J.-P. Banâtre S. B. Jones D. Le Métayer

## Prospects for Functional Programming in Software Engineering

With the cooperation of P. Fradet and A. Sinclair



## Springer-Verlag

Berlin Heidelberg New York London Paris Tokyo Hong Kong Barcelona Budapest

## CONTENTS

Chapter	1 About programming environments	1
	1.1 Introduction	1
	1.2 The software development process	1
	1.3 Characteristics of programming environments	3
	1.3.1 What should be expected from a programming environment?	3
	1.3.2 An example of a programming environment: the CEDAR system	4
	1.4 The choice of the appropriate specification language	7
	1.4.1 The VDM specification language	8
	1.4.2 Other approaches to specification 1	1
	1.5 Refinement of the specification 1	3
	1.5.1 Program development in a conventional language 1	4
	1.5.2 Program development in a functional language 1	5
	1.6 Towards a functional programming environment 1	7
	1.6.1 The choice of a language 1	7
	1.6.2 Current research on functional programming environments 1	8
	1.7 Overview of the book 1	9
	References 2	1
Chapter	2 Aspects of functional programming 2	:3
	2.1 Introduction	:3
	2.2 The main characteristics of functional languages	:3
	2.2.1 Absence of explicit sequencing	:4
	2.2.2 Absence of the assignment statement 2	:4
	2.2.3 Referential transparency 2	:5
	2.2.4 Functions: the essence of functional programming	:5
	2.3 Presentation of two widespread functional languages	<b>90</b>
	2.3.1 LISP	90
	2.3.2 ML	\$3
	2.4 Brief survey of implementation techniques	36
	2.4.1 The SECD machine	36
	2.4.2 Graph reduction	37
	2.5 Why is functional programming relevant?	37
	2.5.1 Semantic simplicity	38
	2.5.2 Correctness aspects	10
	2.5.3 Program transformation	12
	2.6 The reference language	12
	References	14

