

Index

- accounting identity 181, 261
- aging population 229–30, 239
- agricultural labor, monetization 228
- agricultural mechanization 18, 101
- agricultural productivity decline 154–5
- agriculture 52, 65, 67–70, 265
- air conditioning 118, 120–21, 122
- aircraft 33, 39, 109, 111
- AK approach 163, 259, 261
- aluminum 113, 114, 119
- ammonia 23, 70, 79, 115, 116
- animal feed 69, 85, 86, 87, 92, 97, 314
- animal/human muscle work 89, 90, 92, 97–8, 101, 232, 265
- Arrow, Kenneth J. 15, 49, 143, 148, 163, 178
- Arthur, W. Brian 19, 211
- augmentation 6, 160–61, 255
- automation 146, 147, 148, 190, 234, 256, 265
- automobiles 34–6, 38, 106, 108, 109–11, 123, 124, 125–6, 199
- Ayres, Leslie W. 24, 78
- Ayres, Robert U. 11, 12, 24, 39, 45, 49, 63, 64, 78, 106, 113, 118, 120, 121, 122, 126, 137, 142, 147, 168, 170, 171, 197, 198, 200, 234, 235, 253, 262, 263, 293

- barriers to technological progress 17, 26, 34–9, 43–4, 58
- Barro, Robert J. 160, 161, 162, 164, 255, 257
- biology 12, 15, 42, 166, 167
- biomass
 - and conservation of mass 65
 - and exergy 72, 73, 76, 79, 168
 - and exergy/GDP 83
 - Japanese data 333
 - mass as a measure 77
 - and mass flows 71, 72, 73, 76
 - and mass/GDP 83
 - and production function estimation for US and Japan 199
 - and REXSF model of the US economy 240, 242, 246
 - US data 327
 - and useful work 126, 131, 265, 315
- borrowing 229–30, 302, 308
- breakthroughs 11, 17, 26–7, 34–9, 42–3, 44, 54, 58
- buses 123, 125
- business cycles 7, 144–5, 175

- CAFÉ standards 109, 111, 124, 126, 234
- calculus of variations 3–4
- calories 79, 97
- Cambridge controversy 177, 180, 305
- capital
 - concept 304–6
 - and disequilibrium paradigm 10–11, 25
 - and economic development theory 254–5, 256
 - and economic growth 253
 - and endogenous growth theories 163, 164
 - and exergy 151–2, 153
 - and factor share theorem 152, 153
 - and input-output models 157, 158
 - and integrated assessment (IA) models 225
 - Japanese data 329, 339–43
 - and neoclassical paradigm 2, 4–5, 141, 149, 150, 159, 311–12
 - and production functions 175, 176–7, 178–9, 180, 181, 182, 183, 187
 - Cobb-Douglas production function 184–6, 187, 189
 - LINEX production function 190–91, 192–3, 194, 295, 296

- production function estimation
 - for US and Japan 197, 201, 204, 210, 211, 212, 213, 214–16, 217, 219, 220
- and Ramsey theory of optimal growth 3, 145, 147
- and REXSF model of the US economy 237, 238–40, 242
- and REXSF simplified model 264
- and Solow-Swan model of economic growth 5, 6, 7, 148, 149, 150, 159–61, 162, 183, 233, 253
- 'stylized facts' about economic growth 257
- US data 318, 334–8
- and wealth 62
- capital-GDP ratio 257
- capital-labor ratio 4, 5, 257
- capital payments 210
- carbon dioxide 68, 69, 70, 78, 79, 141, 142, 297
- carbon efficiency 112–13
- Casten, Thomas R. 19–20, 213, 235
- catch-up countries, REXSF simplified model *see* REXSF simplified model
- catch-up elasticity 288–91, 293
- causality, and production function estimation for US and Japan 204–5, 214–16
- cement production 113, 114
- central heating 117–18
- central planning 4, 8, 143, 254
- CES (constant elasticity of substitution) function 178, 179
- chemical industry 39, 112, 115, 116, 120
- chemical work 89, 90, 91, 92
- chemicals
 - and exergy 72, 73, 74, 76, 77, 79
 - and exergy/GDP 81, 83
 - and mass flows 70, 71, 72, 73, 74, 76, 77
 - and mass/GDP 81, 83, 84
 - structural properties 53
 - technology 52
- chemistry 39
- chronometers 16, 31–2, 39
- climate change 141–2, 154–5, 225, 253, 309
- see also* greenhouse gases
- closed dynamic production-consumption systems 138
- closed static production-consumption systems 138, 143–4
- coal
 - exergy and useful work in US and Japan 92, 93, 98
 - exergy inputs for Japan 86, 87
 - exergy inputs for US 85, 86
 - and exergy-to-work efficiency improvements since 1900 104, 105, 115, 116, 117–18
 - Japanese data 330
 - and secondary work exergy efficiency 125
 - and technological progress 233–4
 - US data 319–21
- Cobb-Douglas production function and complementarity 179
- and energy 151
- and exergy 184–9
- and integrated assessment (IA) models 225
- and neoclassical paradigm 162
- production function estimation for US and Japan 187, 189, 202, 203, 205–6, 207, 208–9, 210, 211, 216, 219, 220
- and Solow-Swan model of economic growth 5–6, 7, 148–9, 159
- and substitutability 178, 179, 180
- and time factors 179
- and time series data 181
- cointegration 175, 204–5, 214–16
- coke 37, 112, 113, 117–18, 234, 320, 321, 330
- Collins, Martin J. 19–20, 213
- combined heat and power 234–5, 236, 250
- combustion 52, 64, 67, 69, 70, 72, 78–9, 265, 298
- commercial and residential sectors 105–6, 107, 112, 117, 118, 120–21, 199–200
- competitiveness 20, 45, 166
- complementarity 179, 219, 295
- compression ignition engines 38, 52, 90, 106, 108, 109, 111
- concentration and conversion 68, 69–70, 71, 168, 169

