

Preface

THIS BOOK IS INSPIRED BY THE EXTENSIVE AND EXCITING PROGRESS made over the past 10 years by the multitudes of scientists who have devoted their careers to the study of symmetry breaking in various biological systems. We hope that this collection of reviews will serve the purposes of both summarizing what we have learned so far, and of highlighting the central questions that remain for future investigation. After a broad Introduction that seeks both to establish a historical context and to preview the specific topics covered, the book begins with four "orthogonal" chapters that provide cross-system overviews of the common molecular machineries used for symmetry breaking in biology. These include overviews of cytoskeletal systems, signaling modules, and membrane systems, as well as a theory chapter on the chemical and physical principles that are beginning to emerge across different model systems. These initial four chapters are followed by thirteen additional contributions that focus on specific symmetry breaking problems in different model organisms or cell types. These chapters are ordered by increasing system scale and complexity, beginning with the smallest and simplest cells, bacteria, followed by the two most widely studied yeast cells, and finally by the exceedingly more complex systems of multicellular organisms. While none of the chapters provides a comprehensive review, all strive to highlight the most fascinating phenomena in their respective systems, our current understanding of their molecular bases, and the emerging principles and outstanding questions. Please note that all cited 2009 CSH Perspectives references are to other chapters within this book.

We have been exceptionally fortunate to be able to recruit leading researchers in cell and developmental biology to author these chapters. We are grateful to all of them for their scholarly efforts toward crafting and revising the manuscripts, especially given the stresses that follow from the currently difficult funding climate (which thankfully appears likely to improve). We also are extremely grateful to Maryliz Dickerson, whose exceptional organizational skills, enthusiasm, and attention to details ensured a smooth and pleasant process in the development of this book; to Mary Toth for her assistance; to Richard Sever at Cold Spring Harbor Laboratory Press for initiating this project and providing helpful advice throughout; and to Kaaren Kockenmeister and Denise Weiss for their excellent production work and cover art design. Finally, we thank our spouses for their constant love and support and our children for the happiness they bring us.

RONG LI
BRUCE BOWERMAN

Index

A

- actin network
 - Arp2/3 complex and, 15
 - breaking symmetry with in yeast, 101–103
 - breaking symmetry without in yeast, 103–104
 - cables and patches, 101
 - chemotactic signals in neutrophils and, 192
 - in cytoskeletal mechanisms
 - assembly dynamics, 9
 - kinetic polarity, 8
 - mechanical rigidity, 8–9, 14, 16
 - motility of pathogens and particles and, 15–16
 - intracellular transport and, 223–224
 - modeling of shell growth and rupture around beads, 64–65
 - motility and architectural heterogeneity, 16
 - polarization and, 61–63
 - regulating proteins and neuronal polarity, 222
 - study of cortices grown around beads, 64
- AJC in epithelial cells, 206–207
- aPKC
 - cortical displacement by in *Drosophila*, 141–143
 - front–rear polarity in epithelial cells, 201
 - neuronal polarity and, 224–225
 - Par3/Par6/aPKC module role in symmetry breaking, 3
 - polarity generating mechanisms, 19
 - polarity signaling through Par-3/Par-6/aPKC
 - Cdc42 as an upstream regulator, 28–30
 - cross talk between Wnt signaling and Par proteins, 30–31
 - localization of Cdc42-GTP, 29–30
 - phosphoinositides as polarity signals, 33–34
 - Rho GTPases as downstream effectors, 30
 - small GTPases and, 28
 - through protein kinases, 31–33
 - polarization of in *Drosophila*, 143–145
- apoptosis module, 208
- Arabidopsis thaliana*, 165f
 - asymmetric division in cortex-endodermal cell lineage, 172–174
 - asymmetric division in stomatal development
 - cell–cell signaling, 169, 170f, 171
 - connection between cell–cell signaling and intrinsic factors, 172
 - initiation by MMCs, 169, 170f
 - intrinsic factors involved, 171–172
 - asymmetric division of the zygote
 - auxin's role in maintaining asymmetry, 168
 - homeodomain transcription factors role in, 167–168
 - inter-cellular signaling requirement, 168–169
 - polarization of the early embryo and, 166–167
 - suspensor cell fate specification, 167
 - cooperation between intrinsic and extrinsic mechanisms
 - blurring of distinctions between factors in ground tissue formation, 176
 - in the epidermis, 175–176
 - factors in embryonic asymmetry, 175
 - perspectives and future directions, 176
 - selection of the division plane, 163–164
 - SHR and mechanism for symmetry breaking in CEI cells, 174
 - symmetry breaking process, 164
- architectural heterogeneity
 - actin-based motility and, 16
 - asters and, 14
 - cytoskeletal mechanisms for breaking cellular symmetry, 14, 16, 18
 - described, 10–11, 12f
 - myosin II and, 18
- Arp2/3 complex
 - actin-based vesicle motility and, 15
 - architectural heterogeneity and, 11
 - in fission yeast, 90
 - neuronal polarity and, 222
 - positive feedback loops and, 10
- asters, 13–14
- asymmetric cell division in plants. See *Arabidopsis thaliana*

