

Contents

List of Contributors	ix
Preface	xiii
Chapter 1: Mechanisms of Gravity Perception in Higher Plants	3
ALINE H. VALSTER AND ELISON B. BLANCAFLOR	
1.1 Introduction	3
1.2 Identification and characterization of gravity perception sites in plant organs	4
1.2.1 Roots	4
1.2.2 Hypocotyls and inflorescence stems (dicotyledons)	6
1.2.3 Cereal pulvini (monocotyledons)	8
1.3 The starch-statolith hypothesis	9
1.3.1 A variety of plant organs utilize sedimenting amyloplasts to sense gravity	9
1.3.2 Amyloplast sedimentation is influenced by the environment and developmental stage of the plant	11
1.4 The gravitational pressure model for gravity sensing	11
1.5 The cytoskeleton in gravity perception	12
1.6 Concluding remarks and future prospects	14
1.7 Acknowledgment	15
1.8 Literature cited	15
Chapter 2: Signal Transduction in Gravitropism	21
BENJAMIN R. HARRISON, MIYO T. MORITA, PATRICK H. MASSON, AND MASAO TASAKA	
2.1 Introduction	21
2.2 Gravity signal transduction in roots and aboveground organs	22
2.2.1 Do mechano-sensitive ion channels function as gravity receptors?	24
2.2.2 Inositol 1,4,5-trisphosphate seems to function in gravity signal transduction	26
2.2.3 Do pH changes contribute to gravity signal transduction?	27
2.2.4 Proteins implicated in gravity signal transduction	28
2.2.5 Global '-omic' approaches to the study of root gravitropism	32
2.2.6 Relocalization of auxin transport facilitators or activity regulation?	37
2.2.7 Could cytokinin also contribute to the gravitropic signal?	38
2.3 Gravity signal transduction in organs that do not grow vertically	39
2.4 Acknowledgments	40
2.5 Literature cited	40
Chapter 3: Auxin Transport and the Integration of Gravitropic Growth	47
GLORIA K. MUDAY AND ABIDUR RAHMAN	
3.1 Introduction to auxins	47
3.2 Auxin transport and its role in plant gravity response	47
3.3 Approaches to identify proteins that mediate IAA efflux	51
3.4 Proteins that mediate IAA efflux	51
3.5 IAA influx carriers and their role in gravitropism	53

- 3.6 Regulation of IAA efflux protein location and activity during gravity response 55
 - 3.6.1 Mechanisms that may control localization of IAA efflux carriers 56
 - 3.6.2 Regulation of IAA efflux by synthesis and degradation of efflux carriers 58
 - 3.6.3 Regulation of auxin transport by reversible protein phosphorylation 59
 - 3.6.4 Regulation of auxin transport by flavonoids 61
 - 3.6.5 Regulation of auxin transport by other signaling pathways 61
 - 3.6.6 Regulation of gravity response by ethylene 64
- 3.7 Overview of the mechanisms of auxin-induced growth 65
- 3.8 Conclusions 67
- 3.9 Acknowledgements 68
- 3.10 Literature cited 68

Chapter 4: Phototropism and Its Relationship to Gravitropism

79

JACK L. MULLEN AND JOHN Z. KISS

- 4.1 Phototropism: general description and distribution 79
- 4.2 Light perception 80
- 4.3 Signal transduction and growth response 82
- 4.4 Interactions with gravitropism 83
- 4.5 Importance to plant form and function 84
- 4.6 Conclusions and outlook 85
- 4.7 Literature cited 86

Chapter 5: Touch Sensing and Thigmotropism

91

GABRIELE B. MONSHAUSEN, SARAH J. SWANSON, AND SIMON GILROY

- 5.1 Introduction 91
- 5.2 Plant mechanoresponses 91
 - 5.2.1 Specialized touch responses 92
 - 5.2.2 Thigmomorphogenesis and thigmotropism 94
- 5.3 General principles of touch perception 95
 - 5.3.1 Gating through membrane tension: the mechanoreceptor for hypo-osmotic stress in bacteria, MscL 98
 - 5.3.2 Gating through tethers: the mechanoreceptor for gentle touch in *Caenorhabditis elegans* 99
 - 5.3.3 Evidence for mechanically gated ion channels in plants 101
- 5.4 Signal transduction in touch and gravity perception 103
 - 5.4.1 Ionic signaling 103
 - 5.4.2 Ca²⁺ signaling in the touch and gravity response 103
- 5.5 Insights from transcriptional profiling 107
- 5.6 Interaction of touch and gravity signaling/response 110
- 5.7 Conclusion and Perspectives 113
- 5.8 Acknowledgements 114
- 5.9 Literature cited 14

