 4) determines emitter output shape: - Per-fragment families (F1, F2, F3, F4, F5, F8) emit one `.ts` file per source construct. Total per-fragment outputs across the upstream: twenty-five fragments. - Aggregator families (F7, F10, F11, F12) emit one `.ts` file per source application. Total aggregator outputs: four per-app modules.

The emitter's correctness oracle is byte-identical comparison of `emitter/tests/golden/F<N>/*.ts` against the emitter's output on its canonical `.dsl` inputs. The oracle ran clean on twenty- four of the twenty-five fragments on first emission across `.F..F9`; one fragment surfaced a parser-walker bug (Bug #1 in Section 8) that landed within a single intra-slice iteration.

5.3 Assembler (Stage 3)

The assembler stitches per-family per-fragment emissions into per-target modules. Its central data structure is the `TARGETS` map — a Python literal declaring, for each of the sixteen TypeScript target modules, the list of fragment paths (from `emitter/tests/golden/`) to be assembled in order, the `import` statements to be emitted at the top, and the `export` shape at the bottom.

The assembler emits the target's imports from a `TYPE_REGISTRY` — a static map from referenced symbols to their owning module paths — and concatenates the fragment bodies in the order `TARGETS` declares. The resulting per-target module is the input to Stage 4.

The assembler's correctness oracle is byte-identical comparison of `assembler/tests/golden/*.ts` against the assembler's output on its canonical fragment inputs. The oracle ran clean on the three-target pilot at `.F10` and on all sixteen targets at `.F15` after coverage extension.

5.4 Body filler (Stage 4)

Stage 4 fills the assembled targets' handler bodies. The emitter (Stage 2) intentionally emits *stub* function bodies (`throw new Error("stub")`) for each handler; the assembled target inherits those stubs. The body filler reads a `BODY_REGISTRY` — a Python literal mapping `(target_path, function_name)` to a hand-authored TypeScript body — and substitutes each registered body into the target.

The hand-authored body translations are the only stage of the pipeline where the LLM is in the loop in any non-mechanical sense. The body translations were authored by the human-AI loop during `.F11..F14`; each translation was reviewed by the human before commitment to the registry. The final body count is twenty-three filled bodies across the sixteen targets.

The body filler's correctness oracles are two: (i) byte-equal comparison of `bodies/tests/golden/*.ts` against the filled output; (ii) absence of remaining stub bodies in the output. A filled target is "no-stub" if the filler can find no `throw new Error("stub")` in any non-test position. Both oracles ran clean on the sixteen targets at `.F15`.

5.5 Static fixtures and tsc gate (Stage 5)

Stage 4's filled bodies reference ambient names (`queries`, `connection`, `jwt`, `repo`) that do not exist at compile time — they are runtime injections handled by Stage 6. To satisfy `tsc --strict --noEmit`, Stage 5 introduces a static-fixtures sub-stage that:

- Declares ambient globals in `bodies/static/globals.d.ts` (`declare const queries: ...`, `declare const connection: ...`).
- Applies *module augmentation* to extend interfaces the assembler's minimal renderings do not cover (Bug #3 in Section 8).
- Configures `tsc` with `"lib": ["ES2022"]` to exclude DOM types (Bug #2 in Section 8).

After Stage 5, `tsc --strict --noEmit` is clean on all sixteen targets. The gate `bodies/tests/roundtrip.sh tier-2` reports `tsc 16/16 PASS`.

5.6 Runtime adapter and Express (Stage 6)

The final stage wires the tsc-clean assembled targets into an Express HTTP server. The runtime adapter (`runtime/src/`) is hand-authored TypeScript that:

- Implements the ambient globals Stage 5 declared (`queries`, `connection`, `repo`) as in-memory implementations.
- Implements JWT issuance and validation via the `jsonwebtoken` library and bcrypt-based password hashing via the `bcrypt` library.
- Wires the Stage 4 filled targets into Express routes for the authentication flow (register, login) — these endpoints are *pipelined* in the sense that the Express handler is literally the file `bodies/tests/golden/routes/{register,login}.ts`.
- Hand-writes Express routes for the non-authentication endpoints (articles, comments, profiles, tags, follow) — these endpoints share the pipelined runtime infrastructure (`queries`, `repo`, JWT) but their Express handlers were not pipelined.

Section 13 makes this scoping explicit; the central honest claim is "the pipeline proves end-to-end on the authentication flow" rather than "all 293 Postman assertions exercise pipeline-emitted code."

The runtime stage's correctness oracle is the Postman collection itself, exercised through Newman. The collection landed at 293 of 293 assertions passing at `.G3`.

5.7 Stage decoupling through golden artefacts

A core architectural property: each sub-project is *decoupled* from the next via byte-identical golden directories. The assembler does not call the emitter; it reads `emitter/tests/golden/*.ts` from disk. The body filler does not call the assembler; it reads `assembler/tests/golden/*.ts`.

The runtime does not call the body filler; it imports `bodies/tests/golden/*.ts` at module-load time.

This decoupling has three practical consequences:

1. Each stage is independently regenerable. A change to a single emitter does not require re-running the decomposer.
2. Each stage is independently swappable. A future Rust port replaces the emitter and bodies stages; the assembler logic is the same.
3. Each stage is independently debuggable. A failure of the `tsc` gate at Stage 5 can be reproduced by running `bash bodies/tests/roundtrip.sh` against the committed Stage 3 golden, without re-running the decomposer or emitter.

The pattern is familiar from build-system literature — content- addressed artefacts as the contract between stages — but its deployment here at the *pipeline* level is what makes the adaptive-programming discipline (Section 6) tractable across forty-six slices.

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6. Methodology: Adaptive Programming

The pipeline was constructed under a specific methodological discipline we call *Adaptive Programming*. The discipline combines two patterns: explicit `LOCK` invariants declared at every slice opening, and golden-first testing.

6.1 The LOCK chain

Every slice opens with a `step.3000.<id>.txt` skeleton declaring, before any implementation work begins:

- the slice's pilot scope (what the slice will and will not do);
- the open questions the slice must resolve;
- the **LOCKs** — invariants the slice must preserve and conditions the slice's outcome must satisfy.

LOCKs come in two flavours:

```
+-----------------+------------------------------------------+
| §(6b) grep gates| Mechanical checks. File existence, command  |
|                 | exit codes, regex grep over specific paths. |
```

```
|                 | The harness verifies these blindly.         |
+-----------------+---------------------------------------------+
| §(6c) slice-    | Architectural intentions. "No edits to      |
| level LOCKs     | <subsystem> outside this list", "all 23     |
|                 | hand-authored bodies stay UNCHANGED",       |
|                 | "the per-fragment pattern carries". These   |
|                 | are reviewed at retro time.                  |
+-----------------+---------------------------------------------+
```

A LOCK is never broken silently. When a slice needs to lift a prior LOCK — for example `.F17` lifted its predecessor's body lock for exactly one body translation — the lift is named in a new LOCK on the lifting slice. The chain is preserved.

The discipline has practical consequences. At slice opening, the human and the AI assistant agree the LOCK set before any implementation work proceeds. At slice closing, the retro narrative names each LOCK satisfaction explicitly. The result is that every architectural decision in the arc is *named at the slice that made it*, not retrofitted from the diff. The forty-six step-files-and-retros totalling roughly twenty-five thousand lines are the result.

6.2 Golden-first testing

Before writing the implementation of any emitter, assembler, or body-filler component, the expected output is *hand-authored* to a golden file. The implementation is then iterated until `diff -r <output> <golden>` is empty.

The pattern's empirical record on this arc: forty-two of the forty-six slices in the `.E..G3` range landed with **zero implementation iterations**. The hand-authored golden committed the shape contract; the implementation followed mechanically; the byte-equal diff was the success criterion. Four slices had non-zero iteration counts, all attributable to one of three causes:

- `.F17` (4 iterations) — `tsc`-error driven; each iteration reduced the strict-mode error count and surfaced the next blocker. Bugs #2 and #3 (Section 8) are diagnosed here.
- `.F11` (2 iterations) — first non-auth body translation; surfaced an aggregator-family registry shape that required the second pass.
- `.G3` (4 iterations) — Bug #5 (Section 8) — diagnostic work against a confounding test harness; the implementation was correct on first attempt.
- `.F2` (1 iteration) — Bug #1 (Section 8) — emitter walker loop bound.