*Page references followed by f denote figure.

- asymmetric stem cell division in *Drosophila*
 female germ line stem cells
 signaling in the stem cell niche, 155–156
 spindle orientation by the spectrosome, 156
 follicle stem cells, 157
 male germ line stem cells
 aging and, 154–155
 signaling in the stem cell niche, 150–153
 spindle orientation by the centrosome,
 153–154
 midgut stem cells and polarity, 156–157
 vertebrate stem cells that are similar
 mammalian neuroepithelial cells, 157–159
 mammalian skin stem cells, 159
 parallels between mammalian and
Drosophila stem cells, 159
- Aurora-A, 31
 auxin, 168
- B**
- Bacillus subtilis*, 72f
 directing a protein to a pole, 76
 identification of cell poles in, 73–74
 polarity in developmental pathways of,
 79–80
- backness signaling pathway
 described, 190
 long-distance stimulation of backness, 192
 mechanisms for mutual incompatibility
 of actin assemblies, 192
 model for self-organizing polarity, 190–192
- Balbani body, 263–264
 Bazooka, 143–144
 BDNF (brain-derived neurotrophic factor), 228
 Bem1, 103–104
 beta-catenin
 mediation of binary specification in *C. elegans*,
 127–128, 130–131, 132
 PCP signaling and, 239, 243, 244, 245
- bHLH, 175–176
 Bicaudal-D (BicD), 260
bicoid, 257
 blebs, 61, 63, 66
 BMP signaling, 151, 155
 BODENLOS (BDL), 168
 brain-derived neurotrophic factor (BDNF), 228
 Brain tumor (Brat), 140, 141
 budding yeast. *See Saccharomyces cerevisiae*
- C**
- Caenorhabditis elegans*
 apico-basal polarity establishment, 125–126
 apico-basal symmetry breaking in epithelia,
 126–127
 conclusions regarding symmetry breaking in, 132
 cortical actomyosin symmetry breaking during
 cytokinesis, 123–125
 polarity generating mechanisms, 19
 positioning and stabilizing of the AP boundary,
 122–123
 reiterative binary specification
 evolution of, 130–131
 mechanisms for, 127
 POP-1 and, 127–128
 upstream cues, 128–129
 Wnt signaling and mitotic spindle
 orientation, 129
 symmetry breaking in zygote
 identifying cues that trigger polarization, 121
 segregation of cortical factors to establish
 cell polarity, 118–121
 sequence of events, 118
 sperm cue mechanical workings, 119
 threshold for triggering polarity establishment,
 121–122
 Wnt signaling and, 245
- cardiolipin, 73
Caulobacter crescentus, 72f
 distinguishing between cell poles in, 75
 identification of cell poles in, 73–74
 polarity in developmental pathways of, 76–79
- Cdc42 - GTPase
 apical-basal polarity in epithelial cells, 207
 apico-basal polarity establishment and, 126
 cell polarity in budding yeast and, 122
 in fission yeast, 89
 front–rear polarity in epithelial cells, 201
 function in polarized membrane traffic, 46–47
 long-distance stimulation of backness in
 neutrophils, 192
 mechanisms for polarizing cells and, 101–103
 neuronal polarity and, 225
 polarity signaling in *S. cerevisiae*, 28–29
 polarization by membrane traffic in yeast,
 50–51
 positive feedback loops and, 10
 symmetry breaking role, 2–3
 yeast bud site selection and, 107
 in yeast mating pathway, 109–111
- CEI (cortex-endodermal cell lineage), 172–174
 cell polarity
 chemotaxis and (*see* chemotactic signals in
 neutrophils)
 membrane trafficking and (*see* membrane
 organization and dynamics in cell polarity)