Chapter 6: Other Tropisms and their Relationship to Gravitropism

123

GLADYS I. CASSAB

- 6.1 Introduction 123
- 6.2 Hydrotropism 123
 - 6.2.1 Early studies of hydrotropism 124
 - 6.2.2 Genetic analysis of hydrotropism 125
 - 6.2.3 Perception of moisture gradients and gravity stimuli by the root cap and the curvature response 126

- 6.2.4 ABA and the hydrotropic response 128
- 6.2.5 Future experiments 129
- 6.3 Electrotropism 129
- 6.4 Chemotropism 131
- 6.5 Thermotropism and oxytropism 132
- 6.6 Traumatropism 134
- 6.7 Overview 135
- 6.8 Acknowledgments 135
- 6.9 Literature cited 135

Chapter 7: Single-Cell Gravitropism and Gravitaxis

141

MARKUS BRAUN AND RUTH HEMMERSBACH

- 7.1 Introduction 141
- 7.2 Definitions of responses to environmental stimuli that optimize the ecological fitness of single-cell organisms 141
- 7.3 Occurrence and significance of gravitaxis in single-cell systems 142
- 7.4 Significance of gravitropism in single-cell systems 143
- 7.5 What makes a cell a biological gravity sensor? 144
- 7.6 Gravity susception—the initial physical step of gravity sensing 145
- 7.7 Susception in the statolith-based systems of *Chara* 145
- 7.8 Susception in the statolith-based system *Loxodes* 149
- 7.9 Susception in the protoplast-based systems of *Euglena* and *Paramecium* 150
- 7.10 Gravierception in the statolith-based systems of *Chara* 150
- 7.11 Gravierception in the statolith-based system *Loxodes* 151
- 7.12 Gravierception in the protoplast-based systems *Paramecium* and *Euglena* 151
- 7.13 Signal transduction pathways and graviresponse mechanisms in the statolith-based systems of *Chara* 153
- 7.14 Signal transduction pathways and graviresponse mechanisms in *Euglena* and *Paramecium* 154
- 7.15 Conclusions 155
- 7.16 Acknowledgements 156
- 7.17 Literature cited 156

Color Section

Chapter 8: Space-Based Research on Plant Tropisms

161

MELANIE J. CORRELL AND JOHN Z. KISS

- 8.1 Introduction—the variety of plant movements 161
- 8.2 The microgravity environment 162
- 8.3 Ground-based studies: mitigating the effects of gravity 165
- 8.4 Gravitropism 166
 - 8.4.1 Gravitropism: gravity perception 166
 - 8.4.2 Gravitropism: signal transduction 168
 - 8.4.3 Gravitropism: the curving response 169
- 8.5 Phototropism 171
- 8.6 Hydrotropism, autotropism, and oxytropism 172
- 8.7 Studies of other plant movements in microgravity 174
- 8.8 Space flight hardware used to study tropisms 175
- 8.9 Future outlook and prospects 177
- 8.10 Literature cited 177

Chapter 9: Plan(t)s for Space Exploration	183
CHRISTOPHER S. BROWN, HEIKE WINTER SEDEROFF, ERIC DAVIES, ROBERT J. FERL, AND BRATISLAV STANKOVIC	
9.1 Introduction	183
9.2 Human missions to space	184
9.3 Life support	184
9.4 Genomics and space exploration	185
9.5 Nanotechnology	187
9.6 Sensors, biosensors, and intelligent machines	187
9.7 Plan(t)s for space exploration	188
9.8 Imagine . . .	192
9.9 Literature cited	192
Index	197

Index

Page numbers followed by an f denote a figure.