The pattern fails to be zero-iteration when the work crosses from compile-time concerns (where the golden artefact is the oracle) into runtime concerns (where the executable's behaviour is the oracle). `.F18` onwards exercises the runtime, and the oracle changes from byte-equal golden to behavioural Postman collection. Iteration counts rise correspondingly.

6.3 Adaptive Programming as enacted

The arc demonstrates a specific pattern of human-AI collaboration. The human supplies the verbal specification — "the F11 Configuration family should emit a Settings interface with env overrides as defaulted constructor parameters". The AI assistant proposes the LOCK set, the skeleton, and the hand-authored golden. The human reviews the golden — which is small enough to actually review — and accepts or refines. The implementation work then proceeds against the accepted golden, with the mechanical diff as the success criterion.

The throughput characteristics this enables are reported in [3, Section 5]. The present paper's contribution is the empirical extension of that record: the forty-six-slice arc landed in approximately five weeks of focused work, with twenty-five thousand lines of slice documentation as the record of the LOCK-chain discipline being applied mechanically. Whether this scales to substantially larger projects than the demonstrated arc is open; Section 13 names this as a limitation.

---

7. The Forty-Six-Slice Execution Arc

The arc landed in forty-six slices. Grouped by stage:

```
+--------+--------------------+-----------------------+
| Range  | Stage              | Outcome                |
+--------+--------------------+-----------------------+
| .A     | Baseline           | upstream Python on     |
|        |                    | 127.0.0.1:8000 passes  |
|        |                    | 280/280 Postman         |
+--------+--------------------+-----------------------+
| .B..D  | Substrate          | 10 sgdl/F<N>/ grammars |
|        |                    | + .sgr / .fgr / .bfgr  |
|        |                    | + per-family fixtures  |
+--------+--------------------+-----------------------+
| .E..E11| Decomposer         | 10 per-family .dsl     |
|        |                    | files + dag.json        |
```

```
+--------+------------------+---------------------+
| .F..F9 | Loop 3A emitters   | 10 family emitters     |
|        |                    | producing 25 fragment  |
|        |                    | .ts shells              |
+--------+------------------+---------------------+
| .F10   | Loop 3B assembler  | 3-target pilot ->       |
| .F12-15| coverage extends   | 16/16 targets          |
+--------+------------------+---------------------+
| .F11   | Body filler        | stubs -> filled bodies  |
| .F12-14| coverage extends   |                         |
+--------+------------------+---------------------+
| .F16   | tsc gate (8/16)    | static fixtures arrive |
| .F17   | tsc gate (16/16)   | tier-1 + tier-2 clean  |
+--------+------------------+---------------------+
| .F18   | runtime adapter    | tsx executes; smoke    |
|        |                    | register+login          |
+--------+------------------+---------------------+
| .F19   | Express + Newman   | 19/19 Auth subset       |
+--------+------------------+---------------------+
| .G     | JWT + /user + /tags| 40/56 full collection  |
| .G2    | Articles + favorites| 256/260 (98.5%)        |
| .G3    | Comments + Follow  | **293/293** — done     |
+--------+------------------+---------------------+
```

Three slices are architectural turning points worth singling out.

`.F10` — the assembler is born. Before `.F10`, each family emitter produced isolated per-fragment `.ts` files. `.F10` introduced the assembler that walks a `TARGETS` map and stitches fragments into per-target modules. This was the first slice to *compose* pipeline outputs rather than just produce them. The slice landed at three-target pilot scope; subsequent slices extended to sixteen targets without re-architecting the assembler.

`.F17` — the tsc gate flips green. Stage 5 produces TypeScript that has to satisfy `tsc --strict --noEmit`. The body translations reference ambient names (`queries`, `connection`, `jwt`, …) that do not exist at compile time. `.F17` introduced `bodies/static/globals.d.ts` declaring those ambients plus module augmentation for the `Comment` interface — driving tier-2 errors from eighty to zero in four iterations. Bugs #2 and #3 (Section 8) were diagnosed and fixed during this slice.

`.G3` — the central claim is proven. Before `.G3`, four Postman tests remained failing (Comments + Profile read + Follow + Unfollow). `.G3` added the last six endpoints and the score jumped from 256/260 to **293/293**. The arc's stated success criterion was achieved. Notably, the `.G3` source code had been correct on first attempt; the four diagnostic iterations were entirely against a confounding test harness (Bug #5, Section 8).

Each of the forty-six slices has a paired *step file* (step.3000.<id>.txt) declaring scope and LOCKs, a *retro narrative* (step.3000.<id>.diff.txt) capturing what landed, what surprised, and what is next, and an *adiff* (step.3000.<id>.adiff.txt) with the literal commit diff. Total slice documentation across the arc: approximately twenty-five thousand lines.

---

8. Bugs: Five Failure Modes the Pipeline Architecture Exposes

Five distinct bugs are worth documenting in detail. Each illustrates a category of failure mode the pipeline architecture is prone to.

8.1 Bug #1 — the `.F2` parser stream-walker

Symptom. The first non-pilot family emitter (`.F2`, the F11 Configuration emitter) emitted a golden that differed from the hand-authored expected golden by one line.

Diagnosis. The `parse_f11` walker handled the keyword/value sequence correctly but mishandled the *terminating* keyword: the loop exited one token early when the sentinel keyword landed at end-of-stream.

Fix. The inner `while` loop bound was changed from sentinel-equality to i < len(tree).

Why it is interesting. This was the *only* in-flight correction across all ten family emitters (`.F` through `.F9`). Every other emitter landed byte-identical to its hand-authored golden on first attempt. The golden-first pattern works.

Lesson. Hand-author the golden first; the implementation self-corrects against it via mechanical diff.

8.2 Bug #2 — the DOM `Comment` collision

Symptom. During `.F17`, the bodies stage's tsc gate was being driven from eighty errors to zero. After landing `globals.d.ts` with module augmentation, one error stubbornly remained:

```
repositories/comments.ts: Type 'Comment' is missing the following
  properties from type 'Comment': body, author
```

A "Comment is missing properties from Comment" error.

Diagnosis. `tsc --strict` in the default `lib` set pulls in DOM types — including `interface Comment` from `lib.dom.d.ts`. The global class `Comment` was clashing at type-assignment boundaries with the DOM's `Comment`, even though `skipLibCheck` suppressed the visible diagnostics on the lib files themselves.

Fix. One line in `bodies/tsconfig.tier1.json` and `bodies/tsconfig.full.json`:

```
"lib": ["ES2022"]    // explicitly do NOT include DOM
```

Why it is interesting. `skipLibCheck` is a classic "trust the lib" knob, but it does not suppress lib types from influencing type-assignment compatibility checks in *user* code. The DOM `Comment` is a phantom type at the boundary between the global class and the imported interface — invisible until exactly the wrong assignment.

Lesson. When a strict-mode TypeScript project has zero DOM intent, explicitly enumerate `lib`. `skipLibCheck` is not a silver bullet.

8.3 Bug #3 — `comment.id_` and module augmentation

Symptom. Same `.F17` push. After the DOM fix, one error remained:

```
repositories/comments.ts(82,29): Property 'id_' does not exist on
  type 'Comment'.
```

Diagnosis. The assembled `models/comment.ts` exported `interface Comment { body: string; author: Profile }` — no `id_`. The `globals.d.ts` declared a global class `Comment` with `id_`, satisfying the *value* use (`new Comment(row)`), but the body's `comment.id_` reference was through the *imported interface* (`import { Comment } from "../models/comment"`).

Fix. Module augmentation in `globals.d.ts`:

```
declare module "./models/comment" {
    interface Comment {
        id_: number;
    }
}
```

Declaration merging extends the imported interface; `tsc` then sees `id_` on the `Comment` type everywhere.

Why it is interesting. The pipeline's assembled `models/comment.ts` is intentionally minimal (just the in-memory facet); enriching it would require either re-emitting upstream of the assembler (a much bigger change) or augmenting it downstream. Module augmentation is the elegant downstream pattern — non-invasive, scoped, removable.

Lesson. TypeScript's declaration merging across modules is exactly the right tool when one wants to *extend* an interface that is owned by a different stage of the pipeline.

8.4 Bug #4 — the runtime `inMemoryQueries` Proxy trap

Symptom. `.G` added `GET /api/tags` wired to the assembled `repositories/tags.ts.get_all_tags` handler. The handler internally calls `queries.get_all_tags(connection)`. The runtime's `setupRuntime()` did:

```
(inMemoryQueries as any).get_all_tags = async (_conn) =>
    tagsRegistry.map(t => ({ tag: t }));
```

…and the endpoint returned `500: "Cannot read properties of null (reading 'map')"`.

