



```

module HashtblSig =
struct
  type t = (char, int) Hashtbl.t
  let init () = Hashtbl.create ~random:false 42
  let cleanup _ = ()

  open Lin_api
  let a,b = char_printable,nat_small
  let api =
    [ val_ "Hashtbl.clear"    Hashtbl.clear    (t @-> returning unit);
      val_ "Hashtbl.add"     Hashtbl.add     (t @-> a @-> b @-> returning unit);
      val_ "Hashtbl.remove"  Hashtbl.remove (t @-> a @-> returning unit);
      val_ "Hashtbl.find"   Hashtbl.find   (t @-> a @-> returning_or_exc b);
      val_ "Hashtbl.replace" Hashtbl.replace (t @-> a @-> b @-> returning unit);
      val_ "Hashtbl.mem"    Hashtbl.mem     (t @-> a @-> returning bool);
      val_ "Hashtbl.length" Hashtbl.length (t @-> returning int); ]
end

```

Figure 1: Specification of selected Hashtbl functions for testing using Lin.

A distinguishing feature is type `state = (char * int) list` describing with a pure association list the internal state of a hashtable. `next_state` is a simple state transition function describing how the state changes across each `cmd`. For example, `Add (k,v)` appends the key-value pair onto the association list.

`arb_cmd` is a generator of `cmds`, taking `state` as a parameter. This allows for state-dependent `cmd` generation, which we use to increase the chance of producing a `Remove 'c'`, `Find 'c'`, ... following an `Add 'c'`. Internally `arb_cmd` uses combinators `Gen.return`, `Gen.map`, and `Gen.map2` from `QCheck` to generate one of 7 different operations. For example, `Gen.map (fun k -> Mem k) char` creates a `Mem` command with the result obtained from the `char` generator. `arb_cmd` further uses a derived printer `show_cmd` to be able to print counterexamples.

`run` executes the tested `cmd` over the SUT and wraps the result up in a result type `res` offered by `STM`. Combinators `unit`, `bool`, `int`, ... allow to annotate the result with the expected type. `postcond` then expresses a post-condition by matching the received `res`, for a given `cmd` with the corresponding answer from the `model` description. For example, this compares the Boolean result `r` from `Hashtbl.mem` with the result from `List.mem_assoc`. Similarly `precond` expresses a `cmd` pre-condition.

`STM` is also phrased as an OCaml functor. The module resulting from `STM.Make(HashtblModel)` thus includes a binding `agree_test` for running sequential tests comparing the SUT behaviour to the given model. Another binding `agree_test_par` instead runs parallel tests that make a similar comparison over a sequential prefix and two parallel `Domains`, this time also searching for a sequential interleaving of `cmds`. For example, one execution of `agree_test_par` produced the following output. Note how no interleaving of `Remove` from the first parallel `cmd` sequence can make the association list model return `-1` from `Length`:

Results incompatible with linearized model

```

              |
          (Add ('1', 5)) : ()
              |
-----
|                                     |
(Remove '1') : ()                       Clear : ()
                                         Length : -1

```

## 4 Status

Both libraries are open source and available for download on GitHub from <https://github.com/jmid/multicoretests>. As the APIs are still unstable and under development, we have not made a public release yet. Interested users can nevertheless easily install the libraries with `opam`.

During development we have used examples such as `Hashtbl` to confirm that the approach indeed works as intended. The behaviour is continuously confirmed by running GitHub Actions of the latest trunk compiler. As further testament to the usability of the approach, we have used the libraries to test parts of OCaml's `Stdlib`, as well as the `Domainslib` and `lockfree` libraries. In doing so, we have been able to find and report a number of issues which have either already been fixed or have fixes underway:

- `In_channel` and `Out_channel` unsafety [1, 3]
- MacOSX crash [21]
- Buffer unsafety [22, 15]