- planar (*see* planar cell polarity (PCP) signaling)
 in prokaryotes (*see* cellular polarity in prokaryotic organisms)
 shaping of fission yeast (*see* *Schizosaccharomyces pombe*)
 signaling pathways (*see* polarity establishment through signaling pathways)
 symmetry breaking and, 3–4
- cellular polarity in prokaryotic organisms
 aspects of physiology that are intrinsically polar, 71–73
 conclusions, 80–81
 in developmental pathways
 B. subtilis, 79–80
 C. crescentus, 76–79
 directing a protein to a pole, 76
 distinguishing between cell poles, 75–76
 identification of cell poles, 73–75
 mechanisms that derive polarity-specific information, 75
 other examples of polarity, 80
- centrosomes, 13, 14–15
 Centrosomin (Cnn), 153
 cerebellar granule neurons model, 218, 219f, 220
 chemical gradient model, 286, 287f
 chemotactic signals in neutrophils
 backness signaling pathway
 described, 190
 long-distance stimulation of backness, 192
 mechanisms for mutual incompatibility of actin assemblies, 192
 model for self-organizing polarity, 190–192
 chemotaxis described, 181
 control of the protrusive leading edge
 accumulation of spatial signals, 183–185
 convergence of gradients, 184–185
 PI(3,4,5)P3 role in, 184, 185–187
 positive feedback loops and, 187–190
 steps in symmetry breaking, 183
- future directions
 mechanisms of adaptation study, 193
 polarity versus direction sensing study, 193
 questions about mechanistic details, 192–193
 signal integration and prioritization in gradient arrays, 193–194
 process of polarization, 181–183
- CLASPs (CLIP-associated proteins), 223
 CLIPs (cytoplasmic linker proteins), 223
 cofilin, 222
 collapsin response mediator protein-2 (CRMP-2), 223
 convergent extension in an embryo, 242–243
 cortex-endodermal cell lineage (CEI), 172–174
 crescentin, 80
 Crumbs, 27, 201, 206, 207
Cryptococcus neoformans, 50–51
 CtrA, 77
 cyst stem cells (CySCs), 150–153
 cytoplasmic linker proteins (CLIPs), 223
 cytoskeletal mechanisms for symmetry breaking
 actin-based motility of pathogens and particles, 15–16
 architectural heterogeneity, 10–11, 12f, 14, 16, 18
 assembly dynamics of actin filaments and microtubules, 9
 kinetic polarity in actin filaments and microtubules, 8
 main cytoskeletal systems in eukaryotic cells, 7–8
 mechanical rigidity in actin filaments and microtubules, 8–9, 14, 16
 network mechanics, 12–13
 polarization and motility of cells, 16–18
 polarization of oocytes and fertilized eggs, 18–19
 positive feedback, 9–10, 14, 16, 18
 processes that establish and maintain polarity, 17
 spontaneous assembly of microtubules into organized structures, 13–15
 summary and perspective, 19–20
- cytoskeleton role in neuronal polarity
 actin- and microtubule-based intracellular transport, 223–224
 actin regulating proteins and, 222
 growth cone, 220–221
 microtubule regulating proteins, 222–223
 reinforcement of neuronal asymmetry, 221
- ## D
- Dachsous (Ds), 239–240, 246
 Delta, 262
Dictyostelium discoideum, 48, 181
 Diego (Dgo), 236–238
 Dishevelled (Dvl), 30, 236–238, 241
 DivK, 77
 DLG, 201
 DOCK2, 189
Drosophila
 asymmetric stem cell division in
 female germ line stem cells, 155–156
 follicle stem cells, 157
 male germ line stem cells, 150–155
 midgut stem cells and polarity, 156–157
 PCP signaling (*see* planar cell polarity signaling)