- conservation of mass
 described 64, 169–70
 mass-balance principle 62–3, 65,
 67–9, 169–70
 materials processor model 168–9,
 169, 262
 and neoclassical paradigm 140, 141,
 144, 261
 and production functions 182
 constant returns to scale *see* Euler
 condition
 constant savings rate 181
 ‘constrained growth’ law 12
 construction materials 71, 72, 73, 75,
 76, 82, 83, 84
 consumer credit 229, 230, 302
 consumption
 and disequilibrium paradigm 10
 and endogenous growth theories 163
 and materials processor model 168,
 169
 and neoclassical paradigm 1, 2, 9,
 141
 and non-sustainability 135–6
 and optimal extraction of
 exhaustible resources 4
 and positive feedback 163, 232
 and production function estimation
 for US and Japan 214
 and Ramsey theory of optimal
 growth 3, 145
 and recession 144
 and risks of blind extrapolation 227,
 229
 and wealth 62
 and welfare 62
see also electricity consumption;
 energy consumption; natural
 resource consumption;
 petroleum and oil consumption;
 production-consumption
 systems; resource consumption
 convergence theories 160, 255, 257
 conversion and concentration 68,
 69–70, 71, 168, 169
 costs
 automation 146, 147
 and factor share theorem 152
 and integrated assessment (IA)
 models 225
 and neoclassical paradigm 140,
 311–12
 and physical limit barriers 57
 pollution 141, 142
 and positive feedback 9, 163, 233,
 234
 useful work 193, 234–6
 waste flows 63, 141, 144, 170
see also energy costs; extraction and
 harvesting costs; labor costs;
 production cost reductions
 covariance stationarity, and production
 function estimation for US and
 Japan 201–2, 204
 creative destruction 11, 41, 42, 164, 259
 credit 229, 230, 302
 crisis-driven radical innovation 31–9,
 42–5, 57
 cultural knowledge 47–8
 Daly, Herman E. 136, 142, 304
 debt 308
 decentralized combined heat and
 power (DCHP) 235, 236
 deficit spending 144, 145, 227
 Delphi Forecasting 222, 223, 224
 demand
 and crisis-driven radical innovation
 34, 35, 57
 and disequilibrium paradigm 25–6,
 35, 55, 57–8
 and neoclassical paradigm 1, 2, 24,
 54, 55, 233
 and positive feedback 9, 233, 234
 and Solow-Swan model of economic
 growth 7
 dematerialization 53, 63, 84–5, 170,
 242, 246
 depreciation 5, 141, 145, 225, 238–40
 developing countries 252, 263
see also poor countries
 DICE model 225
 Dickey-Fuller statistic, and production
 function estimation for US and
 Japan 201, 210
 diesel and diesel-electric locomotives
 38, 102, 104, 105, 125
 diesel engines *see* compression ignition
 engines
 direct heat 111–18

- discontinuity hypothesis of
 technological progress 39–42
- discounting 3, 4, 135, 136, 225–6
- disequilibrium paradigm 10–12, 25–6,
 55–6, 57–9
- disutility 1, 3
- diversity, and evolutionary theories 167
- domestic labor, monetization 228
- Durbin-Watson statistic, and
 production function estimation
 for US and Japan 202, 203, 210
- dynamic economic growth theories
 144–5
- economic activity 134–5, 303
see also GDP
- economic change 175, 181, 186, 201–2
- economic development theory 162–5,
 254–5, 262–3
- economic discontinuities 41
- economic efficiency 299
- economic growth
 explained ‘stylized facts’ in standard
 theories 258–9
 factors assisting economic growth
 257, 263, 266
 factors preventing economic growth
 263, 266, 271, 292
 ‘stylized facts’ 256–8
 unexplained ‘stylized facts’ in
 standard theories 260–62
- economic growth forecasting 51–4,
 252–3
see also extrapolation in economic
 growth forecasting; REXSF
 model of the US economy;
 REXSF simplified model
- economic value 45, 46, 47, 48, 49–50
- economies of scale
 and disequilibrium paradigm 11,
 12, 25
 and electricity prices 232
 and lock-in 19, 20
 and neoclassical theory of growth
 9, 10
 and positive feedback 9, 11, 163,
 233
 and REXSF model of the US
 economy 249–50
see also Euler condition
- education and training 6, 160, 164,
 255, 302, 305, 307
- efficiency *see* carbon efficiency;
 economic efficiency; energy
 efficiency; exergy-to-work
 efficiency improvements since
 1900; first-law efficiency; fuel
 efficiency; inefficiency; payload
 efficiency; petroleum efficiency;
 second-law efficiency; technical
 efficiency; technological efficiency;
 thermodynamic efficiency
- efficient technologies 250
see also combined heat and power;
 insulation
- elasticities of exergy services 154
- elasticities of output
 and neoclassical paradigm 311–12
 and production functions 178, 181
 Cobb-Douglas production
 function 184–7, 220
 LINEX production function 190
 production function estimation
 for US and Japan 208–9,
 210–13, 216, 217–18, 220
 and Solow-Swan model of economic
 growth 183, 217
- elasticities of useful work 154, 210,
 216
- electric lighting 31, 121, 122, 123
- electric motors 51, 52, 103–4, 120, 122,
 123
- electric pumps 120, 122
- electrical appliances 105–6, 120, 122
- electricity
 costs 147, 148
 and exergy-to-work efficiency
 improvements since 1900
 103–6, 107, 113, 114, 115, 117,
 126, 127, 128
 and exergy-to-work efficiencies 199
 and materials life-cycle 67
 secondary work exergy efficiency
 119–22, 123, 126, 127, 128
 and useful work 89, 90–91, 92, 93–6,
 126, 127, 128, 232
- electricity consumption 120, 264,
 265–6, 291–2, 344–8
see also EP (energy proxy)
- electricity generation 234–5

- electricity prices 105–6, 121, 193, 232, 236
- electrolytic reduction 52, 119
- electronics 39, 52, 53, 122, 123
- embodied information 69
- employment 144–5
see also labor
- endogenous growth theories 48–9, 55–6, 162–5, 211, 213, 255, 258, 259, 260
- energy
 and Cobb-Douglas production function 151
 defined 151
 and disequilibrium paradigm 10
 and extrapolation in economic growth forecasting 233–4, 252
 and factor payments 151, 152, 154
 importance in economic growth 252–3
 and input-output models 157, 158
 and neoclassical paradigm 2, 9, 140, 141, 261
 and positive feedback 233–4
 and production function estimation for US and Japan 197, 198, 204, 213, 214, 219
 and production functions 175
 and Solow-Swan model of economic growth 10, 233
- energy consumption 204, 213, 214, 219, 297
- energy costs 249–50, 253, 297
- energy crisis 23–4, 40, 150, 175, 199, 213
- energy demand 297
- energy efficiency 296–7
- energy flows 168, 169, 182, 183
- energy intensity, and integrated assessment (IA) models 225
- energy prices 218–19, 256, 258
see also electricity prices; gas prices; petroleum and oil prices
- energy quality 141
- energy scarcity and depletion 231–2
see also natural gas scarcity and depletion; petroleum and oil scarcity and depletion
- energy services 152, 157, 158–9
- engines 33, 34–6, 37–8, 53, 91, 148
see also compression ignition engines; factory engines; internal combustion engines (ICEs); prime movers; railway engines; spark ignition engines; steam engines
- entropy law
 described 136–7
 and economic models 137–9
 and exergy 136, 137, 139, 141
 and materials processor model 69, 169
 and neoclassical paradigm 140, 144
 and production functions 182
 and resource scarcity 170–72
 and useful work 91
 and wastes 168, 169, 170, 171
- environmental economics 140, 142
- environmental harm 68, 69, 137, 307
- EP (energy proxy) 266–71, 273–4, 275, 276–7, 278, 279–88, 289–91, 292, 293
- equilibrium
 critique 135–6
 and exergy 78, 136, 137
 and neoclassical paradigm 1, 2, 8, 9, 10, 24, 54–5, 152, 159, 261, 311–12
 and optimal extraction of exhaustible resources 4
 and production function estimation for US and Japan 211, 213, 214
 and Solow-Swan model of economic growth 149, 152, 159, 161
 and Walrasian economics 1, 2, 10, 143
- essentiality *see* non-substitutability
- Euler condition
 and neoclassical paradigm 5, 149, 152, 161–2
 and production functions 175, 181, 183–4
 Cobb-Douglas production functions 184–5, 186, 187
 LINEX production function 190, 192, 194
 production function estimation for US and Japan 209, 211, 213