Diagnosis. `inMemoryQueries` was a `Proxy` whose `get` trap returned a null-stub for *every* property access:

```
new Proxy({}, {
    get(_target, name) {
        return async (_conn, _args?) => null;   // unconditional
    },
});
```

Setting `inMemoryQueries.get_all_tags = …` wrote to the underlying target *object*, but reads still went through the trap and never checked the target.

Fix. Three lines added to the trap:

```
get(target, name) {
    if (Reflect.has(target, name)) {
        return Reflect.get(target, name);   // honour overrides
```

```
    }
    return async (_conn, _args?) => null;
}
```

Why it is interesting. The original Proxy was authored at `.F18` when no overrides existed; the design implicitly assumed "all queries return null." `.G` introduced the first override and the assumption became invisible-but-load-bearing.

Lesson. Proxy `get` traps in a "default + override" pattern *must* defer to the target. The default behaviour belongs in the *fallback* arm, not unconditionally.

8.5 Bug #5 — the stale `tsx` grandchildren

Symptom. `.G3` added the Comments + Profile + Follow endpoints. Manual `curl` against each endpoint worked perfectly:

```
$ curl http://127.0.0.1:8004/api/profiles/alice
HTTP/1.1 200 OK
{"profile":{"username":"alice","bio":"","image":"","following":false}}
```

But `bash runtime/tests/postman.sh` reported **the same 4 failures as `.G2`** — every new endpoint returning 404. Three iterations of "add more `pkill -f`" did not help.

Diagnosis. `postman.sh` started the server via:

```
(cd "$RUNTIME_HOME" && PORT="$PORT" npm run --silent serve) \
    > "$WORK/serve.log" 2>&1 &
SERVER_PID=$!
```

…and on cleanup ran `kill "$SERVER_PID"`. But `npm run serve` spawns *four levels* of child processes:

```
npm exec tsx                        <- $SERVER_PID
  └─ sh -c tsx src/serve.ts
       └─ node tsx src/serve.ts
            └─ node --import tsx … src/serve.ts   <- actually listens
```

`kill $SERVER_PID` killed only the npm wrapper. The grandchild `node`s survived, kept listening on 8001, and continued serving **the old code** across runs. Each new `postman.sh` invocation spawned a fresh `tsx` that could not bind to 8001 (silently failed in the background); Newman then hit the *old* server.

Fix. Replace the bg-shell with `setsid` to create a new process group, then kill the whole group:

```
setsid bash -c "cd '$RUNTIME_HOME' && PORT='$PORT' \
    exec npx --no-install tsx src/serve.ts" > "$WORK/serve.log" 2>&1 &
SERVER_PID=$!

cleanup() {
    kill -TERM -- -"$SERVER_PID" 2>/dev/null || true
    sleep 0.5
    kill -KILL -- -"$SERVER_PID" 2>/dev/null || true
    fuser -k "${PORT}/tcp" 2>/dev/null || true   # belt + braces
}
trap cleanup EXIT
```

After applying the fix, the very next run reported **293/293**.

Why it is interesting. The `.G3` source code had been *correct on first attempt*. The arc's four "iterations" were entirely diagnostic work against a confounding test harness. `.G` and `.G2` had the same underlying bug; their iterations had been *lucky*.

Lesson. When a long-running process is spawned through `npm` (or any multi-process launcher), kill the *process group*, not the PID. `setsid` plus `kill -- -PGID` is the idiomatic Unix incantation. Additionally: assume nothing about whether port-binding silently failed. `fuser -k <port>/tcp` is cheap insurance.

8.6 What the five bugs share

The five bugs fall into three categories of failure mode the pipeline architecture is structurally prone to.

```
+-----+-------------------------+-------------------------------+
| Bug | Stage / file            | Root cause                    |
+-----+-------------------------+-------------------------------+
|  1  | parse_f11 walker (.F2)  | loop bound on sentinel-equality |
|     |                         | instead of length-of-stream     |
+-----+-------------------------+-------------------------------+
|  2  | bodies tsconfig (.F17)  | DOM `Comment` colliding with    |
|     |                         | global class at type-assignment |
```

```
|     |                          | sites; skipLibCheck did not help|
+-----+--------------------------+--------------------------------+
|  3  | bodies/static (.F17)      | imported Comment interface      |
|     |                          | missing id_; needed module      |
|     |                          | augmentation                    |
+-----+--------------------------+--------------------------------+
|  4  | runtime/db.ts (.G)        | Proxy `get` trap returned       |
|     |                          | default unconditionally; never  |
|     |                          | checked target for overrides    |
+-----+--------------------------+--------------------------------+
|  5  | postman.sh kill (.G3)     | kill $PID killed only npm       |
|     |                          | wrapper; grandchild node served |
|     |                          | stale code on the bound port    |
+-----+--------------------------+--------------------------------+
```

Bug #1 is a *pipeline-internal* failure: an emitter walker mishandled its grammar. The golden-first pattern caught it within a single iteration. The lesson generalises to every emitter the pipeline introduces — hand-author the golden first.

Bugs #2 and #3 are *language-toolchain* failures: TypeScript's own `lib` and module augmentation behaviour surfaced at the boundary between assembler output and bodies-stage `tsc` gate. The pipeline architecture made these tractable because the relevant code is *generated* and *small*; both fixes are one-liners in static-fixture files that the next slice cleanly inherited.

Bug #4 is a *runtime-design* failure: a Proxy pattern that was correct under one set of assumptions broke under another the next slice introduced. The lesson is broader than this specific pipeline: defer-to-target is the safe default for `get` traps.

Bug #5 is a *test-harness* failure: the implementation was correct; the test infrastructure lied. The diagnostic time spent here is the single largest "wasted" effort in the arc. The lesson — kill process groups, not PIDs — is independent of the pipeline architecture but illustrates a category of failure that any long-running-process test harness is prone to.

---

9. Empirical Evaluation: 293/293 Postman Conformance

The arc's stated success criterion was producing a TypeScript server scoring at least 280 against the same Postman collection the upstream Python passes. The actual result is 293/293 — exceeding both the criterion and the upstream baseline.

```
+--------+------------------+----------+------------+
| Slice  | What was tested  | Pass     | Note       |
+--------+------------------+----------+------------+
| .A     | upstream Python  | 280/280  | baseline   |
+--------+------------------+----------+------------+
| .F19   | TS / Auth subset |  19/19   | first HTTP |
| .G     | TS / full coll.  |  40/56   | Auth clean |
| .G2    | TS / full coll.  | 256/260  | 98.5%      |
| .G3    | TS / full coll.  | 293/293  | +13 over   |
|        |                  |          | upstream   |
+--------+------------------+----------+------------+
```

Total RealWorld assertion exposure across the upstream Python and TypeScript variants: **573** Postman assertions. Of those, **zero represent a behavioural drift** between Python and TypeScript — every assertion the test framework chose to run passed on both.

The TypeScript arc exercises *more* assertions than the upstream Python (293 versus 280) because some Postman test scripts include conditional branches that only fire when a previous step succeeded. Wire-format compatibility unlocks those branches.

9.1 What 293/293 implies

The Postman collection is the canonical conformance oracle for the RealWorld specification — it is the same collection every RealWorld backend implementation, in every supported language, exercises. A score of 293/293 is the maximum the collection can report against the runtime.

The conformance claim "behaviourally indistinguishable from a conformant reference implementation within the contract of the collection" holds. The Express + TypeScript service produced by the pipeline plus the hand-wired runtime exposes an HTTP surface that the canonical collection cannot distinguish from a conformant Python implementation.

9.2 What 293/293 does not imply

The conformance claim does *not* extend to behaviours outside the collection's contract. The in-memory store has different durability properties than a PostgreSQL backend (which the upstream Python uses); the JWT secret rotation policy is not exercised by the collection; the error-message strings inside the envelope may differ. These are out-of-contract differences that the collection does not test.

The conformance claim also does not imply that all 293 assertions exercise pipeline-emitted code. Section 13 makes this scoping explicit; the conformance is a property of the *runtime as deployed*, not of the pipeline's emission coverage.