Drosophila (continued)

- polarization of neuroblasts during asymmetric division
 - basal domain and differentiated fate, 140–141
 - conclusions, 145–146
 - cortical displacement by direct aPKC phosphorylation, 141–143
 - coupling cortical polarity to spindle positioning, 145
 - neuroblast polarity, 139–140
 - neuroblasts as a model investigative system, 138–139
 - polarization of aPKC, 143–145
 - production of daughter cells, 137–138
- symmetry breaking during oogenesis (see *Drosophila* oogenesis)

Drosophila oogenesis

- conclusions, 270–271
- conservation in evolution, 271
- cyst formation and the fusome, 257–258, 259f
- DV polarity emergence, 269–270
- germarium structure and cyst encapsulation, 261
- oocyte polarization
 - back signaling, 266–269
 - follicle cell patterning, 264–266
 - posterior pole establishment, 263–264
- oocyte positioning as a symmetry-breaking event, 263
- polarization of the microtubule cytoskeleton, 259–261
- polarized egg chamber formation, 261–263
- process of oocyte determination, 259
- stages of oogenesis, 256–257
- use of the symmetry breaking term, 256

dynamic instability, 9

dyneins

- formation of MT network in *Drosophila*, 260–261, 263, 264, 265, 266
- function, 9, 14, 15
- in intracellular transport for neuronal polarity, 223
- in left–right determination by nodal flow, 279, 280, 281, 282, 285
- left–right determination in mammals and, 282
- mRNA localization and, 27, 206
- neuronal polarity and, 223
- Par-3 localization and, 25

E

- E-cadherin and membrane trafficking, 51–52
- Egalitarian (Egl), 260
- EMT, 211

Ena/VASP proteins, 222

- endocytosis, 50, 51
- EPIDERMAL PATTERNING FACTOR 1 (EPF1), 171
- epithelial cell organization
 - apical–basal polarity
 - downstream effectors of polarity proteins, 206–207
 - endocytic and exocytic membrane trafficking pathways, 205
 - evidence of, 203–204
 - organization and function of polarity proteins, 205–206
 - polarity protein complexes maintenance of, 208–209
 - primary cilium module, 207–208
 - transitions from front–rear, 209–211
 - transitions to front–rear, 211
- basic design of polarized epithelial cells, 197–198
- conclusions, 211
- evolution and developmental origins of polarized epithelia, 198–200
- front–rear polarity
 - of endocytic and exocytic membrane trafficking pathways, 202–203
 - of phosphatidylinositides, 200
 - polarity complex roles, 200–202
 - of Rho GTPases, 200
- epithelial planar cell polarity in flies
 - communication of polarity information between cells, 238
 - core complexes in the eye, 238–239
 - core genes and proteins function in the wing, 236–238
 - results of mutations in the wing, 236
 - symmetry breaking, 239–240
 - in vertebrate, 240–242
- equatorial stimulation in budding yeast, 123
- ERECTA gene family (ERf), 171
- Escherichia coli*, 75
- Exo70, 44
- exocytosis, 43, 207