- and Solow-Swan model of economic growth 5, 149, 152, 161–2
- Euler-Lagrange equations 3, 4, 146
- evolutionary theories 11, 42, 166–8, 183, 259
- exergy
 - and capital 151–2, 153
 - defined 78–9, 141
 - and energy quality 141
 - and entropy law 136, 137, 139, 141
 - and equilibrium 78, 136, 137
 - Japanese data 339–43
 - and labor 151, 153
 - and materials life-cycle 67
 - and materials processor model 168, 169
 - as a measure of materials 78–80
 - and neoclassical paradigm 141
 - and optimal control theories 147
 - and production functions 183, 218
 - Cobb-Douglas production function 184–9
 - LINEX production function 190–92, 194
 - production function estimation for US and Japan 197, 198–9, 201, 204, 207, 214–16, 217–19
 - and REXSF model of the US economy 240–45, 246–7, 248–9, 250
 - US data 334–8
 - and useful work 78–80, 89, 92, 93–6, 141
 - and wastes 141, 170
- exergy/capital ratio, and REXSF model of the US economy 240–41
- exergy flows 72, 73–6
- exergy/GDP ratio 80–85, 198, 240, 241–3, 246–7, 248, 249
- exergy inputs 85, 86, 87
- exergy/mass ratio 80–85
- exergy services 90, 154, 168, 258
 - see also* final and finished goods; useful work
- exergy-to-work efficiencies 199–200
- exergy-to-work efficiency
 - improvements since 1900
 - direct heat and quasi-work 111–18
 - prime movers 101–11
- exhaustible resources 4, 21–4
- exogenous processes, and neoclassical theory of growth 6, 8, 9, 24, 50, 150, 159, 183
- exogenous variables, and production functions 176
- experience *see* ‘experience curve’; learning-by-doing; production experience; skills
- ‘experience curve’ 12–15, 20, 31
- exponential trends 224, 252
- exports 68, 207
 - see also* petroleum and oil exporting countries; trade
- externalities 64, 134, 163, 170
 - see also* pollution and harmful wastes; spillovers; wastes
- extraction and harvesting
 - and conservation of mass 62–3, 64–5
 - and disequilibrium paradigm 10
 - and mass flows 68, 69, 70, 71, 72
 - and materials life-cycle 65, 66
 - and materials processor model 168, 169, 262
 - and Solow-Swan model of economic growth 150
- extraction and harvesting costs 4
- extrapolation, concept 223–4
- extrapolation in economic growth forecasting
 - in integrated assessment (IA) models 224–6
 - problem of recursion 236–7
 - risks of blind extrapolation 226–32, 252
 - technological progress 233–6, 252
- factor accumulation 255, 256, 257, 260
- factor payments 5–6, 151, 152, 154, 161, 185, 187, 210, 220
- factor share theorem 152–3, 161, 311–12
- factory engines 102–4
- feedback 182
 - see also* positive feedback
- Fel’dman, G.A. 143, 254
- Felipe, Jesus 176, 181
- final and finished goods 68, 71, 72, 168, 169
- final demand 156, 157, 158

- first-law efficiency 114, 117
 Fisher, Franklin M. 176, 181
 food 68, 69, 85, 86, 87, 92, 97, 314–15
 food shortages 23
 forecasting 42–3, 44, 222–4
 see also economic growth
 forecasting; extrapolation in
 economic growth forecasting
 forest and forestry 52, 68, 69, 70, 307,
 333
 formal knowledge 45–6, 47
 fossil fuels
 and exergy and useful work in US
 and Japan 92, 93–6, 98–101,
 128
 and exergy consumption 72, 73, 74,
 76
 and exergy/GDP 80–81, 83, 84
 mass as a measure 77
 and mass flows 69, 72, 73, 74, 76
 and mass/GDP 80–81, 83, 84
 and non-sustainability 135–6
 and production functions 182, 199
 see also coal; natural gas; petroleum
 and oil
 free markets 24, 54–5, 56
 free trade 226–7, 228
 fuel efficiency 124, 125–6, 235
 fuels
 and economic development theory
 256
 and exergy 78, 79
 and mass flows 68, 69, 70, 71, 72
 and materials life-cycle 67
 and REXSF model of the US
 economy 240, 246, 247, 249
 see also coal; coke; fossil fuels;
 fuelwood; gas; gasoline;
 kerosine; petroleum and oil
 fuelwood 98, 327, 333
 functionality 31, 57, 58
 fungibility 45, 48–9, 258, 261
 see also non-fungibility
 future planning, theories of Pigou 3,
 136, 145
 future utility 140, 225–6
 gas 38, 117, 118
 see also gas prices; gas turbines;
 natural gas; NGL
 gas prices 119–20
 gas turbines 31, 90, 111, 114, 148
 gasoline 34–6, 99, 100, 331
 gasoline engines *see* spark ignition
 engines
 Gaussian probability distribution
 functions, and REXSF model of
 the US economy 245–6
 GDP
 concept 134–5, 303–4, 308, 309
 and conservation of mass 65
 and factor share theorem 152, 153
 growth rates in REXSF model of the
 US economy 245–50
 and integrated assessment (IA)
 models 225, 226
 Japanese data 329, 339–43
 and production functions 175
 Cobb-Douglas production
 function 184–7, 189
 LINEX production function 190,
 191, 192–3, 194
 production function estimation
 for US and Japan 201, 204,
 205–10, 214–16, 217–18
 and Ramsey theory of optimal
 growth 145
 and Solow-Swan model of economic
 growth 5, 6, 148, 149, 162
 ‘stylized facts’ about economic
 growth 256, 257, 258–9
 and substitutability 154–5
 US data 318, 334–8
 GDP fraction, and REXSF simplified
 model 264, 266, 267, 268–71,
 272–4, 276–7, 278, 279, 282, 283,
 284, 285, 286–8, 289, 290, 291,
 292, 293, 344–5
 GDP per capita
 and capital 306–8
 and REXSF simplified model 264,
 275, 278–9, 280, 281, 288, 289,
 290–91, 292, 293
 and Solow-Swan model of economic
 growth 6, 253
 ‘stylized facts’ about economic
 growth 256, 257
 generators 91, 103–4
 geo-political power shifts 34, 40, 58,
 175