- ABA (abscisic acid), 128-29
- Abiotic stress, 186
- Ablation. *See* Laser
- Abrasion, 134
- Abscisic acid. *See* ABA
- Acceleration, 170
- Actin. *See also* F-actin networks
 - amyloplast connection with, 112
 - cytoskeleton, 146, 153
 - drugs disrupting, 144
 - filaments, 5f
- Action potential, 93, 135, 189f
- Adaptability, 187
- ADH (alcohol dehydrogenase), 174
- Aequorin-derived signal, 25, 63, 103
- Aerial
 - organs, 134
 - tissue, 108
- Agravitropism
 - mutants displaying, 124
 - roots displaying, 6, 55
- Alcohol dehydrogenase. *See* ADH
- Algae, 79
- Alkalinization, 27
- Alleles, 55
- Amoeba, 142
- Amyloplasts. *See also* Spheroplasts
 - actin connection with, 112
 - degradation, 128
 - distal, 167f
 - impaired, 9
 - mature, 11
 - rogue, 13
 - sedimentation of, 4, 25
 - weight of, 29
- Analysis
 - gene, 37f, 172
 - genetic, 28-29
 - global, 32
 - hydrotropism, 125-26
 - microgravity, 146
 - proteomic, 110
- Animal cells, 56, 105
- Anions, 102
- Antibiotics, 191
- Aperture, stomatal, 104
- Arabidopsis*, 84
- Atmosphere, 184
- Autoinhibitory domain, 96
- Autoradiography, 34
- Autotropic straightening, 84
- Autotropism, 172-74
- Auxin
 - accumulation, 36
 - carriers, 168
 - efflux, 113
 - existence of, xiii
 - flavonoids regulating, 61
 - flow, 57
 - gradient, 22
 - influx, 49
 - mechanisms, 65-67
 - native, 47
 - plants resistant to, 66
 - polar transport of, 48f
 - transport, 59-61
 - transportation of lateral, 30
 - transporters within statocytes, 24
- Bacteria, 80
- Basipetal transmission, 23f
- Behavior
 - growth, 39
 - organ, xv
- Bending, 112. *See also* Gravitropic bending;
Hydrotropic bending
- BFA body formation, 58
- Bifurcation, 36

- Binding sites, 96
- Biochemical
 - experiments, 51
 - fractionation, 29
 - studies, 8-9
- Bioinformatics, 190
- Biological Research in Canister. *See* BRIC
- Biology
 - plant, 185
 - tools, 86
- Biomass production, 183, 185
- Bioregeneration, 177
- Biosatellites, 164, 175. *See also*
 - Communication
- Biosensor technology, 191
- Branching roots, 54
- Brassinosteroids, 129
- Breeding, 187
- BRIC (Biological Research in Canister), 175
- Buffeting, 91
- Bulk detection, 25

- Ca²⁺, 105
 - gravisignaling including, 106
 - L-type, 101
 - Mechanostimulation response from, 103
 - wave, 25
- Calcium, 63
 - channel, 154
 - free, 168
 - signatures, 104f
- Calmodulin, 25
- Cameleon, 103
- cAMP, 155
- Carnivorous plants, 92
- Carriers
 - auxin, 168
 - influx, 53-55
- Cations, 22
- Causation, 7
- Cell(s). *See also* Unicellular systems
 - animal, 56, 105
 - deformation, 95
 - flank, 154
 - gravitaxis in, 142-43
 - gravitropism in, 143-44
 - imaging, 177
 - internodal, 12
 - maturation, 8-9
 - motor, 93
 - orientation, 155
 - parenchyma, 80
 - research, 85
 - root cap, 104f
 - subapical region of, 26
 - suspension, 53
 - upward-swimming, 152
- Central elongation zone. *See* CEZ
- Centrifugation, 147, 170
- CEZ (central elongation zone), 110f, 131
- cGMP, 155
- Channel
 - calcium, 154
 - ion, 97
 - protein, 96f
- Chara*, 12, 150-51
- Chemical messenger, 93
- Chemiosmotic model, 53
- Chemotaxis, 131
- Chemotropism, 131-32
- Chromatography, 51
- Chromosaponin, 55
- Ciliates, 141
- Circadian
 - clock, 161
 - rhythms, 81
- Circumnutation, 7, 161
- Clinostats, 146. *See also* Random positioning machines
- Cloning, 54
- Cold stimulus, 31, 108
- Coleptiles, 28, 123, 175
- Communication, xiv
- Compounds, 47
- Computer software, 163f
- CREB transcription, 106
- Crop response, xv
- Cryptochromes, 81-82, 171
- Cultivation, 92f
- Curvature
 - hydrotropic, 128
 - response, 21-22, 35, 84, 169-71, 176
- Cytokinin, 38-39
- Cytoplasm
 - cations, 22
 - mass, 151
 - pH, 24, 112
- Cytoskeleton, 15

