



# 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

## ACM Reference Format:

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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

**Alain J. Martin**



## **Predicate Transformer Semantics:**

Predicate Transformer Semantics Ernest G. Manes, 1992-08-13 This book presents a rigorous foundation for defining Boolean categories and will appeal to graduate students and researchers in theoretical computer science **A General Proof Rule for Procedures in Predicate Transformer Semantics** California Institute of Technology. Computer Science Department, A. J. Martin, 1983 **Semantic Techniques in Quantum Computation** Simon Gay, Ian Mackie, 2010 The study of computational processes based on the laws of quantum mechanics has led to the discovery of new algorithms cryptographic techniques and communication primitives This book explores quantum computation from the perspective of the branch of theoretical computer science known as semantics as an alternative to the more well known studies of algorithmics complexity theory and information theory It collects chapters from leading researchers in the field discussing the theory of quantum programming languages logics and tools for reasoning about quantum systems and novel approaches to the foundations of quantum mechanics This book is suitable for graduate students and researchers in quantum information and computation as well as those in semantics who want to learn about a new field arising from the application of semantic techniques to quantum information and computation **Predicate Calculus and Program Semantics** Edsger W. Dijkstra, Carel S. Scholten, 2012-12-06 This booklet presents a reasonably self contained theory of predicate transformer semantics Predicate transformers were introduced by one of us EWD as a means for defining programming language semantics in a way that would directly support the systematic development of programs from their formal specifications They met their original goal but as time went on and program derivation became a more and more formal activity their informal introduction and the fact that many of their properties had never been proved became more and more unsatisfactory And so did the original exclusion of unbounded nondeterminacy In 1982 we started to remedy these shortcomings This little monograph is a result of that work A possible and even likely criticism is that anyone sufficiently versed in lattice theory can easily derive all of our results himself That criticism would be correct but somewhat beside the point The first remark is that the average book on lattice theory is several times fatter and probably less self contained than this booklet The second remark is that the predicate transformer semantics provided only one of the reasons for going through the pains of publication *Consistent relational and predicate transformer semantics of a sequential deterministic language supporting exception handling* Flaviu Cristian, Eike Best, 1983 **Relating State Transformation Semantics and Predicate Transformer Semantics for Parallel Programs** Franciscus Cornelus Breugel, 1993 Foundation of Software Science and Computation Structures Jerzy Tiuryn, 2000-03-15 ETAPS2000 was the third instance of the European Joint Conferences on Theory and Practice of Software ETAPS is an annual federated conference that was established in 1998 by combining a number of existing and new conferences This year it comprised five conferences FOSSACS FASE ESOP CC TACAS and satellite workshops CBS CMCS CoFI GRATRA INT seven

invited lectures a panel discussion and ten tutorials The events that comprise ETAPS address various aspects of the system development process including specification design implementation analysis and improvement The languages methodologies and tools which support these activities are all well within its scope Different blends of theory and practice are represented with an inclination towards theory with a practical motivation on one hand and soundly based practice on the other Many of the issues involved in software design apply to systems in general including hardware systems and the emphasis on software is not intended to be exclusive ETAPS is a loose confederation in which each event retains its own identity with a separate program committee and independent proceedings Its format is open ended allowing it to grow and evolve as time goes by Contributed talks and system demonstrations are in synchronized parallel sessions with invited lectures in plenary sessions Two of the invited lectures are reserved for university talks on topics of interest to the whole range of ETAPS attendees

**Refinement Calculus** Ralph-Johan Back, Joakim Wright, 2012-12-06 Much current research in computer science is concerned with two questions is a program correct And how can we improve a correct program preserving correctness This latter question is known as the refinement of programs and the purpose of this book is to consider these questions in a formal setting In fact correctness turns out to be a special case of refinement and so the focus is on refinement Although a reasonable background knowledge is assumed from mathematics and CS the book is a self contained introduction suitable for graduate students and researchers coming to this subject for the first time There are numerous exercises provided of varying degrees of challenge

**Programming Languages and Systems** Kazunori Ueda, 2010-11-19 The 23 papers presented together with 4 invited papers 2 system and tool presentations and 1 tutorial lecture were carefully reviewed and selected from 95 initial submissions The papers are devoted to both foundational and practical issues in programming languages and systems and feature current research in the following areas semantics logics foundational theory design of languages and foundational calculi type systems compilers interpreters abstract machines program derivation analysis transformation software security safety verification concurrency constraints domain specific languages as well as tools for programming verification and implementation

**A General Proof Rule for Procedures in Predicate Transformers Semantics** Alain J. Martin, 1983

**The Connection Between Axiomatic and Denotational Semantics of Programming Languages**

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**Programming Concepts, Methods and Calculi** E.-R. Olderog, 1994

**CONCUR '95 Concurrency Theory** Insup Lee, 1995-09-09 This book constitutes the proceedings of the 6th International Conference on Concurrency Theory CONCUR 95 held in Philadelphia Pennsylvania in August 1995 The volume presents seven invited contributions by outstanding researchers and 33 refereed full research papers selected by the program committee out of a total of 91 submissions The collection of articles gives a representative overview on what happened in this area of research since the last CONCUR conference took place There are sections on model checking mobile processes process theory true concurrency process algebra probabilistic

automata real time systems testing semantics decidability results refinement theory and linear time logics     Foundations of Software Science and Computation Structures ,2000     *On S-transform, Predicate Transformer, Semantics and Program Correctness* P. Tuang,1981     Proceedings of the Eighth Annual ACM Symposium on Principles of Distributed Computing ,1989     Proceedings of the 1991 International Workshop on the HOL Theorem Proving System and Its Applications, August 28-30, 1991, Davis, California Myla Archer,1992     **International Refinement Workshop and Formal Methods Pacific '98** Jim Grundy,Martin Schwenke,Trevor Vickers,1998-09 IRW FMP 98 provides a forum for the discussion of current research on mathematically based techniques for design and development of computer systems especialloy formal or rigorous methods for developing executable programs from abstract specifications tool support for formal software and practical experience with formal methods Topics also include the specification and verification of hardware and software and the specification and development of real time probabilistic and concurrent systems     The Foundations of Program Verification Jacques Loeckx,Kurt Sieber,Ryan D. Stansifer,1987 The Foundations of Program Verification Second Edition Jacques Loeckx and Kurt Sieber Fachbereich informatik Universit t des Saariandes Saarbr cken Germany In collaboration with Ryan D Stansifer Department of Computer Science Cornell University USA This revised edition provides a precise mathematical background to several program verification techniques It concentrates on those verification methods that have now become classic such as the inductive assertions method of Floyd the axiomatic method of Hoare and Scott s fixpoint induction The aim of the book is to present these different verification methods in a simple setting and to explain their mathematical background in particular the problems of correctness and completeness of the different methods are discussed in some detail and many helpful examples are included Contents Authors Preface Part A Preliminaries Mathematical Preliminaries Predicate Logic Part B Semantics of Programming Languages Three Simple Programming Languages Fixpoints in Complete Partial Orders Denotational Semantics Part C Program Verification Methods Correctness of Programs The Classical Methods of Floyd The Axiomatic Method of Hoare Verification Methods Based on Denotational Semantics LCF A Logic for Computable Functions Part D Prospects An Overview of Further Developments Bibliography Index Review of the First Edition one of the better books currently available which introduces program verification G Bunting University College Cardiff University Computing

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