- geographic latitude, and REXSF
 simplified model 268, 270, 271–2,
 273, 274, 288, 292
- Georgescu-Roegen, Nicholas 2, 9, 69,
 136, 139, 142, 171
- glass 70, 71, 72
- globalization 226–7, 228
- goods
 input-output models 157, 158
 materials processor model 168, 169
 in neoclassical paradigm 1, 2, 24, 54,
 149–50, 233
see also final and finished goods;
 information products and
 services; intermediate products;
 material goods; material goods'
 flows; non-rival goods; paper
 products; single all-purpose
 products; useful products; wood
 products
- gradual incremental (Usherian)
 improvements 9, 10, 17, 26, 31, 45,
 56, 58, 258, 260–61
- Granger-causation, and production
 function estimation for US and
 Japan 205, 214–16
- greenhouse gases 70, 72, 141, 142, 218,
 219, 232, 252, 297
- Guyol, Nathaniel B. 89
- Hamilton, James Douglas 145, 146,
 204, 217–18
- harmful wastes *see* pollution and
 harmful wastes
- Harrod-Domar growth models 4, 143,
 144, 163, 254
- HDPE 115, 116
- health and safety 36, 43
- heat
 and exergy 78–9
 and mass flows 69
 and materials life-cycle 67
 thermodynamic efficiency 298
 and useful work 89–90, 92, 93–6,
 98–101, 127, 232, 265
- Helmer, Olaf 222
- high entropy wastes 168, 169, 171,
 182
- high temperatures 112–17, 122, 123,
 127, 128, 298
- homogeneity 45, 48–9, 259, 261
see also inhomogeneity
- horsepower 90, 92, 101, 102
- Hotelling, H. 4, 23
- human/animal muscle work 89, 90, 92,
 97, 145, 232, 265, 315
- human capital 25, 55, 163, 258, 259,
 302, 305–6, 307, 308
- hydro-electric power 103, 104, 126,
 128, 199, 232, 333
- hydro-electricity producing countries,
 and REXSF simplified model
 267–8, 270, 272, 273, 274, 288,
 292
- incentives to innovate 8, 11, 25, 26, 46
- income allocation theorem 185, 311–12
- income redistribution 229
- incremental (Usherian) improvements
 9, 10, 17, 26, 31, 45, 56, 58, 258,
 260–61
- induced innovation 17–18, 21–4, 26
- industrialized countries *see* rich
 countries
- inefficiency 63
- inertia 178, 224
- informal economy 134
- informal knowledge 47
- information and communications
 technology (ICT) 36, 207, 226,
 227, 235–6, 247, 299
- information flows 182
- information products and services 168,
 235–6
- inhomogeneity 11, 45, 55–6, 258, 261
see also homogeneity
- innovation 8, 11, 159, 164, 165, 167–8,
 169, 305, 306
see also breakthroughs; creative
 destruction; crisis-driven radical
 innovation; gradual incremental
 (Usherian) improvements;
 incentives to innovate;
 induced innovation; radical
 (Schumpeterian) innovation;
 R&D
- input-output models 156–9, 182, 183,
 218, 295
- inputs, and conservation of mass 65
- insulation 118, 121, 298

- integrated assessment (IA) models, and extrapolation 224–6
- intellectual property rights 46, 305
- intermediate products 70, 71, 182, 191, 192, 194
- intermediate temperatures 112, 117–18, 127, 128
- internal combustion engines (ICEs) 31, 37–8, 90, 106, 108–11, 232, 235
- investment *see* savings and investment
- iron industry 112–13, 114, 116, 234
- Japan
 data 314–15, 328–33, 339–43
 exergy inputs 86, 87
 fossil fuel exergy and useful work 92, 93–6, 98
 GDP and factors of production 187, 188
 heat as useful work 93–6, 99
 prime movers as useful work 93–6, 98, 104
 production function estimation *see* production function estimation for US and Japan
 total useful work 126, 128–31
- Jorgenson, Dale W. 150–51, 152, 154
- kerosine 21–2, 31, 98, 331
- Keynes, John Maynard 3, 144–5, 296
- Keynes-Ramsey rule 3
- Klein, Lawrence R. 176
- KLEM (capital, labor, energy, materials) 150–51
- Kneese, Allen V. 24, 63, 64, 137, 170, 171, 262
- know-how *see* ‘experience curve’;
 learning-by-doing; skills
- knowledge
 and disequilibrium paradigm 55–6
 and economic development theory 254, 255
 and endogenous growth theories 48–9, 55–6, 163, 164, 165, 259
 homogeneity and fungibility 45, 48–9, 261
 inhomogeneity and non-fungibility 45, 55–6
 and neoclassical paradigm 25, 55
 as non-rival goods 46
see also cultural knowledge;
 education and training;
 formal knowledge; informal
 knowledge; information flows;
 knowledge accumulation;
 knowledge capital; knowledge
 transfer; monopoly knowledge;
 skills; social knowledge;
 technological knowledge
- knowledge accumulation 47, 49–51
- knowledge capital 25, 305
- knowledge transfer 45–8
- Koopmans, Tjalling C. 2, 7, 8, 64, 143
- Krugman, Paul R. 1
- Kümmel, Reiner 177, 187, 190–91, 194, 206
- labor
 and disequilibrium paradigm 10–11, 25
 and economic development theory 255, 256
 and endogenous growth theories 164
 and exergy 151, 153
 and factor share theorem 152, 153
 and input-output models 157, 158
 and integrated assessment (IA) models 225
- Japanese data 329, 339–43
- monetization of domestic and agricultural labor 228
- and neoclassical paradigm 2, 24, 141, 149, 159, 311–12
- and production functions 175, 179, 180, 181, 182, 183
- Cobb-Douglas production function 184–6, 187, 189
- LINEX production function 190, 191, 192–3, 194, 295, 296
- production function estimation for US and Japan 197, 204, 208–9, 210–11, 212, 214–16, 217, 219, 220
- and Ramsey theory of optimal growth 3
- and REXSF model of the US economy 237–8, 239, 242
- and REXSF simplified model 264