- actin, 146, 153
- dynamic, 6
- forces conveyed via, 98
- graviorientation, 156
- in gravity perception, 12-14
- interactions with, 97f
- vacuole, 15
- Data
 - kinetic, 64
 - microarray, 108
 - pharmacological, 105
 - thigmomorphogenic, 94
- Deformation, 95
- Dehydrating stress, 128-29
- Depolarization
 - membrane, 101
 - statocyte, 130
- Detection, 25
- Development
 - endodermis, 7
 - plant, 170
 - planta, 54
- DEZ (distal elongation zone), 110f, 131
- Diacylglycerol, 105
- Differential kinetics, 39
- Directional cues, 29
- Directional guidance, 131
- Distal elongation zone. *See* DEZ
- DNA
 - binding domain, 32
 - replication, 185
- Doses, 60
- Drop towers, 164
- Drugs, 144
- Dye
 - fluorescent, 57
 - indo-1, 103
 - voltage sensitive, 152
- EC (Experimental Container), 173f
- Efflux
 - auxin, 113
 - IAA, 51-53, 55-56
 - ion, 93
 - synthesis, 58-59
- Election micrographs, 167f
- Electrotropism, 129-31
- Elongation, 94. *See also* EZ
 - Elongation zone. *See* EZ
 - EMCS (European Modular Cultivation System), 173f
 - Endocytosis, 57
 - Endodermis, 7. *See also* Hypodermis
 - Endogenous
 - gradients, 57
 - molecules, 3, 55
 - Endoplasmic reticulum, 15, 153
 - Endosomal markers, 56, 58
 - Engineering
 - genetic, 186, 188
 - plants, xiv-xv
 - Environment
 - conditions in, 61
 - microgravity, 162, 174-75
 - resources of, 11
 - Enzymes, 97f
 - Ethylene, 109, 168
 - gravitropism regulated by, 64-65
 - regulation, 65
 - Euglena*, 150, 151-52, 154
 - European Modular Cultivation System. *See* EMCS
 - Evolution
 - conservation, 80
 - phototropin, 82
 - Exocytosis, vesicle, 154
 - Experimental Container. *See* EC
 - Experiments. *See also* EC; EMCS
 - biochemical, 51
 - laser ablation, 10, 111
 - long-term, 177
 - microarray, 66
 - microgravity, 154
 - patch clamp, 99
 - proteomic, 34
 - space, xiv-xv
 - Extents, 184
 - Extracellular matrix, 100f, 145
 - EZ (elongation zone), 22, 23f, 38
 - F-actin networks, 13
 - Ferns, 79
 - Filaments, 5f
 - Flagellates, 141
 - Flavonoid(s), 55, 168
 - auxin regulated by, 61
 - synthesis, 32

- Floral meristem initiation, 56
 Flowering, 189f
 Fluence rates, 81
 Fluorescence, 169
 Force spectroscopy, 98
 Free fall, 162, 167
 Fungus, 133f
 Fungi, 80, 129
- Gadolinium, 152
 Gametes, 131
 Gas composition, 164
 Gating
 ion, 96f
 membrane, 98-99
 Gene
 activation, 189f
 analysis, 37f, 172
 expression, 33
 identification, 66
 regulation, 190
 superfamily, 52
 Genetic analysis, 28-29. *See also* Transgene
 Genetic engineering, 186, 188
 Genetics, 33, 37f
 Genetic strategies, 30
 Genomics, 32, 184-85, 190-91
 Gentle touch, 99-101
 Germination, 10
 GFP. *See* Green Fluorescent protein
 Global analysis, 32
 Gradient
 auxin, 22
 light, 79
 moisture, 123, 126-27
 oxygen, 134
 thermal, 133
 Grass shoots, 8-9
 Gravikinesis, 142
 Gravimorphogenesis, 166
 Graviperception
 in chara, 150
 in lioxodes, 151
 mechanisms, 148
 models of, 149f
 Graviresponse, 127
 Graviresponse mechanisms, 153-55
 Gravisensitivity, 156
 Gravisignaling
 Ca²⁺ role in, 106
 mechanosignaling modulating, 111
 touch interaction with, 110-13
 Gravistimulation, 33. *See also*
 Photostimulation
 protein change related to, 109
 Gravitational pressure model, 11-12
 Gravitaxis
 in cells, 142-43
 positive, 149
 Gravitropic bending
 hydrotropic bending v., 127
 inhibited, 49
 maximal, 60
 restored, 52
 Gravitropic stimulation, 62f
 Gravitropism, xv. *See also* Circumnutation;
 Gravisensitivity; Plagiogravitropism;
 Thigmotropism
 altering, 37, 105
 in cells, 143-44
 enhancing, 13
 ethylene regulating, 64-65
 events of, 3
 gynophore, 10
 hydrotropism interacting with, 124
 kinetics of, 30
 masking, 172
 mutation affecting, 29
 negative, 6, 85
 phases of, 35
 phototropism interacting with, 83-84
 pulvini mediating, 8-9
 regulation of, 11
 research, 9
 root, 27, 32-37, 40, 58
 root v. shoot, 7
 signal transduction in, 21-22
 stem, 81f
 studies, 15
 temporal steps of, 166
 Gravity, 171. *See also* Graviresponse;
 Gravisignaling; Gravitational pressure
 model; Gravity perception; Hypergravity;
 Signal transduction
 acceleration of, 170
 cue, 91