9.3 Replication

The arc's reproduction is `bash p2t/runtime/tests/postman.sh` run against the committed runtime sources. The script:

1. Starts the TypeScript server under `setsid` in a fresh process group on `PORT=8001`.
2. Runs Newman against `tests/postman/Conduit.postman_collection.json`.
3. Reports `293 / 293 PASS` and tears the process group down.

The script's robustness to stale processes is itself the outcome of Bug #5; pre-fix invocations of the harness were unreliable.

---

10. Implementation Details

Sections 4 through 6 describe the ten-family DSL taxonomy, the three-loop pipeline shape, and the Adaptive-Programming methodology at the architectural level. The present section descends one level and walks the concrete pieces of code that make those abstractions work: a single end-to-end worked example through the F3 RouteContract family (§10.1), and a closer look at the two stages whose internals are load-bearing for the pipeline-shape generalisation claim of §11 — the decomposer (§10.2) and the deterministic assembler (§10.3). The bodies- filler stage and runtime adapter, both of which are language-and-framework-specific, are not revisited here; their architectural roles are stated in §5.4 and §5.6 respectively, and their LOCK-chain records land in the slice-documentation corpus.

The intent of this section is to make the pipeline concrete enough that a reader could re-implement an analogous tool against a different upstream or a different target language without reverse-engineering the architecture from the high-level diagrams alone. What follows are the deterministic parts of the pipeline; the AI-assisted parts (the body-filler registry, the verbal-spec → LOCK-chain front of every slice) are described methodologically in §6 and remain outside this section's scope.

10.1 F3_RouteContract use case

The F3 family captures HTTP-route metadata — method, path, status code, response model, auth mode, request body shape, path/query parameter declarations — as a framework-agnostic record. F3 fragments are emitted as TypeScript modules exporting `const`-shaped metadata; the framework adapter at runtime (Express, in the present arc) re-interprets those constants into framework- specific registration calls. F3 is one of the six *per-fragment* families: each Python handler becomes one F3 fragment, one DSL file, one TypeScript module.

We trace the `register` endpoint end-to-end through the five pipeline stages.

10.1.1 The Python source

The upstream's authentication route module declares two route handlers, `login` and `register`, in `app/api/routes/authentication.py`. The `register` handler is reproduced below verbatim from the upstream Python (`nsidnev/fastapi-realworld-example- app`, pinned to a known commit):

```
@router.post(
    "",
    status_code=HTTP_201_CREATED,
    response_model=UserInResponse,
    name="auth:register",
)
async def register(
    user_create: UserInCreate = Body(..., embed=True, alias="user"),
    users_repo: UsersRepository = Depends(get_repository(UsersRepository)),
    settings: AppSettings = Depends(get_app_settings),
) -> UserInResponse:
    if await check_username_is_taken(users_repo, user_create.username):
        raise HTTPException(
            status_code=HTTP_400_BAD_REQUEST,
            detail=strings.USERNAME_TAKEN,
        )
    ...
```

The route's *contract* — what F3 captures — is the declarative front of this construct: the decorator attributes (`post`, `""`, `status_code=HTTP_201_ CREATED`, `response_model=UserInResponse`) plus the function signature's `Body(..., embed=True, alias="user")` annotation on the `user_create` parameter. F3 does *not* capture the function body (that is F4 RouteHandler's concern), nor the exception classes raised inside the body (that is F10 ErrorHandling's concern), nor the validation calls (F8 ValidationRule).

The F3 source-locus extraction rule is stated mechanically: a top-level (`async def`) function carrying a `@router.<method>(...)` decorator, where `<method>` is one of `get / post / put / delete / patch`. The decorator's positional argument is the path-relative-to-router; its `status_code` keyword is resolved against a hard-coded subset of Starlette HTTP status constants; its `response_ model` keyword's `Name.id` is captured as a string. The function's keyword-argument defaults are scanned for `Body(...)`, `Path(...)`, `Query(...)`, and `Depends(get_current_user_authorizer(...))` shapes to derive request-body, path-params, query- params, and auth-mode respectively.

10.1.2 The F3 grammar

The F3 source grammar is a single SGDL file at `p2t/sgdl/F3_RouteContract/build/F3_RouteContract.sgr` (101 source lines including blank/comment lines). The relevant productions are:

```
(routeRule ::=
  '(' 'route' identifier
      {
          <methodRule>
        | <pathRule>
        | <statusCodeRule>
        | <responseModelRule>
        | <authRule>
        | <requestBodyRule>
        | <pathParamsRule>
        | <queryParamsRule>
      }
  ')'
)

(methodRule ::=
  'method' ( 'GET' | 'POST' | 'PUT' | 'DELETE' | 'PATCH' )
)

(authRule ::=
  'auth' ( 'none' | 'jwt_required' | 'jwt_optional' )
)
```

```
(requestBodyRule ::=
  'request_body' '(' identifier
      {
          <embedFlagRule>
        | <aliasRule>
      }
  ')'
)
```

The grammar follows the *parenthesized-bare-terminal alternative* shape (e.g. `'method' ( 'GET' | 'POST' | ... )`), which became viable after a substrate- level fix to the CCS parser-generator (cppcc commits `b7b0e17` and `24e8d9d`, p2t step `.D3.cppcc`). Before that fix the enum form emitted broken C++ and the only viable shape was leaf-rule decomposition into per-alternative rules. After the fix the inline enum form is the cleaner default; the comment declaring this is preserved in the grammar source.

CCS processes this grammar and emits, into the family subproject's `srcloc//incloc/` directories, five artefacts:

```
+-------------------------------------+-------------+
| Artefact                             | Target     |
+-------------------------------------+-------------+
| F3_RouteContractParser.{cc,h}       | C++         |
| F3_RouteContractGenerator.{cc,h}    | C++         |
| F3_RouteContractKeyWordDefinition.cc | C++        |
| F3_RouteContractKeyWordDefinition.py | Python     |
| F3_RouteContractKeyWordDefinition.mjs| JavaScript |
| F3_RouteContractKeyWordDefinition.rs | Rust       |
+-------------------------------------+-------------+
```

The C++ artefacts compile into a per-family binary `ccs3_F3_RouteContract` whose CLI accepts a `.dsl` text input and produces canonical `.fgr` (decimal- text) and `.bfgr` (raw binary) substrate forms, and their round-trip decompiled siblings (`.urt`, `.lis`, `.log`). The Python/JS/Rust artefacts are the per- language keyword tables that the corresponding SCB runtime needs to navigate the binary substrate form. The architectural reuse of the four-language SCB-API quartet is the architectural property that makes the family-grammar artefacts immediately re-usable across the C++, Python, JS, and Rust ecosystems (the present paper uses only the Python side; cross-language SCB reuse is reported separately in the companion technical paper).

10.1.3 The fixtures

The grammar is tested against three committed fixtures under `p2t/sgdl/F3_RouteContract/run/`:

- `F3_demo_full.dsl` (14 lines, exercises every production including `path_params` and `query_ params`),
- `F3_login.dsl` (10 lines, models the upstream's `login` handler exactly),
- `F3_register.dsl` (11 lines, models the upstream's `register` handler exactly).

The roundtrip harness at `p2t/sgdl/F3_RouteContract/ tests/roundtrip.sh` exercises the family binary against each fixture, confirms the SCB serialise/ deserialise round-trips byte-equally, and is the oracle the F3 substrate slice landed against (p2t step `.D3` for F3, the parallel substrate slice `.D8` for F4).

The `F3_register.dsl` fixture is the contract the decomposer must produce from the Python source. Its content is:

```
(route register
    method POST
    path ""
    status_code 201
    response_model UserInResponse
    auth none
    request_body ( UserInCreate
        embed
        alias "user"
    )
)
```

The decomposer's golden-first oracle is byte- identical equality between this hand-authored fixture and the decomposer's emitted output on the upstream's Python source. The fixture *is* the golden.

10.1.4 The decomposer extractor

`p2t/decomposer/src/p2t_decomposer/extract_f3.py` (299 lines) extracts F3 fragments from the upstream. The extractor's public entry point is:

```
def extract_to_dir(root: PathLib, out_dir: PathLib) -> List[str]:
    ...
    for rel in F3_ROUTE_FILES:
        path = root / rel
        mod = ast_walk.parse_module(path)
        for node in mod.body:
            if not isinstance(node, (ast.FunctionDef, ast.AsyncFunctionDef)):
                continue
            decorator = _router_decorator(node)
            if decorator is None:
                continue
            route = _build_route(node, decorator)
            ...
            emit_f3(route, out)
```

The extractor reads only the files it has been told about (`F3_ROUTE_FILES = ["app/api/routes/ authentication.py"]` in the present arc; expanding to non-auth routes is a single-list extension). Inside each file it visits every top-level function definition, detects the `@router.<method>(...)` decorator shape, and constructs a `RouteContract` dataclass from the decorator and the function signature. The decorator's keyword arguments are extracted by name; the function's parameter defaults are scanned for `Body(...)` (request body), `Path(...)` (path parameter), `Query(...)` (query parameter), and `Depends(get_current_user_ authorizer(...))` (auth mode).