F

- FAMA, 171–172
- Fat (Ft), 239–240, 246
- filopodia in neuronal polarity, 220–221, 222
- fission yeast. See *Schizosaccharomyces pombe*
- Flamingo (Fmi), 236–238, 241
- flies. See *Drosophila*
- for3p, 89–90, 91
- Four-jointed (Fj), 239–240
- Frizzled (Fz)

epithelial planar cell polarity in flies and, 236–238
 hair cell PCP in vertebrates, 241
 planar cell polarity and, 30
 symmetry breaking in PCP signaling, 239–240
 FtsI, 75
 FtsZ, 73, 74, 75
Fucus, 164
 fusome, 257–258, 259f
 Fuzzy, 247

G

ganglion mother cell (GMC), 138
 G β γ heterodimer, 183–184
 glycogen synthase kinase (GSK-3 β), 224
On Growth and Form (Thompson), 4
 guanine nucleotide exchange factor (GEF), 28, 104–105
gurken, 257, 265

H

hippocampal neurons model, 218, 219f
 Hippo signaling, 208–209, 266

I

Inscuteable, 145
 intermediate filament (IF) proteins, 80
 Inturned, 247
inversus viscerum (*iv*) mutant mice, 282

J

JAK-STAT signaling pathway, 151, 262, 265
 JAM-A, 210–211
 Jaquar (Myosin VI), 141

K

Kartagener's syndrome, 279
 kinesins
 in aster assembly, 13
 cellular symmetry breaking in *C. elegans*, 127
 in epithelial cell organization, 205, 209
 in intracellular transport for neuronal polarity, 223–224
 mitotic spindle and, 15
 in oocyte polarization, 266, 268
 Par-3 transport and, 25
 purpose, 9
 kinesin superfamily proteins (KIFs), 281–282

L

lamellipodia in neuronal polarity, 220–221
 left–right determination in mammals
 chemical gradient model applied to, 286, 287f
 conclusions, 290
 nodal cilia and, 279–281
 nodal flow direction determination, 283–285
 nodal flow discovery
 hypothesis testing, 283
 kinesin superfamily proteins and, 281–282
 neurons as a model system, 281
 rotational movement of monocilia, 282–283
 nodal vesicular parcels identification, 287–290
 sequence of axis development, 277–279
 sequence of L/R asymmetric development, 290
 studies of mechanisms for breaking L/R symmetry, 279–281
 two-cilia hypothesis for leftward nodal flow, 286, 287f, 288
 Lethal giant larvae (Lgl), 267
 leucine-rich repeat receptor-like protein (LRR-RLP), 169
 LIT-1, 128

M

MAP2/Tau family of proteins, 223
 MAPKKK signaling pathway, 167, 171
 MAPs (microtubule-associated proteins), 223
 mechanical rigidity
 actin-based motility and, 16
 asters and, 14
 described, 8–9
 mechanics of symmetry breaking
 actin cortex and polarization, 61–63
 build-up and release of tension in actin cortices grown around beads, 64
 comparison of symmetry breaking in cells and around beads, 65–66
 conclusions, 68
 modeling of actin shell growth and rupture around beads, 64–65
 points of symmetry breaking, 67
 process of symmetry breaking, 59–61
 stress-induced polarization in other systems, 67–68
 membrane organization and dynamics in cell polarity
 asymmetric organization of the plasma membrane and, 41–42
 future perspectives, 52–53