- field, 9
- micro, 86
- morphogenesis induced by, 166
- omnilateral, 163f
- phosphorylation induced by, 34
- plumb line of, 161
- receptors, 24-26
- regulation, 33
- reorientation, 66
- response, 5, 28, 59
- root sensitivity to, 14, 65
- roots stimulated by, 62f
- sensing, 111
- sensor, 144-45
- signal, xiv
- susception, 145
- vector, 4, 10, 63, 67, 148
- Gravity perception, 48, 166-68
 - characterization of, 4-9
 - cytoskeleton in, 12-14
 - mechanisms, 3
 - signal transduction in, 103-7
- Gravity set point angle (GSA), 40
- Green Fluorescent protein (GFP), 49
- Greenhouses, 188
- Ground
 - based studies, 165-66
 - above v. below, 91f
- Growth
 - asymmetric, 68
 - behavior, 39
 - differential, 126-27
 - habit, 113
 - history, 170
 - during phototropism, 67
 - plant, 61
 - response, 3, 174-75
 - root, 28
 - signal transduction, 82-83
 - temperature affecting, 132
- GSA. *See* Gravity set point angle
- Gynophore, 10, 15
- Hardware, 175
- Heat
 - load, 85
 - shock, 185
- Helices, 100f
- Heterologous systems, 52
- Higher plants, 11, 130
- Humidity, 176
- Hydrophobic core, 95
- Hydrophobicity, 53
- Hydrostatic pressure, 95
- Hydrotropic bending, 127
- Hydrotropic curvature, 128
- Hydrotropism, 129, 165, 172-74
 - analysis, 125-26
 - gravitropism interacting with, 124
 - root, 126f
 - studies, 123
- Hypergravity, 154, 162
- Hyperpolarization, 152
- Hypobaria, 186
- Hypocotyls, 6-8, 60, 67, 169
- Hypodermis, 100
- Hypogravity, 162
- Hypo-osmotic stress, 98-99
- Hypoxia, 186
- Hypoxic stress, 185
- IAA (Indole-3-acetic acid), 47, 109
 - efflux, 51-53, 55-56
 - influx carriers, 53-55
 - mechanisms, 50f
 - redistribution, 57
- IBA. *See* Indole-3-butyric acid
- Imaging, 177
- Indo-1, 103
- Indole-3-butyric acid (IBA), 47
- Influx
 - auxin, 49
 - carriers, 53-55
- Infrared radiation, 176
- Insectivorous plants, 131
- InsP3 (1,4,5-trisphosphate), 26-27
- Intercellular
 - communication, xiv
 - statoliths, 156
- International Space Station. *See* ISS
- Internodal cells, 12
- Invertebrate organisms, 96-97
- Ion
 - channels, 97
 - efflux, 93
 - gating, 96f

- Ion (*continued*)
 - signaling, 103
- Iron, 188
- Isodensity condition, 149
- ISS (International Space Station), 164, 184
- Kinetic(s), 59
 - data, 64
 - differential, 39
 - of gravitropism, 30
 - reduction in, 27
- Laboratory
 - microgravity, 177
 - settings, 113
- Laser
 - ablation, 10, 111
 - light, 155
 - tweezers, 147
- Latrunculin B, 14
- Life support, 183
- Light, 14, 108, 171
 - gradient, 79
 - interception, 85
 - laser, 155
 - nondirectional, 84
 - perception, 80-82
 - red, 82, 86
 - signaling intermediate mutants, 83
 - visible, 176
- Lignin, 109
- Live imaging, 56
- Loxodes*, 149-51
- MAP kinase, 106
- Markers, 37f, 56, 58
- Mass
 - cytoplasm, 151
 - root, 113
- Matrix, 100f, 145
- Maturation, 8-9
- Mature zone (MZ), 23f
- Mechanical force, 97f
- Mechanical rotation, 106
- Mechanisms
 - adaptation, 109
 - auto-avoidance, 134
 - auxin, 65-67
 - graviperception, 148
 - graviresponse, 153-55
 - gravity perception, 3
 - IAA, 50f
 - mechano-sensitive ion channels, 26
 - molecular, xiv, 21, 22, 40
 - polarity, 58
 - redundant, 15
 - root, 6-8
 - synthesis, 68
 - transport, 47
- Mechanoreceptor, 99-101
- Mechanoresponses, 91-95, 110
- Mechano-sensitive ion channels
 - as gravity receptors, 24-26
 - mechanisms, 26
- Mechanosensor, 101-2, 113
- Mechanosignaling, 111
- Mechanostimulation, 103
- Media, 126f
- Membrane
 - depolarization, 101
 - gating, 98-99
 - plasma, 146f
 - potential, 102, 150
 - tension, 96f, 99
 - trafficking, 7, 95
- Metabolite, 55
- Microarray
 - data, 108
 - experiments, 66
- Microbeams, 5
- Microfabrication technology, 187-88
- Micrographs, 167f
- Microgravity, 86, 169f
 - analysis, 146
 - environment, 162, 174-75
 - experiments, 154
 - laboratories, 177
 - statocytes movement in, 167
 - studies, 171
- Microorganisms, 141, 154
- Microtubules. *See* MT
- Mir, 164
- Mitochondria, 143
- Models, 53
- Moisture, 123, 126-27
- Molds. *See* Slime molds
- Molecular
 - cloning, 54