The extractor is approximately 250 lines of vanilla `ast` walking with no recursion deeper than the function signature. The output `RouteContract` dataclass is shared with the emitter side and is the data type that the per-fragment `.dsl` writer serialises.

The output for the `register` Python source is the fixture shown in §10.1.3, byte-for-byte. The golden-first oracle (Section 6.2 of the parent paper) is satisfied: the decomposer extractor implementation was iterated against the hand- authored fixture until `diff -r decomposer/tests/ golden/F3/F3_register.dsl <emitted>` reported empty output. The first attempt landed clean (the extractor itself surfaced no in-flight corrections across its `.E9` slice; the in-flight correction the family graph exercised was Bug #1 of §8 in the F11 emitter, not F3).

10.1.5 The emitter

`p2t/emitter/src/p2t_emitter/emit_f3.py` (98 lines) reads a `.dsl` file, parses it through the shared s-expression tokeniser-and-nester (`sexpr.py`) plus an F3-specific structural walker (`parse_f3.py`), and emits a TypeScript fragment. The emitter's output shape is intentionally framework-agnostic — exported constants only, no Express/Hono/Fastify registration calls:

```
// Auto-generated from F3 RouteContract.
// Source: p2t/decomposer (.E9) -> dag.json (.E11) -> p2t/emitter (.F9)
// Do not edit by hand.

export const METHOD = "POST" as const;
export const PATH = "" as const;
export const STATUS_CODE = 201;
export const RESPONSE_MODEL = "UserInResponse" as const;
export const AUTH = "none" as const;

export const REQUEST_BODY = {
    type: "UserInCreate",
    embed: true,
    alias: "user",
} as const;
```

This file is the F3 contribution to the eventual assembled `routes/register.ts`. It carries enough information for the framework adapter to register the route with Express (or any other framework sharing comparable concepts) without re-reading the original Python.

The emitter's golden-first oracle is byte-equal comparison against the committed golden at `emitter/tests/golden/F3/F3_register.ts`. The oracle ran clean on first emission.

10.1.6 The assembler — F3 + F4 pairing

The F3 fragment is one of two fragments that contribute to the assembled `routes/register.ts`. Its partner is the F4 RouteHandler fragment emitted from the same Python handler:

```
// Auto-generated from F4 RouteHandler.
// Source: p2t/decomposer (.E9) -> dag.json (.E11) -> p2t/emitter (.F9)
// Do not edit by hand.

export interface RegisterHandlerInputs {
    user_create: UserInCreate;
    users_repo: UsersRepository;
    settings: AppSettings;
}
```

```
export async function register(
    inputs: RegisterHandlerInputs,
): Promise<unknown> {
    // TODO: implementation (the .F9 pilot emits structural shells only)
    throw new Error("not implemented");
}
```

The F4 fragment carries the handler signature (`RegisterHandlerInputs`), the function shape (`async function register(...): Promise<unknown>`), and a stub body. Its return type is `unknown` — deliberately under-specified at emission time — because F4 alone cannot know the F3 fragment's `response_model`. The pairing happens at the assembler.

The assembler is described in §10.3 in full; the F3-specific behaviour is one rewrite rule:

```
# from assemble.py
def _upgrade_f4_return_type(f4_body: str, response_model: str) -> str:
    return f4_body.replace(
        "Promise<unknown>", f"Promise<{response_model}>"
    )
```

The assembler walks the F3 fragment first, extracts its `RESPONSE_MODEL` const value, and applies `_upgrade_f4_return_type` against the F4 fragment's body. The resulting assembled `routes/register.ts` declares `Promise<UserInResponse>` correctly. The assembled output is the committed golden under `assembler/tests/golden/routes/register.ts`.

10.1.7 Stage continuation through to runtime

After the assembler, the bodies stage (Section 5.4) fills the F4 stub with a hand-authored body from its registry. The body translation is human-AI- collaborative, gated by `tsc --strict --noEmit`, and recorded as a byte-equal golden at `bodies/tests/golden/routes/register.ts`. The runtime stage (Section 5.6) wires this file literally as the Express handler for `POST /api/users`.

The F3 fragment, the F4 partner, the assembled target, the body-filled target, and the runtime binding are all individually inspectable through their committed goldens. Re-running the decomposer on a fresh checkout regenerates them byte-equally; this is the empirical content of the round-trip oracle property described in §3 of the parent paper.

10.1.8 Summary of the F3 trace

```
+--------+--------+--------+--------+--------+--------+
|        | Python | .dsl   | .ts    | assemb |bodies/ |
|        | upstrm | (.E9)  | (.F9)  | (.F10) | runtime|
+--------+--------+--------+--------+--------+--------+
| lines  |   ~25  |   11   |   ~15  |   ~30  | filled |
| oracle | n/a    | golden | golden | golden | tsc +  |
|        | (input)|        |        |        | Postman|
| stage  | upstrm |Stage 1 |Stage 2 |Stage 3 |Stages  |
|        |        |        |        |        |  4–6   |
+--------+--------+--------+--------+--------+--------+
```

The trace exhibits the central architectural property the paper claims: each stage is a small deterministic transformation whose correctness is mechanically checked against a hand-authored golden. No stage requires understanding any other stage's internals to be reviewed, reproduced, or replaced.

10.2 Decomposer

The decomposer (`p2t/decomposer/`) is the first stage of the pipeline and the only stage that reads the upstream Python source. Its responsibilities are:

1. For each of the ten families, walk the upstream AST and emit one or more `.dsl` files matching that family's grammar.
2. Drive each emitted `.dsl` through the family's `ccs<N>` binary to produce the canonical `.bfgr` substrate form (the *Loop 1* CCS compilation).
3. Record the cross-family inventory of fragments as a `dag.json` document the assembler reads at Stage 3.

10.2.1 Module layout

```
decomposer/
    src/p2t_decomposer/
        ast_walk.py        -- shared Python ast helpers
        cli.py             -- per-family CLI dispatch
        emit_dsl.py        -- shared .dsl writers
        extract_f1.py      -- DataModelEntity
        extract_f2.py      -- DataModelRelationship
        extract_f3.py      -- RouteContract
        extract_f4.py      -- RouteHandler
```

```
        extract_f5.py      -- RepositoryQuery
        extract_f7.py      -- AuthPolicy (aggregator)
        extract_f8.py      -- ValidationRule
        extract_f10.py     -- ErrorHandling (aggregator)
        extract_f11.py     -- Configuration (aggregator)
        extract_f12.py     -- ApplicationBootstrap (aggregator)
        orchestrator.py    -- Loop 1 driver + dag.json
    tests/
        golden/            -- one subdir per family
        roundtrip.sh
```

The architectural choice that makes the decomposer tractable across ten families is *family-by-family isolation*: each `extract_f<N>.py` is independent of every other, has its own scope statement, and contributes its golden artefacts to its own subdirectory under `tests/golden/`. The shared modules (`ast_walk.py`, `emit_dsl.py`) hold the few helpers all extractors need; the rest is per-family specialised.

10.2.2 The bipartite extractor shape

Section 4 notes that the ten-family taxonomy is bipartite — six families are per-fragment (one DSL file per source construct) and four are aggregator (one DSL file per application). The decomposer's CLI surface reflects this directly:

```
+-----------+------------------------+----------------------+
| Family    | CLI flag               | Output               |
+-----------+------------------------+----------------------+
| F1        | --out-dir <path>       | F1_<entity>.dsl × N  |
| F2        | --out-dir <path>       | F2_<rel>.dsl × N     |
| F3        | --out-dir <path>       | F3_<route>.dsl × N   |
| F4        | --out-dir <path>       | F4_<handler>.dsl × N |
| F5        | --out-dir <path>       | F5_<query>.dsl × N   |
| F8        | --out-dir <path>       | F8_<check>.dsl × N   |
| F7        | --out <path>           | F7_realworld_auth    |
|           |                        | .dsl                 |
| F10       | --out <path>           | F10_realworld_errors |
|           |                        | .dsl                 |
| F11       | --out <path>           | F11_realworld_       |
|           |                        | settings.dsl         |
| F12       | --out <path>           | F12_realworld_       |
```

```
|           |                          | bootstrap.dsl        |
+-----------+--------------------------+----------------------+
```

A per-fragment extractor exposes `extract_to_dir(root, out_dir) -> List[str]`; an aggregator extractor exposes `extract_to_file(root, out_path) -> None`. The Loop 1 orchestration driver adapts both shapes.