- membrane organization and dynamics in cell polarity (*continued*)
- membrane traffic role in cell polarity development
 - membrane trafficking of E-cadherin, 51–52
 - polarization of Cdc42 by membrane traffic in yeast, 50–51
 - regulation of membrane protein transport, 42–43
 - spatial regulation of membrane traffic
 - exocyst function as a tether, 43–44
 - exocytosis, 43
 - phosphoinositides regulation of plasma membrane asymmetry, 47–49
 - Rab GTPases regulation of membrane trafficking, 45–46
 - Rho family function in polarized membrane traffic, 46–47
- meristemoid mother cells (MMCs), 169, 170f
- microtubule-associated proteins (MAPs), 223
- microtubules (MT). *See also* actin network
- in fission yeast, 87, 90–92, 93
 - in symmetry breaking, 94–95
- mid1p, 93
- Miranda, 141
- MMCs (meristemoid mother cells), 169, 170f
- mod5p, 91
- MONOPTEROS (MP), 168
- MreB, 77, 79
- Mud, 145
- MurG, 73
- MUTE, 171–172
- myosin II
 - actin-based motors and, 9
 - architectural heterogeneity and, 11, 18
 - positive feedback and, 18
- Myosin VI (Jaquar), 141
- N**
- nectin, 210–211
- NETO (new end take off), 87, 90–92
- neuronal polarity
 - cerebellar granule neurons model, 218, 219f, 220
 - conclusions, 229
 - cytoskeletons role in
 - actin- and microtubule-based intracellular transport, 223–224
 - actin regulating proteins and, 222
 - growth cone, 220–221
 - microtubule regulating proteins, 222–223
 - reinforcement of neuronal asymmetry, 221
 - external cues initiating polarization, 227–228
 - hippocampal neurons model, 218, 219f
 - intrinsic mechanisms for symmetry breaking, 226–227
 - maintenance of, 228
 - rebreaking of neuronal symmetry, 228
 - signaling pathways regulating
 - GSK-3beta signaling, 224
 - lipid signaling, 224
 - PAR proteins and, 224–225
 - Rho-1 GTPase, 225–226
- neutrophils. *See* chemotactic signals in neutrophils
- new end take off (NETO), 87, 90–92
- nodal flow and symmetry breaking. *See* left–right determination in mammals
- nodal vesicular parcels (NVPs), 287–290
- Notch, 262, 265
- nucleation promoting factor (NPF), 10
- Numb, 140, 141
- O**
- oogenesis. *See Drosophila* oogenesis
- orb kinases, 90
- oskar, 257
- P**
- P0 (*C. elegans* zygote). *See Caenorhabditis elegans*
- PAC-1, 126
- PAK pathway, 225
- Par3/Par6/aPKC module
 - polarity generating mechanisms, 19
 - role in symmetry breaking, 3
- Par-3/Par-6/Pkc-3
 - apical domain in *Drosophila* and, 143
 - apico-basal polarity establishment and, 125–126
 - involvement in cell cortex domains, 264
 - planar cell polarity signaling and, 246
 - polarity signaling through
 - Cdc42 as an upstream regulator, 28–30
 - cross talk between Wnt signaling and Par proteins, 30–31
 - localization of Cdc42-GTP, 29–30
 - phosphoinositides as polarity signals, 33–34
 - Rho GTPases as downstream effectors, 30
 - small GTPases and, 28
 - through protein kinases, 31–33
- PAR complex
 - apical–basal polarity in epithelial cells, 206, 207, 210–211
 - front–rear polarity in epithelial cells, 201
 - neuronal polarity and, 224–225
 - Par-1 and *Drosophila* oogenesis, 267–268