Chapter	3 Program analysis by abstract interpretation	45
	3.1 The need for a method of program analysis	45
	3.2 The basic principles of abstract interpretation	47
	3.2.1 Standard semantics	48
	3.2.2 Non-standard semantics and abstract interpretation	49
	3.2.3 Application of the abstract interpretation	54
	3.3 Restricting the interpretation to finite domains	56
	References	57
Chapter	4 Compile-time garbage collection by sharing analysis	59
	4.1 Introduction	59
	4.2 The target for optimization	60
	4.3 Language syntax and semantics	63
	4.4 Detection of sharing in functional expressions	65
	4.5 Sharing based garbage collection	74
	4.6 Finite domains and compile-time garbage collection	80
	4.7 Comparison with previous work	84
	References	86
Chapter	5 Analysis of functional programs by program transformation	87
Chapter	5 Analysis of functional programs by program transformation 5.1 Introduction	87 87
Chapter	<ul> <li>5 Analysis of functional programs by program transformation</li> <li>5.1 Introduction</li> <li>5.2 Survey of program transformation techniques</li> </ul>	87 87 88
Chapter	<ul> <li>5 Analysis of functional programs by program transformation</li> <li>5.1 Introduction</li> <li>5.2 Survey of program transformation techniques</li></ul>	87 87 88 89
Chapter	5 Analysis of functional programs by program transformation         5.1 Introduction         5.2 Survey of program transformation techniques         5.2.1 Program optimization         5.2.2 Program synthesis	87 87 88 89 92
Chapter	5 Analysis of functional programs by program transformation         5.1 Introduction         5.2 Survey of program transformation techniques         5.2.1 Program optimization         5.2.2 Program synthesis         5.2.3 Program compilation	87 87 88 89 92 92
Chapter	5 Analysis of functional programs by program transformation         5.1 Introduction         5.2 Survey of program transformation techniques         5.2.1 Program optimization         5.2.2 Program synthesis         5.2.3 Program compilation         5.2.4 Proof of properties of programs	87 87 88 89 92 92 93
Chapter	<ul> <li>5 Analysis of functional programs by program transformation</li> <li>5.1 Introduction</li> <li>5.2 Survey of program transformation techniques</li> <li>5.2.1 Program optimization</li> <li>5.2.2 Program synthesis</li> <li>5.2.3 Program compilation</li> <li>5.2.4 Proof of properties of programs</li> <li>5.3 Program analysis by program transformation</li> </ul>	87 87 88 89 92 92 93 95
Chapter	5 Analysis of functional programs by program transformation         5.1 Introduction         5.2 Survey of program transformation techniques         5.2.1 Program optimization         5.2.2 Program synthesis         5.2.3 Program compilation         5.2.4 Proof of properties of programs         5.3 Program analysis by program transformation         5.4 Time complexity analysis in a first order language	<ul> <li>87</li> <li>87</li> <li>88</li> <li>89</li> <li>92</li> <li>92</li> <li>93</li> <li>95</li> <li>98</li> </ul>
Chapter	<ul> <li>5 Analysis of functional programs by program transformation</li> <li>5.1 Introduction</li> <li>5.2 Survey of program transformation techniques</li> <li>5.2.1 Program optimization</li> <li>5.2.2 Program synthesis</li> <li>5.2.3 Program compilation</li> <li>5.2.4 Proof of properties of programs</li> <li>5.3 Program analysis by program transformation</li> <li>5.4 Time complexity analysis in a first order language</li> <li>5.5 Extension of the analysis to higher order languages</li> </ul>	87 88 89 92 92 93 95 98 102
Chapter	<ul> <li>5 Analysis of functional programs by program transformation</li> <li>5.1 Introduction</li></ul>	<ul> <li>87</li> <li>87</li> <li>88</li> <li>89</li> <li>92</li> <li>92</li> <li>93</li> <li>95</li> <li>98</li> <li>102</li> <li>105</li> </ul>
Chapter	<ul> <li>5 Analysis of functional programs by program transformation</li> <li>5.1 Introduction</li></ul>	<ul> <li>87</li> <li>87</li> <li>88</li> <li>89</li> <li>92</li> <li>93</li> <li>95</li> <li>98</li> <li>102</li> <li>105</li> <li>107</li> </ul>
Chapter	<ul> <li>5 Analysis of functional programs by program transformation</li> <li>5.1 Introduction</li> <li>5.2 Survey of program transformation techniques</li> <li>5.2.1 Program optimization</li> <li>5.2.2 Program synthesis</li> <li>5.2.3 Program compilation</li> <li>5.2.4 Proof of properties of programs</li> <li>5.3 Program analysis by program transformation</li> <li>5.4 Time complexity analysis in a first order language</li> <li>5.5 Extension of the analysis to higher order languages</li> <li>5.6 A measure of the potential parallelism of programs</li> <li>5.7 Evaluation of the space complexity of programs</li> <li>5.8 ACE: An automatic complexity evaluator</li> </ul>	<ul> <li>87</li> <li>87</li> <li>88</li> <li>89</li> <li>92</li> <li>92</li> <li>93</li> <li>95</li> <li>98</li> <li>102</li> <li>105</li> <li>107</li> <li>111</li> </ul>
Chapter	<ul> <li>5 Analysis of functional programs by program transformation</li> <li>5.1 Introduction</li></ul>	<ul> <li>87</li> <li>87</li> <li>88</li> <li>89</li> <li>92</li> <li>93</li> <li>95</li> <li>98</li> <li>102</li> <li>105</li> <li>107</li> <li>111</li> <li>111</li> </ul>
Chapter	<ul> <li>5 Analysis of functional programs by program transformation</li> <li>5.1 Introduction</li> <li>5.2 Survey of program transformation techniques</li> <li>5.2.1 Program optimization</li> <li>5.2.2 Program synthesis</li> <li>5.2.3 Program compilation</li> <li>5.2.4 Proof of properties of programs</li> <li>5.3 Program analysis by program transformation</li> <li>5.4 Time complexity analysis in a first order language</li> <li>5.5 Extension of the analysis to higher order languages</li> <li>5.6 A measure of the potential parallelism of programs</li> <li>5.7 Evaluation of the space complexity of programs</li> <li>5.8 ACE: An automatic complexity evaluator</li> <li>5.8.1 Organization of the system</li> <li>5.8.2 Using ACE</li> </ul>	<ul> <li>87</li> <li>87</li> <li>88</li> <li>89</li> <li>92</li> <li>93</li> <li>95</li> <li>98</li> <li>102</li> <li>105</li> <li>107</li> <li>111</li> <li>111</li> <li>112</li> </ul>
Chapter	<ul> <li>5 Analysis of functional programs by program transformation</li> <li>5.1 Introduction</li> <li>5.2 Survey of program transformation techniques</li> <li>5.2.1 Program optimization</li> <li>5.2.2 Program synthesis</li> <li>5.2.3 Program compilation</li> <li>5.2.4 Proof of properties of programs</li> <li>5.3 Program analysis by program transformation</li> <li>5.4 Time complexity analysis in a first order language</li> <li>5.5 Extension of the analysis to higher order languages</li> <li>5.6 A measure of the potential parallelism of programs</li> <li>5.7 Evaluation of the space complexity of programs</li> <li>5.8 ACE: An automatic complexity evaluator</li> <li>5.8.1 Organization of the system</li> <li>5.8.2 Using ACE</li> <li>5.8.3 Some results of analysis</li> </ul>	<ul> <li>87</li> <li>87</li> <li>88</li> <li>89</li> <li>92</li> <li>93</li> <li>95</li> <li>98</li> <li>102</li> <li>105</li> <li>107</li> <li>111</li> <li>111</li> <li>112</li> <li>113</li> </ul>
Chapter	<ul> <li>5 Analysis of functional programs by program transformation</li> <li>5.1 Introduction</li> <li>5.2 Survey of program transformation techniques</li> <li>5.2.1 Program optimization</li> <li>5.2.2 Program synthesis</li> <li>5.2.3 Program compilation</li> <li>5.2.4 Proof of properties of programs</li> <li>5.3 Program analysis by program transformation</li> <li>5.4 Time complexity analysis in a first order language</li> <li>5.5 Extension of the analysis to higher order languages</li> <li>5.6 A measure of the potential parallelism of programs</li> <li>5.7 Evaluation of the space complexity of programs</li> <li>5.8 ACE: An automatic complexity evaluator</li> <li>5.8.1 Organization of the system</li> <li>5.8.3 Some results of analysis</li> <li>5.8.4 Discussion</li> </ul>	<ul> <li>87</li> <li>87</li> <li>88</li> <li>89</li> <li>92</li> <li>93</li> <li>95</li> <li>98</li> <li>102</li> <li>105</li> <li>107</li> <li>111</li> <li>111</li> <li>112</li> <li>113</li> <li>117</li> </ul>
Chapter	<ul> <li>5 Analysis of functional programs by program transformation</li> <li>5.1 Introduction</li> <li>5.2 Survey of program transformation techniques</li> <li>5.2.1 Program optimization</li> <li>5.2.2 Program synthesis</li> <li>5.2.3 Program compilation</li> <li>5.2.4 Proof of properties of programs</li> <li>5.3 Program analysis by program transformation</li> <li>5.4 Time complexity analysis in a first order language</li> <li>5.5 Extension of the analysis to higher order languages</li> <li>5.6 A measure of the potential parallelism of programs</li> <li>5.7 Evaluation of the space complexity of programs</li> <li>5.8 ACE: An automatic complexity evaluator</li> <li>5.8.1 Organization of the system</li> <li>5.8.2 Using ACE</li> <li>5.8.3 Some results of analysis</li> <li>5.8.4 Discussion</li> <li>5.9 Conclusion</li> </ul>	<ul> <li>87</li> <li>87</li> <li>88</li> <li>89</li> <li>92</li> <li>93</li> <li>95</li> <li>98</li> <li>102</li> <li>105</li> <li>107</li> <li>111</li> <li>112</li> <li>113</li> <li>117</li> <li>118</li> </ul>