## 5 Related Work

`QuickCheck` [5] originally introduced property-based testing within functional programming with combinator-based generators, properties, and test-case reduction. It has since been ported to over 30 other programming languages, including `Quviq QuickCheck` [19]—a commercial port to Erlang.

```

module HashtblModel =
struct
  type sut = (char, int) Hashtbl.t
  type state = (char * int) list
  type cmd =
    | Clear
    | Add of char * int
    | Remove of char
    | Find of char
    | Replace of char * int
    | Mem of char
    | Length [@@deriving show { with_path = false }]

  let init_sut () = Hashtbl.create ~random:false 42
  let cleanup (_:sut) = ()

  let arb_cmd (s:state) =
    let char =
      if s = []
      then Gen.printable
      else Gen.(oneofl [oneofl (List.map fst s);
                        printable]) in
    let int = Gen.nat in
    QCheck.make ~print:show_cmd
      (Gen.oneof
       [Gen.return Clear;
        Gen.map2 (fun k v -> Add (k,v)) char int;
        Gen.map (fun k -> Remove k) char;
        Gen.map (fun k -> Find k) char;
        Gen.map2 (fun k v -> Replace (k,v)) char int;
        Gen.map (fun k -> Mem k) char;
        Gen.return Length;
       ])

  let next_state (c:cmd) (s:state) = match c with
    | Clear -> []
    | Add (k,v) -> (k,v)::s
    | Remove k -> List.remove_assoc k s
    | Find _ -> s
    | Replace (k,v) -> (k,v)::(List.remove_assoc k s)
    | Mem _ -> s
    | Length -> s

  let run (c:cmd) (h:sut) = match c with
    | Clear -> Res (unit, Hashtbl.clear h)
    | Add (k,v) -> Res (unit, Hashtbl.add h k v)
    | Remove k -> Res (unit, Hashtbl.remove h k)
    | Find k -> Res (result int exn,
                    protect (Hashtbl.find h) k)
    | Replace (k,v) -> Res (unit, Hashtbl.replace h k v)
    | Mem k -> Res (bool, Hashtbl.mem h k)
    | Length -> Res (int, Hashtbl.length h)

  let init_state = []

  let precondition (_:cmd) (_:state) = true
  let postcondition (c:cmd) (s:state) (res:res) =
    match c, res with
    | Clear, Res ((Unit, _), _)
    | Add (_, _), Res ((Unit, _), _)
    | Remove _, Res ((Unit, _), _) -> true
    | Find k, Res ((Result (Int, Exn), _), r) ->
      r = (try Ok (List.assoc k s)
           with Not_found -> Error Not_found)
    | Replace (_, _), Res ((Unit, _), _) -> true
    | Mem k, Res ((Bool, _), r) -> r = List.mem_assoc k s
    | Length, Res ((Int, _), r) -> r = List.length s
    | _ -> false
end

```

Figure 2: Description of a Hashtbl test using STM.

Model-based testing was initially suggested as a method for testing monadic code with Haskell’s QuickCheck [6]. An explicit framework was later proposed in the GAST property-based testing library for Clean [10]. The commercial Quviq QuickCheck [19] was later extended with a state-machine model framework for testing stateful systems [2]. This approach was extended further to test parallel code for data races [7]. This general approach for parallel testing has since been adopted in other ports, such as Erlang’s open source Proper [14], Haskell Hedgehog [9], ScalaCheck [20], and Kotlin’s propCheck [17]. STM continues this adoption tradition. qcstm [11] is a previous OCaml adoption, also building on QCheck. It was missing the ability to perform parallel testing though. STM seeks to remedy this limitation.

Crowbar [8] is another QuickCheck-style testing framework with combinator-based generators. In contrast to QuickCheck, it utilizes AFL-based coverage guidance to effectively guide the generated input towards unvisited parts of the SUT. Crowbar does not come with a state-machine framework. Monolith [16] is a model-based testing framework also building on AFL-based coverage guidance. In contrast to STM, Monolith’s models are oracle implementations

with operations matching the type signatures of the tested operations. Neither Crowbar nor Monolith come with skeletons to perform parallel or concurrent testing. Furthermore the AFL-based coverage-guidance underlying both Crowbar and Monolith works best for deterministic, sequential code.

ParaFuzz [13] is another approach to fuzz test multicore OCaml programs. It simulates parallelism in OCaml through concurrency, enabling scheduling order to be controlled by AFL, which helps to trigger and find scheduling-dependent bugs. A caveat is that ParaFuzz assumes data race freedom.

Ortac can extract Monolith-based tests from a formal specification written in Gospel, a specification language for OCaml [12]. Gospel specifications include models, pre-conditions, and post-conditions close to those of STM. The extracted tests however inherit Monolith’s and AFL’s focus on sequential code.

ArtiCheck [4] tests random combinations of OCaml calls from type signature descriptions, similarly to Lin. Whereas Lin and STM target impure interfaces, ArtiCheck targets persistent (pure) interfaces. ArtiCheck furthermore targets sequential rather than parallel or concurrent tests.

## 6 Conclusion

We have presented two libraries, `Lin` and `STM` for testing parallel and concurrent code for OCaml 5.0. Despite still being under development, we believe both libraries could be helpful to developers of OCaml 5.0 programs.

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