- and Solow-Swan model of economic growth 5, 6, 7, 148, 149, 159, 160–61, 183, 233, 253
- specialization 228–9
- ‘stylized facts’ about economic growth 257
- US data 318, 334–8
- labor costs 1, 2, 5, 12, 24, 25, 54, 55
- labor payments, and production function estimation for US and Japan 210
- labor productivity 219, 226, 255, 257
- labor shortages 17–18
- land 21, 306–7
- large economies 161
- ‘laws’ of progress 12–16
- learning-by-doing 9, 10, 11, 12–15, 20, 31, 49, 163, 178, 233
 - see also* ‘experience curve’;
 - production experience; skills
- Leontief, Wassily W. 156–7, 176, 182, 295
- Leontief function 179, 180, 219–20, 295
- Lewis, W. Arthur 143, 254
- life-cycle model of technology 20
- lighting 16, 21–2, 31, 93–6, 98, 128
- LINEX production function
 - complementarity and substitutability 219, 295
 - and exergy 190–92, 194
 - and production function estimation for US and Japan 202, 203, 205, 206–7, 208, 209–10, 211, 212, 216, 219–20
 - and REXSF model of the US economy 237, 242, 247
 - and useful work 191–5, 295–6
- lock-out and lock-in 19–20, 135–6
- logistics function 15–16
- long-term economic behavior 175, 179
- long-term economic growth 12, 27, 187
- low entropy resources 168, 171, 182
- low temperatures 112, 117, 118, 122, 123, 127, 128
- Lucas, Robert E. Jr. 163, 255, 259
- machines 53, 182, 234
 - see also* agricultural mechanization; automation
- macroeconomic changes 17–19, 226–7
- macroeconomic level 5, 25, 55, 57, 159
- Maddison, Angus 177, 180, 197, 239, 264, 304
- Malthus, Thomas Robert 21, 23, 171–2
- man-made capital 213, 306, 307, 309
- man-made discontinuities 41
- Mankiw, N. Gregory 2, 149, 156, 161, 255
- manufacturing 66, 67
- manure 68, 69
- marginal disutility 1, 3
- marginal productivities 5, 6, 149, 161, 183, 184–5, 186, 187, 210–11
- marginal utility 1, 3
- market prices 69, 193
- markets 2, 24, 43, 54–5, 56
- Martinás, Katalin 12, 49, 137
- mass 77–8
 - see also* conservation of mass; mass-balance principle; mass/exergy ratio; mass flows
- mass-balance principle 62–3, 65, 67–9, 169–70
- mass/exergy ratio 80–85
- mass flows 67–77
- material flows 62–3, 168–9, 182, 262
- material goods 65
- material goods’ flows 62–3
- materials
 - and disequilibrium paradigm 10
 - mass as a measure 77–8
 - and neoclassical paradigm 2, 9, 140, 149, 261
 - and production-consumption system 137–8
 - and Solow-Swan model of economic growth 10, 161, 233
 - structural properties 53–4
 - see also* concentration and conversion; extraction and harvesting; material flows; material goods; material goods’ flows; materials life-cycle; materials processor model; raw materials; resources
- materials life-cycle 63, 65–77, 182
- materials processor model 168–9, 262
- Meadows, Dennis L. 23, 309

- mechanical power 67, 90, 91, 92, 127, 147, 148, 265
see also animal/human muscle work; heat; prime movers
- medicine 36, 43
- metal cutting/drilling/grinding 120, 122
- metallurgy 37
- metals
 and conservation of mass 65
 and exergy consumption 72, 73, 75, 76
 and exergy/GDP 82, 83, 84
 mass as a measure 77
 and mass flows 68, 70, 71, 72, 73, 75, 76
 and mass/GDP 82, 83, 84
 and materials life-cycle 67
 structural properties 53
 technology 52
- micro-scale problem solving 16–17
- microeconomic level 5, 8, 18, 25, 55, 57, 159, 176, 183
- military 26, 31–3, 34, 58, 303, 305
see also wars
- minerals 68, 71–2
- Mirowski, Philip 141
- monetary flows 176–7, 180, 182
- monetization of domestic and agricultural labor 228
- monetization of unearned future wages 229–30, 302
- money 169, 260, 303, 304
- monopoly knowledge 26, 163
- monopoly profits 46
- Moroney, John R. 217
- motive power 90, 91, 232, 265
- motor vehicles 71, 99, 106, 108–11, 123–4, 125–6
see also automobiles; buses; trucks
- Mulder, Peter 257, 258–9, 260
- multi-collinearity, and production function estimation for US and Japan 202–3
- multi-sector economies 152, 153–6, 169, 182, 183–4
- multipliers
 and input-output models 158–9
 and optimal control theories 146
 and Solow-Swan model of economic growth 5, 6, 148, 149, 150, 253
- muscle work 89, 90, 92, 97–8, 232, 265, 315
- myopia in future planning 3, 136, 145
- natural capital 299, 306–8, 309
- natural capital scarcity and depletion 213, 307
- natural events 40–41, 175, 303
- natural gas
 and exergy and useful work in US and Japan 92, 95, 98
 and exergy inputs for Japan 86, 87
 and exergy inputs for US 85, 86
 and exergy-to-work efficiency improvements since 1900 112, 115, 116
 Japanese data 333
 US data 324–6
see also NGL
- natural gas scarcity and depletion 231, 232
- natural resource consumption 256, 258
- natural resource prices 231–2
- natural resource scarcity and depletion 18, 21–4, 231–2, 303, 307
- natural resources 24, 152, 153, 175, 180
see also natural capital
- needs 17, 26, 31–3, 34, 56, 58
see also crisis-driven radical innovation; induced innovation
- negative externalities 134
see also pollution and harmful wastes; wastes
- Nelson, Richard R. 11, 42, 166, 167–8, 178, 179, 259
- neoclassical paradigm
 and conservation of mass 140, 141, 144, 261
 critiques 2–3, 8–10, 159–61
 thermodynamic critique 139–42, 144
 and energy 2, 9, 141, 261
 and equilibrium 1, 2, 8, 9, 10, 24, 54–5, 152, 159, 261, 311–12
 and materials 2, 9, 140, 149, 261
 optimal growth theories, recent formulations 7–8
 overview 1–3, 24, 54–5
 Ramsey theory of optimal growth 3–4, 143, 145–7, 229