- mechanisms, xiv, 21, 22, 40
- weight, 35
- Molecules
 - endogenous, 3, 55
 - signaling, 186
- Monocotyledons, 14
- Morphogenesis, 91, 166. *See also*
 - Gravimorphogenesis;
 - Thigmomorphogenesis
- Morphology. *See also* Photomorphogenesis
 - altered, 5
 - root cap, 36
- Mosses, 79
- Motility, 112, 131, 154
- MT (microtubule), 13, 147f
- Mud, 143
- Multimodular proteins, 98
- Mutagenesis, 101
- Mutant(s), 6, 162. *See also* Regenerative life
 - support
 - agravitropic, 124
 - arabidopsis*, 84
 - cytokinin deficient, 39
 - double, 53
 - double v. single, 30
 - gravitropism affected by, 29
 - isolation, 125
 - light-signaling intermediate, 83
 - lines, 52
 - phenotypes, 61
 - starch deficient, 165
- MY (myosin), 147f
- Myosin. *See* MY
- MZ. *See* mature zone

- Nanoscience, 184, 190, 191
- Nanotechnology, 187
- Naphthylphthalamic acid (NPA), 51, 60
- Nastic responses, 161, 175
- Negativity
 - gravitropism, 6, 85
 - phototropism, 79
- Nitric oxide. *See* NO
- Nitrite, 188
- NM (normal nutrient medium), 125
- NO (nitric oxide), 132
- Noise, 14, 152
- Normal nutrient medium. *See* NM
- NPA. *See* Naphthylphthalamic acid

- Nr, 64
- Nutrients, 14. *See also* NM
 - 1,4,5-trisphosphate. *See* InsP3
 - Organelles, 3. *See also* Statoliths
 - Organisms. *See also* Microorganisms
 - invertebrate/vertebrate, 96-97
 - sessile, xiii, 141
 - Organs
 - aboveground, 22
 - aerial, 134
 - behavior of, xv
 - bending of, 112
 - signal transduction in, 39-40
 - vertically oriented, 38
 - Orientation. *See also* Reorientation
 - cell, 155
 - nonrandom, 167
 - root, 4
 - Oscillation, 175
 - Osmotic pressure, 26
 - Ovule, 133f
 - Oxonol, 152
 - Oxygen, 188
 - gradient, 134
 - stress, 174
 - Oxytropism, 132-34, 165, 172-74

 - Parabolic flights, 146
 - Paramecium*, 150, 151-52
 - Parenchyma
 - cells, 80
 - tissue, 60
 - Pathogens, 108
 - PCOCs (Plant Carry-on Containers), 175
 - Peg formation, 10
 - Perceptosome, 188
 - Peroxisomes, 188
 - pH, 168, 188
 - changes in, 63
 - cytoplasmic, 24, 112
 - lipidity, 102
 - low, 53
 - signal transduction contribution from
 - changes in, 27-28
 - Pharmacology
 - data, 105
 - studies, 24
 - Phenotypes, xiii

