



A Predicate Transformer Semantics for Effects (Functional Pearl)

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Reasoning about programs that use effects can be much harder than reasoning about their pure counterparts. This paper presents a predicate transformer semantics for a variety of effects, including exceptions, state, non-determinism, and general recursion. The predicate transformer semantics gives rise to a refinement relation that can be used to relate a program to its specification, or even calculate effectful programs that are correct by construction.

CCS Concepts: • **Theory of computation** → *Logic and verification; Constructive mathematics; Type theory; Program semantics; Program specifications*; • **Software and its engineering** → *Functional languages*.

Additional Key Words and Phrases: predicate transformers, effects, refinement, program calculation, weakest precondition semantics, programming with dependent types, free monads, Agda

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1 INTRODUCTION

One of the key advantages of pure functional programming is *compositionality*. Pure programs may be tested in isolation; referential transparency—the ability to freely substitute equals for equals—enables us to employ equational reasoning to prove two expressions equal [Wadler 1987]. This has resulted in a rich field of program calculation in the Bird-Meertens style [Bird 2010; Bird and De Moor 1996], transforming an inefficient executable specification to an efficient alternative implementation.

Many programs, however, are *not* pure, but instead rely on a variety of effects, such as mutable state, exceptions, general recursion, or non-determinism. Unfortunately, it is less clear how to reason about such impure programs in a compositional fashion, as we can no longer exploit referential transparency to reason about subexpressions regardless of their context.

In recent years, *algebraic effects* have emerged as a technique to incorporate effectful operations in a purely functional language [Plotkin and Power 2002; Pretnar 2010]. Algebraic effects clearly separate the syntax of effectful operations and their semantics, described by *effect handlers*. In contrast to monad transformers [Liang et al. 1995], different effects may be processed in any given order using a series of handlers.

This paper defines a predicate transformer semantics for effectful programs, culminating in a constructive framework for deriving verified effectful programs from their specifications, inspired by existing work on program calculation in the refinement calculus [Back and von Wright 2012; Morgan 1994]. We will briefly sketch the key techniques, before illustrating them with numerous examples throughout the remainder of the paper.

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Predicate Transformer Semantics

Marcel A. Müller



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