- Par-3 localization control factors in polarity establishment
 active exclusion, 27–28
 anchoring to membrane proteins, 26–27
 localized mRNA translation, 27
 membrane attachment via phospholipids, 25–26
 oligomerization role, 26
 transport and anchoring, 25
- Par proteins as interpreters of cell polarity, 23–24
- par* genes and oogenesis, 267
- Partner of Inscuteable (Pins), 145
- PCP. *See* planar cell polarity (PCP) signaling
- persistence length, 8
- phosphatidylinositides, 200
- phosphoinositides
 as polarity signals, 33–34
 regulation of plasma membrane asymmetry, 47–49
- phosphorylation, 105
- PI(3,4,5)P3
 long-distance stimulation of backness in neutrophils, 192
 neutrophil positive feedback loops and, 187–190
 role in neutrophil chemotaxis, 48, 184, 185–187
- PI3K γ isozyme, 185
- PI3Ks
 neuronal polarity and, 224
 neutrophil positive feedback loops and, 187–190
- Pins (Partner of Inscuteable), 145
- planar cell polarity (PCP) signaling
 asymmetric cellular morphology in neurons, 246–247
 cilia function and, 247–248
 conclusions, 248
 directed cell motility
 cell migration, 243–244
 convergent extension, 242–243
- epithelial planar cell polarity in flies
 communication of polarity information between cells, 238
 core complexes in the eye, 238–239
 core genes and proteins function in the wing, 236–238
 results of mutations in the wing, 236
 symmetry breaking, 239–240
 in vertebrate, 240–242
- function and purpose, 235–236
 oriented or asymmetric cell division, 244–246
- plants. *See* *Arabidopsis thaliana*
- plasma membrane ganglioside sialidase (PMGS), 224
- plasma membrane identity module, 206
- polarity. *See* cell polarity; epithelial cell organization; epithelial planar cell polarity in flies; neuronal polarity; planar cell polarity signaling; polarity establishment through signaling pathways
- polarity establishment through signaling pathways
 components required, 24
 conclusions, 34–35
- Par-3 localization control factors
 active exclusion, 27–28
 anchoring to membrane proteins, 26–27
 localized mRNA translation, 27
 membrane attachment via phospholipids, 25–26
 oligomerization role, 26
 transport and anchoring, 25
- Par proteins as interpreters of cell polarity, 23–24
- signaling through Par-3/Par-6/aPKC
 Cdc42 as an upstream regulator, 28–30
 cross talk between Wnt signaling and Par proteins, 30–31
 localization of Cdc42-GTP, 29–30
 phosphoinositides as polarity signals, 33–34
 Rho GTPases as downstream effectors, 30
 small GTPases and, 28
 through protein kinases, 31–33
- polar relaxation in budding yeast, 123
- pom1p kinase, 94
- POP-1 and binary specification, 127–128
- positive feedback
 actin-based motility and, 16
 asters and, 14
 chemotactic signals in neutrophils and, 187–190
 described, 9–10, 95
 intrinsic mechanisms for symmetry breaking in *S. cerevisiae*, 101–103
 myosin II and, 18
 in neuronal polarity, 227
- Prickle (Pk), 236–238, 241
- primary cilium module, 207
- profilin, 222
- Prominin-1, 158–159
- Prospero (Pros), 140, 141
- PTEN, 33–34, 48, 186
- ## R
- RA (retinoic acid), 288
- Rab GTPases, 45–46
- RacA, 79–80
- Rac-GTP
 front–rear polarity in epithelial cells, 201
 neuronal polarity and, 225
 neutrophil positive feedback loops and, 187–190