- and resources 23–4, 140
- Solow-Swan model of economic growth *see* Solow-Swan model of economic growth
- 'stylized facts' about economic growth 257, 258–9
- and technological progress 8, 9, 24, 25, 48, 140, 260
- and technology 11, 45
- and thermodynamics 139–42, 144
- and wastes 64, 136, 144, 261
- net worth 302
- Newton's laws 223, 224
- NGL 92, 94, 98, 99, 324–5, 333
- nitrogen 23, 68, 69, 79, 115
- non-fungibility 45, 55, 261
 - see also* fungibility
- non-linear models 8, 17
- non-optimality 8
- non-rival goods 46
- non-substitutability
 - and factor share theorem 153–4
 - and input-output models 158
 - and multi-sector economies 154–6
 - and production functions 177–8, 182, 218, 219–20, 295
 - see also* substitutability
- non-sustainability 135–6
 - see also* sustainability
- Nordhaus, William D. 225, 303–4, 309
- nuclear energy 85, 86, 87, 232, 333
- oil *see* oil coefficient; oil crisis (1973–4); petroleum and oil
- oil coefficient 266, 275, 276–7, 278, 279–80, 282–3, 284, 285–8, 289–90
- oil crisis (1973–4) 23–4, 40, 114, 150, 175, 199, 213
- OLS, and production function
 - estimation for US and Japan 202, 203–4, 205, 209, 213
- open systems 138
 - see also* materials processor model
- optimal control theory 145–7
- optimal extraction model of exhaustible resources 4
- optimal growth theories 3–4, 7–8, 143, 145–7, 229
- optimal savings 3, 7–8
- optimality 8, 135–6, 141
- oxygen 67–9, 70, 78–9
- paper industry 114, 116
- paper products 67, 70, 71, 72
- path dependence 17, 20, 135–6
- pattern recognition 223–4
- payload efficiency 123–5
- Pearl, Raymond 12, 15
- perpetual growth 309–10
- perpetual inventory method (PIM) 4–5, 6, 177, 180, 239–40, 304, 306
- perpetual motion machines 137, 139, 143
- petroleum and oil
 - and discontinuity hypothesis 40, 42
 - and exergy and useful work in US and Japan 92, 94, 99, 100, 322–3
 - and exergy inputs for Japan 86, 87
 - and exergy inputs for US 85, 86
 - and exergy-to-work efficiency improvements since 1900 117, 118
 - and induced innovation 21–3
 - Japanese data 331–2
 - US data 322–3
 - see also* oil coefficient; oil crisis (1973–4)
- petroleum and oil consumption 264, 265–6, 292
 - see also* EP (energy proxy)
- petroleum and oil exporting countries 266–8, 270, 272, 273, 274, 292, 303
- petroleum and oil prices 42, 119–20, 150–51, 217–18, 231–2
- petroleum and oil refining 113, 114
- petroleum and oil scarcity and depletion 231–2, 252–3, 297
- petroleum cracking 99, 100
- petroleum efficiency 99, 100
- photosynthesis 67–9, 79
- physical capital 176–7, 180, 305
- physical limit barriers 36–9, 41, 42, 44, 53–4, 57, 58
- physical science 39
- Pigou, A.C. 3, 136, 145
- plastics 70, 72
- pollution and harmful wastes
 - and conservation of mass 63, 64
 - costs 141, 142

- and disequilibrium paradigm 10
- and exergy 141
- and mass flows 70, 72
- and materials life-cycle 67
- and neoclassical theory 64
- and REXSF model of the US economy 243, 247, 249
- and Walrasian equilibrium 10
- poor countries 160, 255, 257
 - see also* developing countries
- population, aging 229–30, 239
- population data 318, 329, 334–43
- population growth 21, 23, 237, 256, 257
- positive feedback 9–11, 25, 55, 59, 163, 233–7
- potential entropy 137
- potential work 78, 137
- power 67, 90–91
- power generation 19–20, 30–31, 37–8
- predictability 42–3, 44
 - see also* economic growth forecasting; forecasting
- prices
 - and disequilibrium paradigm 25
 - and neoclassical paradigm 1, 2, 24, 25, 54–5, 140
 - and optimal extraction of exhaustible resources 4
 - and perpetual inventory method (PIM) 177
 - and positive feedback 9, 163, 233, 234
 - and resource scarcity and depletion 42
 - and Walrasian economics 142–3
 - see also* energy prices; market prices; natural resource prices
- primary materials conversion 52, 66, 67
- primary work 91, 126–31
 - see also* heat; prime movers
- prime movers
 - exergy-to-work efficiency improvements since 1900 101–11
 - and materials life-cycle 67
 - and useful work 93–6, 98–101
 - see also* engines; turbines
- problem solving 16–17, 42–3
- processing *see* concentration and conversion; materials processor model
- production 1, 2, 9, 62, 141, 149, 233
- production-consumption systems 137–8
- production cost reductions 9, 11, 55
- production experience 237, 247, 250
- production frontiers 178, 183, 184
- production function estimation for US and Japan
 - critique of results 218–20
 - estimation 200–205
 - evidence of elasticity of exergy as useful work 217–18
 - goodness of fit conclusions 213–16
 - numerical results 205–13
 - time series data 197–201
- production functions
 - complementarity 179, 219, 295
 - concepts 182–4
 - critique 176–81
 - described 175
 - and disequilibrium paradigm 10–11
 - and endogenous growth theories 163, 164
 - and exergy 183, 218
 - and neoclassical paradigm 141, 161–2
 - and non-substitutability 177–8, 182, 218, 219–20, 295
 - and Solow-Swan model of economic growth 5–6, 7
 - and substitutability 177, 178–80, 182, 219, 292
 - and useful work 141, 179, 182, 183, 218
 - see also* Cobb-Douglas production function; LINEX production function; production function estimation for US and Japan
- products *see* goods; services
- profit maximization 176, 183, 211–12
- profits 25, 43, 46, 55, 305, 311–12
- progress, ‘laws’ 12–16
- ‘progress function’ 12–15, 20, 31
- pulp industry 114, 116
- punctuated equilibrium 42
- quasi-work 91, 101, 111–18
- radical (Schumpeterian) innovation
 - and barriers 17, 26
 - described 17, 57

- and disequilibrium theories 12, 57
- and economic growth 260, 261
- and endogenous growth theories 164, 260
- and evolutionary theories 11
- versus gradual incremental (Usherian) improvements 12, 45
- and neoclassical theory of growth 10, 25, 260
- and S-shaped curve 15–16
- and spillovers 45, 261
- 'stylized facts' about economic growth 258
- railroads 124–5
- railway engines 38, 102, 103, 104, 105, 125
- Ramsey theory of optimal growth 3–4, 143, 145–7, 229
- RAND 222
- rational expectations 8, 135–6
- rationality 2, 10, 140, 260
- raw materials 65–77, 234
- raw materials extraction 62–3, 64–5, 168, 169, 262
- R&D**
 - and breakthroughs 11, 26
 - and disequilibrium paradigm 25, 55
 - and endogenous growth theories 164
 - and evolutionary theories 167
 - and gradual (Usherian) improvements 26, 31
 - and knowledge as non-rival good 46
 - and knowledge capital 305
 - and neoclassical paradigm 8, 25, 55
 - and positive feedback 233, 234
 - process 56–7
 - see also* innovation
- real estate 230, 302
- rebound effect 105–6, 296–7
- recessions 144, 145, 217–18, 226, 309
- recycling 67, 68, 70, 71, 136, 170, 171, 236
- refrigeration 118, 120–21, 122
- regulations 19–20, 43
- renewable energy 85, 86, 87, 234, 333
- rents 5, 149, 151
- residential and commercial sectors 105–6, 107, 112, 117, 118, 120–21, 199–200
- resource consumption 11, 23–4, 237, 247
 - see also* electricity consumption; energy consumption; natural resource consumption; petroleum and oil consumption; production-consumption systems
- resource prices 11, 303
- resource scarcity and depletion
 - and discontinuity hypothesis 40
 - and entropy law 170–72
 - and induced innovation 17–18, 21–4, 26, 57
 - and neoclassical paradigm 140
 - and price increases 42
 - and REXSF model of the US economy 249–50
 - and substitutability 308
 - see also* energy scarcity and depletion; natural capital scarcity and depletion; natural gas scarcity and depletion; natural resource scarcity and depletion; petroleum and oil scarcity and depletion
- resources 147
 - see also* concentration and conversion; extraction and harvesting; materials; natural resources; resource consumption; resource prices; resource scarcity and depletion
- returns on capital stock 5, 6, 149, 159–60, 162, 257, 305
- returns on labor 5, 6, 149
- returns on R&D investment 31, 42
- returns to scale *see* economies of scale; Euler condition
- REXSF model of the US economy
 - described 236–45
 - empirical results and sensitivity 245–50
- REXSF simplified model
 - assumptions 262–3
 - catch-up countries only 275, 278–88, 349
 - catch-up elasticity 288–91, 293
 - conclusions 291–3

