On Dynamic Lifting and Effect Typing in Circuit Description Languages (Extended Abstract)

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Abstract

Despite the undeniable fact that large-scale, error-free quantum hardware has yet to be built \cite{12}, research into programming languages specifically designed to target architectures including quantum hardware has taken hold in recent years \cite{11}. Most of the proposals in this sense (see \cite{5, 15, 16} for some surveys) concern languages that either express or can be compiled into some form of quantum circuit \cite{9}, which can then be executed by quantum hardware. This reflects the need to have tighter control over the quantum resources that programs employ. In this scenario, the idea of considering high-level languages that are specifically designed to describe circuits and in which the latter are in fact first-class citizens is particularly appealing.

A typical example of this class of languages is \textsc{Quipper} \cite{6, 7}, whose underlying design principle is that of enriching a very expressive functional language like \textsc{Haskell} with the possibility of manipulating quantum circuits. In other words, programs do not just build circuits, but also treat them like data. \textsc{Quipper}'s meta-theory has been studied in recent years through the introduction of a family of research languages that correspond to suitable \textsc{Quipper} fragments and extensions, which usually take the form of linear $\lambda$-calculi. This family includes languages such as \textsc{Proto-Quipper-S} \cite{14}, \textsc{Proto-Quipper-M} \cite{13}, \textsc{Proto-Quipper-D} \cite{3, 4} and \textsc{Proto-Quipper-L} \cite{8}.

An aspect that so far has only marginally been considered by the research community is the study of the meta-theory of so-called dynamic lifting, i.e. the possibility of allowing any classical value flowing in one of the wires of the underlying circuit, naturally unknown at circuit building time, to be visible in the host program for control flow. As an example, one could append a unitary to some wires only if a previously performed measurement has yielded a certain outcome. This is commonly achieved in many quantum algorithms via classical control, but \textsc{Quipper} also offers a higher-level solution precisely in the form of dynamic lifting, as shown in the example program in Figure 1. Notably, such a program cannot be captured by any of the calculi in the \textsc{Proto-Quipper} family, with the exception of Lee et al.'s \textsc{Proto-Quipper-L} \cite{8}, arguably the most recent addition to the family.

Looking at the \textsc{Quipper} program in Figure 1, one immediately realizes that the two branches of both occurrences of the if operator change the underlying circuit in a uniform way, i.e. the number and type of the wires are the same in either branch. What if, for instance, we wanted to condition the execution of a measurement on a lifted value, like in Figure 2? Such situations can arise, for example, in one-way quantum computing, and the so-called measurement calculus \cite{2} indeed allows the execution of a measurement to be conditioned on the result of a previous measurement. Unfortunately, \textsc{Quipper} does not allow the program in Figure 2 to be typed. It is therefore natural to wonder whether this is an intrinsic limitation, or if a richer type system can deal with a more general form of circuits.

In this talk, we introduce a generalization of \textsc{Proto-Quipper-M}, called \textsc{Proto-Quipper-K}, in which dynamic lifting is available in a very general form. The evaluation of a \textsc{Proto-Quipper-K} term $M$ can involve the lifting of a bit value into a variable $u$ and consequently produce in
teleport :: Qubit -> Qubit -> Qubit -> Circ Qubit

teleport b q a = do
  a <- qnot a 'controlled' q
  q <- hadamard q
  (x,y) <- measure (q,a)
  (u,s) <- dynamic_lift (x,y)
  b <- if s then gate_X b else return b
  if u then gate_Z b else return b

Figure 1: Quantum teleportation circuit with dynamic lifting. The gray box represents
the dynamic lifting of bit wires \(x, y\) and the extension of the circuit on wire \(b\) with one of four
possible continuations, depending on the results of the intermediate measurement.

oneWay :: Qubit -> Qubit -> ???

oneWay q a = do
  q <- hadamard q
  x <- measure q
  u <- dynamic_lift x
  if u then measure a else return a

Figure 2: An example of conditional measurement. This program is ill-typed in Quipper.

output not a single result in the set \(VAL\) of values, but possibly one distinct result for each possible value of \(u\). Therefore, it is natural to think of \(M\) as a computation that results in an
object in the set \(\mathcal{K}_{\{u\}}(VAL)\), where \(\mathcal{K}_{\{u\}} = X \mapsto (\{u\} \to \{0, 1\}) \to X\) is a functor such that
an element of \(\mathcal{K}_{\{u\}}(X)\) returns an element of \(X\) for each possible Boolean assignment to \(u\).

This approach, though apparently straightforward, scales up in a nontrivial way. Since the
lifting of a bit can happen conditionally on the value of a previously lifted variable, in the
event that more than one variable is lifted, we have to resort to a tree-like structure to keep
track of the eventual dependencies between consecutive liftings. We call such a structure a
lifting tree and employ it pervasively throughout our work. In general, a program whose lifting
pattern is captured by a lifting tree \(t\) produces a lifted value as a result, namely an element of
\(\mathcal{K}_t(VAL)\), where \(\mathcal{K}_t = X \mapsto (P_t \to X)\) and \(P_t\) is the set of all assignments of lifted variables
which describe valid root-to-leaf paths in \(t\). Since by design we want to handle situations in
which a circuit, and by necessity the term building it, can produce results which have distinct
types—and not only distinct values—depending on the values of the lifted variables, we also
employ (in the spirit of the type and effects paradigm [10]) an effectful notion of type, typing
computations according to some lifted type, that is, an element of \(\mathcal{K}_t(TYPE)\), where \(TYPE\) is the set of Proto-Quipper-K types.

Proto-Quipper-K is thus capable of producing not only circuits like the one in Figure 1, but
rather a more general class of circuits whose structure and type essentially depend on the values
flowing through the lifted channels, like the one in Figure 2. The main results that we give,
beside the introduction of the language itself, its type system, and its operational semantics,
are the type soundness results of subject reduction and progress, which together let us conclude
that well-typed Proto-Quipper-K programs do not go wrong from an operational point of view.
An extended version of our work is already available in [1].
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