



# A Predicate Transformer Semantics for Effects (Functional Pearl)

WOUTER SWIERSTRA and TIM BAANEN, Universiteit Utrecht, The Netherlands

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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Authors' address: Wouter Swierstra, [w.s.swierstra@uu.nl](mailto:w.s.swierstra@uu.nl); Tim Baanen, [t.baanen@uu.nl](mailto:t.baanen@uu.nl).

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# Predicate Transformer Semantics

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