- electrification and urbanization 264, 265–6, 344–8, 364
 groupings and non-linear regressions 271–5, 276–7, 278, 279
 hypotheses 263–4
 methodology and data 264–6, 350–52
 and perpetual growth 310
 scatter diagrams and linear regressions 266–71
 rich countries 160, 255, 257, 263, 303
 road transport 106, 108–11, 298–9
 Robinson, Joan 176–7
 Romer, Paul M. 48, 55–6, 162, 163, 164–5, 213, 255, 259, 260–61
 Rostow, W.W. 254
 Ruth, Matthias 140

 S-shaped curve 15–16, 26, 58, 243–5, 247, 254
 Sala-I-Martin, Xavier 160, 161, 162, 164, 255, 257
 salt 21–2, 79
 Samuelson, Paul A. 2, 146–7
 saturation 160, 247
 savings and investment
 and capital 307
 and economic development theory 254, 256
 and integrated assessment (IA) models 225
 and neoclassical paradigm 9
 and positive feedback 163
 and production function estimation for US and Japan 214
 and Ramsey theory of optimal growth 3, 145
 and recession 144
 and REXSF model of the US economy 238–9, 240
 and Solow-Swan model of economic growth 145, 150, 162
 ‘stylized facts’ about economic growth 257, 258–9
 Schelling, Thomas C. 154–5
 Schumpeter, Joseph A. 11, 15–16, 17, 41, 145, 164, 166, 259
 see also creative destruction; radical (Schumpeterian) innovation
 sea transport 16, 31–3, 34, 38, 39

 second-law efficiency 91, 112, 113–14, 117, 118, 121, 142
 secondary processing 52
 secondary work
 defined 91, 118–19
 efficiency 118–26, 298–9
 total primary and secondary work 126–31
 sectors 51–4, 156–8, 258
 selection 166, 167
 Serageldin, Ismael 307–8
 serial auto-correlation, and production function estimation for US and Japan 202, 203
 service output per unit work 118–19
 services 1, 2, 24, 54, 149–50, 168, 169, 233
 see also energy services; exergy services; information products and services; social welfare services
 short-term fluctuations 175, 201, 203, 205
 single all-purpose products 2, 7, 149, 152, 154, 156, 161, 182–3
 single sector models 7–8, 150–51, 152, 153, 154, 156, 169, 175, 184
 see also income allocation theorem; Solow-Swan model of economic growth
 skills 47, 49, 254, 255
 small economies 161
 Smith, Adam 21, 142, 228, 301–2
 SNA (system of national accounts) 4, 6
 social discount rate 225–6
 social inventions 15–16
 social knowledge 47–8
 social learning 12, 163
 social planner 4, 8
 social skills 47
 social utility 3–4
 social welfare services 229
 societal benefits 46
 societies, and wealth 300–302
 soda ash synthesis 115, 116
 Söllner, Fritz 140, 142
 Solow, Robert M. 2, 5–6, 23–4, 146–7, 178, 217, 225, 226, 253, 309
 Solow residual 181, 184–6, 187, 189, 194, 195, 253

- Solow-Swan model of economic growth
 critique 159–62, 259
 described 4–7, 147–50, 152, 153,
 182–3, 233, 253
 and economic development 162,
 254–5
 and energy and materials 10, 161,
 233
 and integrated assessment (IA)
 models 225
 and ‘stylized facts’ about economic
 growth 258–9
 and technological progress 150, 159,
 160–61, 187, 189, 233, 253
 space heating 112, 117–18, 127, 298
 spark ignition engines 34–6, 37–8, 52,
 90, 106, 108, 109, 111
 specialization of labor 228–9
 spending 144, 145, 227, 229
 spillovers
 and breakthroughs 26–7, 44, 58–9
 defined 44
 and disequilibrium paradigm 25, 56
 and endogenous growth theories
 163, 164, 259
 and evolutionary theories 11
 forecasting 44
 and free riders 49
 and gradual incremental (Usherian)
 improvements 45
 and long-term economic growth 27
 and radical (Schumpeterian)
 innovation 45, 261
 ‘stylized facts’ about economic
 growth 258, 259
 spontaneous invention 17, 25
 stage theory of economic development
 254
 standardization 20
 static economic growth theories 142–4,
 159
 steady-state 136, 142
 steam 90, 101–2, 112, 117, 127, 199,
 232
 steam-electric power 103–5
 steam engines 30, 38, 102–3, 104, 105,
 233–4
 steam locomotives 102, 103, 104, 105,
 125
 steam turbines 30–31, 33, 38, 148
 steel 70, 71
 steel industry 112–13, 114, 116, 117,
 127, 234
 Steer, Andrew 307–8
 Stern, David I. 205, 214
 stock markets 230
 structural breaks
 and production function estimation
 for US and Japan 201, 203, 205,
 206, 207, 208, 209, 210, 211,
 212, 213, 214
 and REXSF model of the US
 economy 241–2
 structural properties of materials 53–4
 sub-prime mortgages 227–8, 229
 subsoil assets 307, 308
 substitutability
 and agricultural productivity decline
 154–5
 and factor share theorem 153
 and input-output models 157, 158
 and neoclassical paradigm 140, 152
 physical limit barriers 54
 and production functions 177,
 178–80, 182, 219, 292
 production function estimation
 for US and Japan 205, 216,
 219–20
 and resource scarcity and depletion
 308
 and Solow-Swan model of economic
 growth 148–9, 152
see also agricultural mechanization;
 automation; non-
 substitutability
 supply 1, 2, 9, 24, 35, 54, 55, 233, 234
 supply-side I-O model 158–9
 sustainability 10, 12, 63, 134
see also non-sustainability
 Swan, Trevor 5, 147, 253
see also Solow-Swan model of
 economic growth
 systems dynamics 237
see also REXSF model of the US
 economy; REXSF simplified
 model
 taxes 5, 227, 229, 230
 technical efficiency
 and economic growth 297