10.2.3 Loop 1 orchestration

`orchestrator.py` (the `cli.py all` subcommand) runs every per-family extractor in declaration order, then for each emitted `.dsl` invokes the matching `ccs<N>` binary to produce the canonical `.bfgr` substrate form. The output directory layout after a clean run is:

```
<out_dir>/
    F1/
        F1_user.{dsl,fgr,bfgr,urt,lis,log}
        F1_article.{dsl,fgr,bfgr,urt,lis,log}
        F1_comment.{dsl,fgr,bfgr,urt,lis,log}
        F1_profile.{dsl,fgr,bfgr,urt,lis,log}
    F2/
        F2_follow.{dsl,fgr,bfgr,...}
        F2_favorite.{dsl,...}
    F3/
        F3_login.{dsl,...}
        F3_register.{dsl,...}
    F4/
        F4_login_handler.{dsl,...}
        F4_register_handler.{dsl,...}
    F5/
        (10 fragments)
    F8/
        (5 fragments)
    F7_realworld_auth.{dsl,fgr,bfgr,urt,lis,log}
    F10_realworld_errors.{dsl,...}
    F11_realworld_settings.{dsl,...}
    F12_realworld_bootstrap.{dsl,...}
    dag.json
```

The `.bfgr` files are the canonical binary form that downstream consumers (the emitter, any other language's SCB runtime) load directly without re- parsing the `.dsl` text. The `.dsl` text is kept in the same directory both for human readability and as the unit under golden-first comparison.

10.2.4 dag.json — the Loop 1 manifest

`dag.json` is the inventory document the assembler reads at Stage 3. Its schema in the present arc is deliberately minimal:

```
{
    "version": "0.1.0",
    "pinned_commit": "<upstream HEAD SHA>",
    "nodes": [
        {
            "family": "F1",
            "fragment": "user",
            "shape": "per_fragment",
            "dsl": "F1/F1_user.dsl",
            "bfgr": "F1/F1_user.dsl.bfgr"
        },
        ...
        {
            "family": "F7",
            "fragment": "realworld",
            "shape": "aggregator",
            "dsl": "F7_realworld_auth.dsl",
            "bfgr": "F7_realworld_auth.dsl.bfgr"
        },
        ...
    ],
    "edges": []
}
```

The 29 nodes in the present arc are the 25 per- fragment family members plus 4 aggregator family members. The `edges` array is empty in the `.E11` pilot (cross-fragment dependency analysis is deferred to a follow-up slice); this is a known limitation that does not affect the assembler's present hard-coded `TARGETS` map but would become load-bearing if `TARGETS` were derived from the manifest instead of authored separately.

The `pinned_commit` field is read from `PINNED_COMMIT.txt` at decomposer-startup and captures the upstream Python HEAD the run was exercised against. The field exists for reproducibility —

re-running the decomposer against the same upstream commit produces the same `dag.json`, byte-equal.

10.2.5 What the decomposer is and is not

The decomposer is the only AI-free stage of the pipeline. Every extractor is hand-authored Python operating on Python AST nodes; no LLM is in the loop. This is a deliberate architectural choice: the data-model lift from Python AST to per-family DSL is mechanically tractable for the upstream shape covered, and a deterministic extractor is substantially easier to test, debug, and re-run than a probabilistic alternative.

What the decomposer is *not*: a general Python-to- DSL translator. Its scope is exactly the construct shapes the ten families recognise; constructs outside those shapes are ignored. A construct that arguably falls within a family's scope but is shaped differently than the extractor expects triggers a *substrate fix* (a slice that extends a grammar) or an extractor extension (a slice that broadens the recognised AST shape). The forty-six-slice arc did not require any new-family substrate fix; the arc's twelve decomposer slices (`.E` through `.E11`) extended existing extractors and grammars as the upstream constructs accumulated.

10.3 Assembler

The assembler (`p2t/assembler/`) is Stage 3 of the pipeline. Its responsibility is to read the per-fragment `.ts` files produced by the ten family emitters and stitch them into per-target TypeScript modules ready for the bodies-filler stage.

10.3.1 Module layout

```
assembler/
    src/p2t_assembler/
        assemble.py    -- per-target assembly logic
        cli.py         -- CLI dispatch
        targets.py     -- TARGETS map + TYPE_REGISTRY
    tests/
        golden/        -- 16 assembled target .ts files
        roundtrip.sh
```

The assembler is approximately 460 lines of code across the three modules. The bulk (`assemble.py`, 298 lines) is the assembly logic; the configuration (`targets.py`, 161 lines) is mostly the hard-coded `TARGETS` map; the CLI (`cli.py`, 89 lines) is dispatch.

10.3.2 The TARGETS map

`targets.py` declares a Python literal listing every target file the pipeline produces and, for each target, the ordered list of `(family, fragment)` pairs whose emissions are spliced into that target. The full map at `.F15` is sixteen entries; an abridged form:

```
TARGETS: List[Target] = [
    Target(
        path="models/user.ts",
        sources=[FragmentRef("F1", "user")],
    ),
    Target(
        path="repositories/users.ts",
        sources=[
            FragmentRef("F5", "get_user_by_email"),
            FragmentRef("F5", "get_user_by_username"),
            FragmentRef("F5", "create_user"),
            FragmentRef("F5", "update_user"),
        ],
    ),
    Target(
        path="routes/register.ts",
        sources=[
            FragmentRef("F3", "register"),
            FragmentRef("F4", "register_handler"),
        ],
    ),
    ...
    Target(
        path="auth/policies.ts",
        sources=[FragmentRef("F7", "realworld")],
    ),
    ...
]
```

The map encodes three shapes:

```
+--------+-----------------------------+--------------+
| Shape  | Description                 | Count        |
+--------+-----------------------------+--------------+
| 1:1    | one fragment -> one target  | 6  (F1 × 4,  |
|        |                             |     F2 × 2)  |
| n:1    | multiple fragments -> one   | 4  (F5 × 2,  |
|        | target (multi-fragment      |     F8 × 1,  |
|        | aggregation)                |     F1+F1   |
|        |                             |     × 0)    |
| pair   | F3 + F4 paired fragments    | 2  (login,   |
|        |                             |     register)|
| aggr   | one aggregator-family       | 4  (F7,      |
|        | fragment -> one target      |     F10,     |
|        |                             |     F11,     |
|        |                             |     F12)    |
+--------+-----------------------------+--------------+
```

The hard-coding is a deliberate `.F10` choice (a lock of the assembler slice): the manifest could in principle be derived from the decomposer's `dag.json` plus per-family slot conventions, but hard-coding kept the assembler's correctness contract simple. Future-work item (Section 14, the cross-source extension) considers unifying `TARGETS` with `dag.json`.

10.3.3 The TYPE_REGISTRY

The assembler must emit TypeScript `import` statements at the top of each assembled target. The `TYPE_REGISTRY` is a static map from a referenced TypeScript type name to the target file that defines it:

```
TYPE_REGISTRY: Dict[str, str] = {
    "User": "models/user.ts",
    "Article": "models/article.ts",
    "Comment": "models/comment.ts",
    "Profile": "models/profile.ts",
}
```

Four entries. The remaining cross-fragment type references — `UserInResponse`, `UserInCreate`, `UsersRepository`, `AppSettings`, etc. — are intentionally *not* in the registry: they are either ambient (declared at the bodies stage's static fixtures, Section 5.5) or defined in modules outside the per-family emitter's scope. A type that is neither in the registry nor flagged as ambient triggers no warning; the type simply stays unimported in the assembled output. This is correct in practice because the bodies stage's `tsc --strict` gate catches any genuinely missing type.

The registry's small size reflects an architectural decision: the assembler should not duplicate semantics the type system already enforces. `tsc` is the authoritative arbiter of type-correctness for assembled output; the assembler's `TYPE_REGISTRY` is only the minimum needed for `tsc` to know where to look.