.

1

Chapter	6 From lambda calculus to machine code by program transformation	121
	6.1 Introduction	121
	6.2 Compilation of the computation rule	122
	6.3 Compilation of environment management	126
	6.4 Conclusion	133
	References	136
Chapter	7 On input and output in functional languages	139
	7.1 Introduction	139
	7.1.1 Why is there a problem?	139
	7.1.2 A historical perspective	141
	7.2 Lazy evaluation and streams for input and output	142
	7.2.1 Lazy evaluation, streams and processes	142
	7.2.2 Interactive programs	147
	7.3 An interactive text editor	149
	7.4 Repackaging streams: higher order functions and continuations	151
	7.4.1 A basic set of interface functions	151
	7.4.2 The text editor: an improved version	153
	7.4.3 Generalizing the interface functions	155
	7.5 Process networks, parallelism and non-determinism	155
	7.5.1 Process networks	156
	7.5.2 Parallelism	157
	7.5.3 Non-determinism	158
	7.6 An operating system structure	160
	7.6.1 The network design	160
	7.6.2 Low level disk control, and a simple file system	165
	7.7 Discussion	168
	References	.170
Chapter	8 For imperative programmers	173
	8.1 Introduction	173
	8.2 Denotational semantics	174
	8.3 Correctness considerations	178
	8.3.1 The imperative case	179
	8.3.2 The functional case	185
	8.3.3 Comparison of the imperative paradigm and the functional paradigm	189
	8.4 Efficiency considerations	191
	8.5 History-sensitive programming in a purely functional language	195
	8.6 Related works	205
	8.7 Functional programming is not a mirage	207
	References	209