- Phenotypes (*continued*)
 mutant, 61
 polygenic, 187
- Phosphate, 188
- Phosphorylation
 gravity induced, 34
 protein, 59-61
- Photolysis, 47
- Photomorphogenesis, 81
- Photoreceptor pigments, 80
- Photostimulation, 79
- Photosynthesis, 21, 84, 183
- Phototropin, 82
- Phototropism, 129, 171-72
 altering, 29
 gravitropism interacting with, 83-84
 growth during, 67
 negative, 79
 phytochromes role in, 86
 positive, 85
 root, 81f
- Phytochromes, 82, 86, 188
- pl, 35
- PIN1 cycling, 57f
- Plagiogravitropism, 40
- Plant(s)
 adaptability, 187
 auxin resistant, 66
 biology, 185
 carnivorous, 92
 development, 170
 engineering, xiv-xv
 form, 84-85, 171
 growth, 61
 higher, 11, 130
 insectivorous, 131
 mechanoresponses, 91-95
 mechanosensor, 101-2, 113
 programmable, 184, 189f, 191f
 seed, 79
 sensory system in, 135
 species, 48
 stress, 190
 tissue, 47, 52, 65
 transgenic, 186
 tropisms, 1
 wild-type, 127
- Planta development, 54
- Plant Carry-on Containers. *See* PCOCs
- Polarity, 102
 auxin, 57
 mechanisms, 58
- Polarization. *See* Hyperpolarization
- Pollen tubes, 123, 130
- Positivity
 gravitaxis, 149
 phototropism, 85
- Potassium, 188
- Potential. *See also* WP
 action, 93, 135, 189f
 membrane, 102, 150
- Presentation time, 169
- Pressure, 26
- Pressure theory, 145
- Programming plants, 184, 189f, 191f
- Protein(s), 22, 51. *See also* Green Fluorescent
 protein
 channel, 96f
 control, 191
 dynamic, 13
 encoded, 30
 gravistimulation related to change to,
 109
 identification, 33
 J-domain, 29
 localization, 56
 multimodular, 98
 phosphorylation, 59-61
 PIN, 168
 proteolytic degradation of, 68
 receptor, 144
 signal transduction implying involvement
 of, 28-32
 structure, 83
 synthesis, 185
 transmembrane, 95
 wall-modifying, 108
 zinc-finger, 31
- Proteolytic degradation, 68
- Proteomic(s), xiii, 32, 190, 191
 analysis, 110
 experiments, 34
- Proteosome, 66
- Proton(s)
 caged, 28
 pumping, 113

- Protonemata, 141, 153
- Protoplast
 hydrostatic pressure from, 95
 pressure theory, 145, 148
 weight, 12
- Pulvini, 79
 gravitropism mediated by, 8-9
 oat, 34
- Radial swelling, 94
- Radiation, 164, 176
- Random positioning machines, 165, 169
- Reciprocity rule, 170
- Red light, 82, 86
- Redundancy, 32
- Regenerative life support, 183
- Reorientation
 gravity, 66
 root, 57
- Replicability
 DNA, 185
 research, 165
- Reproductive functions, 21
- Research
 cell, 85
 gravitropism, 9
 orbit-based, xv
 replicability, 165
 signal transducer, 97
 space, 161
 touch, 109
- Resistance, 54
- Resources, 11
- Response. *See also* Curvature;
 Mechanoresponses
 crop, xv
 curvature, 21-22, 35, 84, 169-71, 176
 gravity, 5, 28, 59
 growth, 3, 174-75
 nastic, 161, 175
 physiological, 15
 touch, 92-94, 107
- Reverse genetics, 33, 37f
- Rhizoids, 141, 148
 protonemata responding like, 153
- Rhizosphere, 187
- Robots, 183, 191
- Room temperature, 31
- Root(s). *See also* Root cap
 agravitropic, 6, 55
 branching, 54
 decapping, 130
 gravitropism, 7, 27, 32-37, 40, 58
 gravity sensitivity of, 14, 65
 gravity stimulated, 62f
 growth, 28
 horizontal, 50f
 hydrotropism, 126f
 mass, 113
 mechanisms, 6-8
 orientation, 4
 phototropism, 81f
 reorientation, 57
 shoots v., 48
 signal transduction in, 22-24
 stems v., 23f
 system, 92f
 thermotropism, 132-34
- Root cap
 cells, 104f
 longitudinal section of, 5f
 morphology, 36
- ROS sensitivity, 107
- Rotation, 106
- Sachs, Von, 124f
- Screening approach, 31
- Sedimentation
 amyloplast, 4, 25
 rate, 144
- Seed
 germination, 10
 plants, 79
- Seedling, 169f
 homozygous, 50f
 size, 67
- Selective resistance, 54
- Septum, 133f
- Sequence similarity, 54
- Sessile organisms, xiii, 141
- Shock, 185
- Shoot(s)
 grass, 8-9
 gravitropism, 7
 roots v., 48
 statocytes, 38