10.3.4 Per-fragment vs aggregator dispatch

The assembler's first job per target is to locate the source `.ts` files in the emitter's golden directory. Per-fragment families live under subdirectories (`F1/F1_user.ts`, `F3/F3_register.ts`); aggregator families live as flat files (`F7_auth.ts`, `F10_errors.ts`). The fragment-locator function handles both shapes:

```
def _fragment_ts_path(emitter_root: Path, ref: FragmentRef) -> Path:
    if ref.family in _PER_FRAGMENT_FAMILIES:
        return (
            emitter_root
            / ref.family
            / f"{ref.family}_{ref.fragment}.ts"
        )
    if ref.family in _AGGREGATOR_STEMS:
        return (
            emitter_root
            / f"{ref.family}_{_AGGREGATOR_STEMS[ref.family]}.ts"
        )
    raise NotImplementedError(f"unknown family {ref.family}")
```

The `_AGGREGATOR_STEMS` map is the assembler's record of each aggregator emitter's chosen filename. dag.json uses the canonical name `realworld` for every aggregator (matching the substrate's top-level grammar identifier); each aggregator's emitter chose its own filename stem during slices `.F` through `.F4`. The assembler reconciles these by translating between the two conventions internally.

10.3.5 Header stripping and ENTITY hoisting

Each per-fragment `.ts` carries a three-line auto- generated banner that must be stripped before the fragment can be concatenated into an assembled target:

```
// Auto-generated from F5 RepositoryQuery.
// Source: p2t/decomposer (.E7) -> dag.json (.E11) -> p2t/emitter (.F8)
// Do not edit by hand.

(actual content)
```

The stripping is a five-line helper that walks leading `//` lines plus one optional blank separator. The stripping is the first transform every fragment goes through.

The second transform applies when multiple fragments target one assembled file. Each per-fragment F5 emission, for example, declares a top-of-file `export const ENTITY = "User" as const;` constant; if every fragment in a multi-fragment target agrees on the ENTITY value, the assembler *hoists* the single declaration to the top of the assembled target and strips the per-fragment copies. If the fragments disagree (different ENTITYs), no hoisting happens and the assembler errs on the side of preserving the per-fragment declarations. The `repositories/users.ts` target illustrates the consistent case: four F5 fragments all declare `ENTITY = "User"`; the assembled target carries it once.

A similar transform strips per-fragment OPERATION constants but does not attempt to hoist them (OPERATION is by construction per-operation, never shared).

10.3.6 F3 + F4 pairing

The F3 + F4 pairing introduced in §10.1.6 is the assembler's only stateful cross-fragment operation. Concretely:

1. The assembler walks the target's fragments in declared order.
2. When it sees an F3 fragment, it extracts the `RESPONSE_MODEL` const value (e.g., `UserInResponse`) and remembers it.
3. When it later sees an F4 fragment in the same target, it rewrites the F4 body's Promise<unknown> to Promise<<response_model>>.

The rewrite is a literal string replacement: F4 emitters always emit the placeholder Promise<unknown> when they cannot know the return type; the assembler unconditionally upgrades it. If a target has an F4 without a paired F3, the placeholder survives, and the bodies stage's `tsc` gate will surface the issue. In practice the four F3+F4 paired routes all behave correctly under this rule.

10.3.7 Cross-fragment imports

The assembler scans the concatenated body for PascalCase identifiers and resolves each against `TYPE_REGISTRY`. Matched types contribute import lines, deduplicated by source path. The path-computation helper is a small relative-path walker:

```
def _import_path(from_target: str, to_target: str) -> str:
    """Build a TS import path from one target file
    to another (without `.ts` extension)."""
    from_parts = Path(from_target).parent.parts
    to_parts = Path(to_target).with_suffix("").parts
    up_count = len(from_parts)
    common = 0
    for a, b in zip(from_parts, to_parts):
        if a == b:
            common += 1
        else:
            break
    up = up_count - common
    rel = to_parts[common:]
    parts: List[str] = []
    if up == 0:
        parts.append(".")
    else:
        for _ in range(up):
            parts.append("..")
    parts.extend(rel)
    return "/".join(parts)
```

`from_target="repositories/users.ts"`, `to_target="models/user.ts"` resolves to `"../models/user"`. The function is small enough to inline-comment; it is the only TypeScript-specific path-handling the assembler does.

10.3.8 Output shape

After header-stripping, ENTITY hoisting, F3+F4 pairing, and import emission, the assembler writes the assembled target. The `routes/register.ts` output is the assembled form shown in §10.1.6 — the F3 fragment's constants concatenated with the F4 fragment's upgraded interface and handler shell, prefixed by a freshly-generated banner that records which fragments contributed.

10.3.9 Architectural claims the assembler makes

plausible

The assembler is the stage that demonstrates the *decoupling-through-goldens* property the paper claims (Section 5.7). The assembler reads from `emitter/tests/golden/` and writes to `assembler/tests/golden/`; nothing in the assembler calls the emitter as a library. This means:

1. A change to a single emitter does not require re-running the decomposer or assembler — only the affected emitter's goldens are regenerated.
2. The assembler is testable independently of the emitter and decomposer by exercising it against committed emitter goldens.
3. A future stage between the emitter and assembler (e.g., a per-fragment normaliser or formatter) can be inserted without changing the assembler's contract.

These are the practical consequences of stage decoupling. They are why the assembler is roughly 460 lines despite stitching together sixteen targets across ten families: every per- target decision is a small deterministic rule the per-target goldens validate.

10.3.10 What the assembler is not

The assembler is not the body filler. Stub bodies emitted by the per-family emitters survive the assembler unchanged; replacing them with hand- authored translations happens at Stage 4 (Section 5.4) and is the only stage of the pipeline where the LLM is in the loop in any non-mechanical sense.

The assembler is also not the type resolver. Cross-fragment type imports are emitted from the small `TYPE_REGISTRY`; everything else is left ambient and verified at the bodies stage's `tsc` gate. The architectural intent is that the `tsc` gate, not the assembler, is the type- correctness oracle.

---

11. Discussion

The pipeline's empirical result supports several broader claims about substrate-grounded cross-language translation.

The data-model lift is the load-bearing engineering work. The forty-six-slice arc spent thirty-eight slices (`.A` through `.F17`) lifting the Python source's data model to the ten-family DSL representation and emitting the TypeScript surface. Only nine slices (`.F18` through `.G3`) were spent on runtime wiring. The compression ratio — approximately 9 600 lines of Python source to approximately 2 000 lines of pipeline-emitted TypeScript — reflects the intentional minimalism of the per-fragment emitters: they emit stubs that the body filler fills with logic.

The behavioural conformance oracle changes what AI-assisted translation can claim. End-to-end LLM-based code translation reports throughput numbers but typically lacks a behavioural conformance ground truth. The canonical RealWorld Postman collection provides exactly that: a contract the original implementation passes, that a translation can be exercised against, and that the maximum score is well-defined. The present paper's 293/293 result is grounded in this contract; it is not a "looks right" claim but a "passes the same behavioural assertions" claim.

Adaptive Programming generalises beyond the substrate's own construction. [3] reports the methodology against the construction of substrate-internal artefacts. The present paper extends the empirical record: the same methodology, with the same LOCK-chain discipline and golden-first testing, produced the pipeline reported here. The throughput patterns are recognisably similar — forty-two of forty-six slices on zero implementation iteration — supporting [3]'s broader claim that the methodology is the load-bearing pattern rather than a substrate-specific artefact.

The decoupling-through-golden pattern is a deployment choice the substrate makes practical. A pipeline whose stages call each other in-process would be substantially harder to re-run from intermediate state, to debug from a single stage's input, or to swap one stage's implementation without re-running upstream. The byte-equal golden pattern makes each stage a stand-alone tool; the substrate's round-trip oracle (Section 3) is what makes the goldens stable enough to be the contract between stages.

---

12. What Generalises

The pipeline was exercised on one Python source application (`nsidnev/fastapi-realworld-example-app`) producing one TypeScript target (`Express` + `tsx`). Several aspects of the result generalise; others are tied to this specific worked example.

The ten-family taxonomy generalises to data-model-shaped applications. The decomposer succeeded on every construct of the upstream without requiring a new family. Whether the taxonomy holds against a different Conduit-shaped application — for example, the Django RealWorld implementation — is an empirical question Section 14 lists as future work. The expectation is that minor decomposer extensions handle the framework differences; the family taxonomy itself is hypothesised to be stable.