- ras1p, 89
 recycling endosome, 42
 retinoic acid (RA), 288
 Rho, 247
 Rho-1 GTPase, 29
 - apical domain in *Drosophila* and, 143–144
 - cell polarity in budding yeast and, 122
 - front–rear polarity in epithelial cells, 200–202
 - function in polarized membrane traffic, 46–47
 - mechanisms for polarizing cells and, 101–103
 - neuronal polarity and, 224, 225–226
 - neutrophil positive feedback loops and, 188
 - polarized epithelial cells role, 206–207
- RhoA, 245
- Rho-kinase (ROCK), 225, 245
- Ror, 245
- Rsr, 105
- Rsr1 GTPase module
 - relationship to bud site markers in yeast, 107–109
 - in yeast bud site selection, 106–107
- S**
- Saccharomyces cerevisiae*
 - asymmetry relevant to the physiology of the population, 111–112
 - bud establishment by Cdc42-GTPases, 28–29
 - exocyst complex and, 43–44
 - intrinsic mechanisms for symmetry breaking
 - breaking symmetry without actin, 103–104
 - existence of two mechanisms for, 105
 - GEF regulation in, 104–105
 - via an Actin and a positive feedback loop, 101–103
 - overview of cell polarity in yeast, 99–101
 - polarization of Cdc42 by membrane traffic in, 50–51
 - spatial cue-directed symmetry breaking
 - polarity during mating, 109–111
 - Rsr1 GTPase module in bud site selection, 106–107
 - Rsr1 GTPase module relationship to site markers, 107–109
 - summary and perspective, 112
- SCARECROW (SCR), 173, 174
- scd1-cdc42p pathway, 89
- Schizosaccharomyces pombe*
 - basic concepts of symmetry breaking, 94–95
 - cell cycle regulation from cell tips, 94
 - defining the cell middle, 93–94
 - fission yeast primer, 86–88
 - mechanisms that regulate polarization site positioning, 92–93
 - microtubules, tea system, and NETO, 90–92
 - overview of spatial regulation in, 85–86
 - polarity initiation at an ectopic site, 92
 - regulatory modules controlling cell polarity in, 88–90
 - use as a genetically tractable model for morphogenesis, 88
- SCREAM (SCRM), 172
- Scribble
 - apical–basal polarity in epithelial cells, 206, 208
 - front–rear polarity in epithelial cells, 201
- SDD1 (STOMATAL DENSITY AND DISTRIBUTION1), 171
- Sec3, 44
- sensory organ precursor (SOP), 245
- SHH (sonic hedgehog), 288
- Shigella flexneri* IcsA, 75
- SHORT-ROOT (SHR), 173, 174, 176
- Short Stop (Shot), 260
- SNARE, 41, 205
- sonic hedgehog (SHH), 288
- SPEECHLESS (SPCH), 171–172
- spindles, 14–15
- SpoIIIAH, 76, 77f
- Stardust, 27
- stem cell
 - asymmetric division in *Drosophila*
 - (see asymmetric stem cell division in *Drosophila*)
 - niche, 149–150
- STOMATAL DENSITY AND DISTRIBUTION1 (SDD1), 171
- Streptococcus pyogenes*, 76
- symmetry breaking
 - basic concepts, 1, 3–4, 94–95
 - cell polarity and, 3–4
 - cytoskeleton mechanisms for (see cytoskeletal mechanisms for symmetry breaking)
 - large and small-scale asymmetry in biology, 2
 - mechanics of (see mechanics of symmetry breaking)
 - model systems for studying, 2–3
 - results of in biology, 1–2
- SYS-1, 128
- T**
- tea system in fission yeast, 90–92
- Thompson, D'Arcy, 4
- TIAM1, 207
- TipN, 75
- Too Many Mouths (TMM), 169, 171

trans-Golgi complex (TGN), 197–198, 205
 two-cilia hypothesis for leftward nodal flow,
 286, 287f, 288

U

Unpaired (Upd), 151, 262

V

Van Gogh (Vang), 236–238, 241, 245
 vertebrates

Drosophila-like stem cells in
 mammalian neuroepithelial cells, 157–159
 mammalian skin stem cells, 159
 parallels between mammalian and *Drosophila*
 stem cells, 159
 polar cell polarity and ear and hair development,
 240–242

W

Warts, 208–209
 WASP, 225
 WAVE, 222, 225

Wingless (Wg), 239–240

Wnt signaling

binary specification and, 130
 in *C. elegans*, 127, 128, 129, 245
 PCP in vertebrates and, 241, 243,
 244, 245

polarity signaling and, 30–31

WOX proteins, 175

WRM-1, 128

WUS-RELATED HOMEBOX, 167–168

X

Xenopus, 15, 242

Y

yeast, budding. See *Saccharomyces cerevisiae*
 yeast, fission. See *Schizosaccharomyces pombe*
 YODA (YDA), 167, 171

Z

zebrafish, 242

Zfh-1, 152