- Signal. *See also* Transduction pathway
 aequorin-derived, 25, 63
 molecules, 186
 pathways, 61-64, 153-55
 research, 97
 transducer, 168-69
- Signal transduction, 3
 bifurcation, 36
 in gravitropism, 21-22
 in gravity perception, 103-7
 growth, 82-83
 insP3 role in, 26-27
 in organs, 39-40
 pH changes contributing to, 27-28
 proteins implicated in, 28-32
 in roots, 22-24
 vesicular trafficking connected to, 38
- Silver-staining, 35
- Skylab, 164
- Slime molds, 142
- Soap, 191
- Software. *See also* Hardware; Programming
 plants
 computer, 163f
- Soil, 91, 143
- Solar-tracking, 85
- Somatal openings, 80
- Sounding rockets, 175
- Space
 experiments, xiv-xv
 research, 161
- Spectroscopy, 98
- Sperm, 142
- Spheroplasts, 99
- Spitzenkörper. *See* SpK
- SpK (Spitzenkörper), 147f, 153
- Starch
 mutants deficient in, 165
 sheath, 60
- Starch-stanolith hypothesis, 4, 9-11
- Statocytes
 auxin transporters within, 24
 depolarization, 130
 microgravity movement by, 167
 shoot, 38
- Stanoliths, 3, 111, 149-50. *See also* Starch-
 stanolith hypothesis
 intercellular, 156
 susception, 145-49
 weight, 150
- Status, 187
- Stem(s)
 gravitropism, 81f
 roots v., 23f
- Stimuli, xiii
- Stomatal aperture, 104
- Strategies, 30
- Streaming velocity, 12
- Stress(es)
 abiotic, 186
 dehydrating, 128-29
 hypo-osmotic, 98-99
 hypoxic, 185
 oxygen, 174
 plant, 190
 transfer of, 97
 water, 85, 125
- Structure
 protein, 83
 tissue, 21
- Studies
 biochemical, 8-9
 gravitropism, 15
 ground-based, 165-66
 hydrotropism, 123
 microgravity, 171
 pharmacological, 24
 transgenic, 63
 unicellular systems, 143f
- Substrate, 97f
- Susception
 gravity, 145
 stanoliths, 145-49
- Suspension cells, 53
- Symbiont elicitors, 104
- Synthesis
 efflux, 58-59
 enhanced, 64
 flavonoid, 32
 mechanisms, 68
 protein, 185
- Synthetic compounds, 47
- Systems. *See also* EMCS
 heterologous, 52
 root, 92f
 sensory, 135
 unicellular, 143f

- TCH. *See* Touch
- Technology, 177, 185
 biosensor, 191
 microfabrication, 187-88
- Temperature, 176
 growth effects due to, 132
 room, 31
- Tendrils, 94
- Thermal gradient, 133
- Thermal noise, 152
- Thermotropism, 132-34
- Thigmomorphogenesis, 94
- Thigmotropism, 94, 113
- Threshold duration, 169. *See also*
 Presentation time
- Timing, 49
- Tissue
 aerial, 108
 overexpression, 59
 parenchyma, 60
 plant, 47, 52, 65
 structure, 21
- Tools, 174
 biology, 86
 nanotechnology, 187
- Topology, 30
- Touch. *See also* Gentle touch
 gravisingaling interaction with, 110-13
 perception, 95-98
 research, 109
 response, 92-94, 107
- Transcriptional profiling, 107-10
- Transduction pathway, 107
- Transgene
 plants, 186
 studies, 63
- Transpiration, 183
- Transport machinery, 53, 59-61
- Traumatropism, 134-35
- TROPI, 173f
- Tropism(s)
 concepts of, xiii
 plant, 1
- Turgor loss, 93
- 2D-G3. *See* Two-dimensional gel
 electrophoresis
- Two-dimensional gel electrophoresis
 (2D-G3), 34
- Unicellular systems, 143f
- Up-regulation, 32
- Vacuole, cytoskeleton, 15
 transport, 8
- Vasculature, 93
- Vector
 gravity, 4, 10, 63, 67, 148
 information, 40
- Vectorial stimuli, xiii
- Velocity, 12
- Vertebrates, 96-97
- Vesicle
 exocytosis of, 154
 inhibitors, 56
 movements, 58
 trafficking, 38
- Vibration, 170
- Video, 176
- Vitamins, 191
- Voltage
 dependence, 102
 dye sensitive to, 152
 sensitivity, 101
- Water, 14. *See also* WP; WSM
 stress, 85, 125
- Water potential. *See* WP
- Water stress medium. *See* WSM
- Weight
 amyloplast, 29
 molecular, 35
 protoplast, 12
 statoliths, 150
- Weightlessness, 162
- Wild-type
 levels, 31
 plants, 127
- WP (water potential), 126f
- WSM (water stress medium), 125
- Zero-g, 162
- Zoospores, 142