The three-loop pipeline shape generalises to other target languages. A re-targeting at Rust (Section 14) would preserve the decomposer, the per-family grammar set, and the assembler logic; only the per-family emitters, the body translations, and the runtime adapter are language-specific. The pipeline-shape generalisation is the load-bearing claim of the Rust port future-work item; it is hypothesised to extend to any target language with a comparable runtime model (Go, Java, Kotlin, C#).

The LOCK-chain discipline generalises beyond the pipeline construction. Other applications of Adaptive Programming within the same project family — the SCB API quartet for C++, Python, JavaScript, and Rust [2, Section 7] — exhibit the same patterns. The empirical record across multiple projects supports the methodology's portability.

The 293/293 conformance result does not generalise as a performance promise. The runtime as deployed uses an in-memory store and is not optimised for throughput. The conformance claim is behavioural; the performance claim would require a separate benchmarking arc.

The specific runtime architecture is contingent on Express, JWT, and bcrypt. A different HTTP framework (Fastify, hapi, koa) would require a different runtime adapter; the pipeline's emitter and assembler stages would not change. The runtime stage is the language-and-framework- specific boundary the pipeline isolates.

---

13. Limitations and Threats to Validity

The work reported here is honest about what it does and does not establish.

The pipeline does not cover every endpoint. The authentication flow (register, login) is end-to-end pipelined: the Express handlers are literally the files `bodies/tests/golden/routes/{register,login}.ts`. The non-authentication endpoints (articles, comments, profiles, tags, follow) execute against hand-wired Express routes in `runtime/src/server.ts`. These hand-wired routes share the pipelined infrastructure's data structures (the `queries` proxy, the `repo` instance, the JWT machinery) but their Express handler code was not produced by the emitter, assembler, or body filler stages.

```
+-------------+-----------------------+-----------------------+
| Property    | Pipelined endpoints    | Hand-wired endpoints   |
+-------------+-----------------------+-----------------------+
| Auth (2 ep) | YES                   | NO                    |
```

```
| Articles    | NO                     | YES                    |
| Comments    | NO                     | YES                    |
| Profiles    | NO                     | YES                    |
| Tags        | partially (the .ts      | the Express handler    |
|             | handler is assembled)   | is hand-written        |
+------------+-----------------------+-----------------------+
```

The claim "we proved the pipeline produces a behaviourally equivalent TypeScript server" is *true for the authentication flow*. The claim "all 293 Postman assertions exercise pipeline-emitted code" is *false*: roughly half the assertions exercise hand-wired Express handlers in `runtime/src/server.ts`.

The extension of the pipeline to cover the remaining endpoints is mechanical work that follows the established pattern of `.F9` (per-family emitter coverage) plus `.G2`/`.G3` (runtime wiring). It is listed in Section 14 as a future-work item with an estimated four-to-six-slice budget.

Single-source single-target single-application empirical record. The pipeline has been exercised on one source application against one target language. Whether the methodology holds against a different upstream — for example, a Django implementation of the same specification — is unmeasured. Whether the methodology holds against a target language with substantially different runtime semantics (Rust, Go, Haskell) is unmeasured. Both are empirical extensions listed in Section 14.

Single-practitioner record. The arc was the product of one practitioner's work, in collaboration with one AI assistant, over approximately five weeks of focused construction. The throughput patterns reported here (forty-two of forty-six slices on zero implementation iteration) reflect that specific collaboration. Whether the same methodology delivers the same patterns with other practitioners, or with other AI assistants, is an empirical question we have not run.

Self-measurement. The methodology was developed by the same practitioner who exercised it. The throughput claims compare against the same practitioner's prior conventional estimates, not against a blinded comparison group. The self-measurement threat is the same one [3, Section 8] names; it applies to the present empirical record without modification.

LLM dependency in the body-fill stage. The hand-authored body translations in `bodies/src/p2t_bodies/registry.py` were produced through human-AI collaboration. The pipeline's *architecture* does not depend on an LLM — a hand-only practitioner could fill the registry — but the *throughput* the arc realised does. Replication without LLM assistance would land later but should land.

Postman-collection coverage is not test-coverage. The 293 assertions cover the HTTP-surface behaviour the canonical collection chose to test. They do not cover internal invariants (e.g. that a created article's slug is uniquely derived) or out-of-band properties (e.g. password hashes are not retrievable). The conformance oracle is behavioural at the HTTP surface only.

In-memory store semantics differ from the upstream's PostgreSQL. Durability across server restarts is absent; concurrent-write semantics are different; transaction isolation does not exist. The Postman collection does not exercise these differences. A production deployment would require a separate persistence adapter.

---

14. Future Work

Four lines of forward work are open.

Pipeline coverage extension to remaining endpoints. The straightforward extension of the present work: emit the articles, comments, profiles, and follow endpoints through the same decomposer → emitter → assembler → bodies path that handled register and login. Estimated budget: four-to-six slices, each following the established `.F9` + `.G2` shape. The resulting service would have *every* assertion of the 293 exercise pipeline-emitted code.

Multi-language emission — Rust. Re-target the pipeline at Rust as a second emission language. The decomposer and the ten family grammars are reused unchanged; the per-family emitters, body translations, and runtime adapter are new. Estimated budget: ten-to-fourteen slices. Success criterion: ≥ 280 Postman assertions passing against the same Conduit collection. The Rust arc would validate the central architectural claim of language-agnosticism: the 10-family taxonomy is independent of target language; only the family-emit and runtime-adapter surfaces are language-specific.

Cross-source generalisation. Run the pipeline against a different Python implementation of the same RealWorld specification — for example, the Django or Flask implementation in the RealWorld catalog. The decomposer's extractors would need extension for the new framework's patterns; the family taxonomy itself is hypothesised to hold. If the ten families absorb the new source without substrate-fix, the taxonomy generalisation claim is strengthened.

Live LLM body filler. The body-fill stage's `BODY_REGISTRY` is currently hand-authored. A modest engineering effort replaces the registry with live LLM calls plus a cache-based oracle. The `tsc` gate already validates LLM output automatically; the only new infrastructure is the cache and the

API-key handling. Estimated budget: three slices. This work item connects directly to the broader Adaptive Programming throughput story [3, Section 4].

Each item carries its own LOCK-chain skeleton and golden- first oracle. None requires breakthrough work; all extend the established pattern.

---

15. Conclusion

We have reported a worked example of substrate-grounded cross-language application translation. A Python FastAPI implementation of the canonical RealWorld backend specification has been mechanically lifted to a ten-family DSL representation, emitted as TypeScript fragments, assembled into target modules, body-filled, gated through `tsc --strict`, and wired into an Express server that passes all 293 assertions of the canonical RealWorld Postman collection. The methodological discipline that drove the arc — explicit `LOCK` invariants at every slice opening, hand-authored golden artefacts validated by byte-equal diff — landed forty-two of forty-six slices on zero implementation iteration, with the remaining four iteration-budget slices attributable to specific named failure modes documented herein. The pipeline reuses substrate infrastructure described in [2] and exemplifies the position argued in [3]: when AI assistance operates against a substrate that holds specifications as first-class artefacts with mechanical oracles, construction throughput rises substantially because the human's attention is on small reviewable specifications rather than on artefacts the human must review.

The result is local-only in availability and modest in scope: one source application, one target language, with the authentication flow end-to-end pipelined and the remaining endpoints hand-wired against pipelined infrastructure. The empirical conformance claim — 293 of 293 RealWorld Postman assertions passing — is grounded in the canonical conformance oracle the specification provides. The methodological claim — forty-two of forty-six slices on zero implementation iteration — is grounded in the LOCK-chain record across the forty-six slice documents. We close with the observation that the cross-language translation problem, in its general form, remains as intractable as it has always been; but a useful subset of the problem — data-model-shaped applications with behavioural conformance oracles — appears, on the empirical evidence of the present worked example, to be tractable through the architecture and methodology described.

References

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Manuscript prepared for submission to arXiv (cs.SE primary, cs.PL and cs.AI cross-list). Comments to the author welcomed at the contact address above. The substrate referenced throughout is operated by Bet Three LLC under US Patent 8,464,232; engagement with the reference implementation is through commercial channels. The companion technical paper [2] provides implementation backing for the substrate; the companion position paper [3] articulates the broader substrate-grounded-construction framing of which the present work is one worked example.