- and energy scarcity and depletion 232
- Japanese data 339–43
- LINEX production function with useful work 191–2, 194–5
- as measure of technological progress and total factor productivity (TFP) 80
- and production function estimation for US and Japan 198, 214, 218–19
- and REXSF model of the US economy 243–5, 246–7, 248, 249, 250
- and secondary work 118–26
- US data 334–8
- technological discontinuity 41
- technological efficiency 53
- technological forecasting 51–4
- technological knowledge 45, 46, 47, 48, 49–51, 167, 253
- technological progress
 - and discontinuity hypothesis 39–42
 - and disequilibrium paradigm 25–6, 55, 57–9, 168
 - and economic development theory 255–6, 262–3
 - and economic forecasting 51–4
 - and economic growth 262–3
 - empirical ‘laws’ of progress 12–16
 - and evolutionary theories 11, 167–8
- extrapolation in economic growth forecasting 233–6, 252
- fungibility 45, 258
- homogeneity 45, 259, 261
- and induced innovation *see* induced innovation
- inhomogeneity 11, 45, 258, 261
- and integrated assessment (IA) models 225
- and knowledge accumulation 49–51
- and lock-out/lock-in 19–20
- macroeconomic theory of change and innovation 17–19
- as multiplier in Solow-Swan model of economic growth 6
- and neoclassical paradigm 8, 9, 24, 25, 48, 55, 140, 260
- non-fungibility 45, 261
- and optimal extraction of exhaustible resources 4
- and positive feedback 59, 233–6
- as problem solving 16–17
- and production functions 178–9, 181, 186, 194
- and REXSF model of the US economy 237
- and Solow-Swan model of economic growth 150, 159, 160–61, 187, 189, 233, 253
- ‘stylized facts’ about economic growth 258, 259
- and technical efficiency 80
- technological trajectories 30–31
- transfers from industrialized to developing countries 263
- and useful work 263
- and wealth 62
- technology 11, 45, 52–4
- TFP (total factor productivity) and economic development theory 255–6, 262–3
- and economic growth 262–3
- and equilibrium 54
- and integrated assessment (IA) models 225
- and Solow-Swan model of economic growth 6, 7, 150, 160, 161, 187, 189, 253
- and technical efficiency 80
- thermodynamic efficiency 234–5, 243–4, 298–9
- thermodynamic equilibrium 136, 137, 261
- thermodynamics 139–42, 144, 168, 169
 - see also* conservation of mass; entropy law; thermodynamic efficiency; thermodynamic equilibrium; useful work
- time factors
 - production functions 175–6, 178–9
 - Cobb-Douglas production function 185
 - LINEX production function 190–91, 194, 195
 - and REXSF simplified model 270–71
 - Solow-Swan model of economic growth 6, 253

- time preferences 225–6, 229
- time series data 179, 181, 197–201, 239–40, 298
 - see also* extrapolation, concept
- Tobin, James 303–4
- town gas 38, 117
- trade 34, 226–7, 228
 - see also* exports; petroleum and oil exporting countries
- trade deficits 207, 227
- transport fuel 34–6
 - see also* fuel efficiency; gasoline
- transportation
 - classification 52
 - and crisis-driven radical innovation 31–3, 34–6, 38, 39
 - and exergy-to-work efficiency improvements since 1900 106, 108–11, 127, 128
 - and secondary work exergy efficiency 123–6, 298–9
 - and useful work 265–6
 - see also* automobiles; motor vehicles; transport fuel
- trends 223–4, 226
 - see also* extrapolation, concept
- trucks 38, 106, 108, 109, 111, 124, 125, 126
- turbines 30–31, 33, 38, 52, 53, 90, 91, 104, 111, 114, 148
- two factor production functions, described 175
- two-sector economies 152–3, 164, 169, 191–5

- unemployment 144, 145
- unit roots, and production function estimation for US and Japan 201, 203, 204, 210, 214
- urbanization 265, 291–2, 307–8, 344–8
- US
 - Cobb-Douglas production function with exergy 187, 189
 - data 314–27, 334–8
 - economic importance 262
 - exergy inputs 85, 86
 - exergy/mass and exergy/GDP trends 80–85
 - fossil fuel exergy and useful work 92, 93–6, 98
 - GDP and factors of production 187, 188
 - heat as useful work 93–6, 99, 101, 111–18
 - human/animal muscle work 89, 90, 92, 97–8, 101
 - mass and exergy flows 67–77
 - materials life-cycle 65–7
 - prime movers as useful work 93–6, 98, 99–111
 - production function estimation
 - for US *see* production
 - function estimation for US and Japan
 - REXSF model of the economy
 - see* REXSF model of the US economy
 - and REXSF simplified model 262, 266, 272–3, 274, 275, 278, 279, 280, 281, 282, 283, 284, 286–8, 290–91, 292, 293
 - risks of blind extrapolation 226–32
 - secondary work efficiency 119–31
 - technological progress and Solow residual 187, 189
 - total useful work 126–31
- useful products 69
- useful work
 - animal/human muscle work 89, 90, 92, 97–8, 232, 265, 315
 - costs 193, 234–6
 - defined 89–92, 296
 - elasticities 154
 - and energy scarcity and depletion 232
 - and exergy 78–80, 89, 92, 93–6, 141
 - see also* exergy-to-work efficiency improvements since 1900
 - and factor share theorem 152–3
 - and fossil fuel exergy 92, 93–6
 - Japanese data 339–43
 - and materials life-cycle 66, 67
 - and materials processor model 168
 - prime movers and heat 89–90, 93–6, 98–101, 232, 265
 - and production functions 141, 179, 182, 183, 218
 - LINEX production function 191–5, 295–6

- production function estimation for
 - US and Japan 197, 198, 199, 201, 204, 207, 208–9, 210, 211, 212, 214–16, 217–18, 219
- and REXSF model of the US
 - economy 240–45, 246–7, 248–9, 250
- and REXSF simplified model 264, 265, 284, 310
- secondary work 118–26
- and Solow-Swan model of economic growth 183
- and technological progress 263
- and thermodynamic efficiency 234–5
- total primary and secondary work 126–31
- US data 334–8
- useful work/GDP, and production function estimation for US and Japan 198, 199
- useful work payments 210
- utility 1, 2, 3–4, 140, 141, 145–6, 225–6
- utility maximization 2, 3, 260
- utility of future consumption, and integrated assessment (IA) models 225–6
- value 1, 45, 46, 47–8, 49–50, 169
- value added 69, 157, 182, 247, 249
- von Neumann, John 2, 143–4, 170
- wages 5–6, 24, 25, 54, 55, 147, 148, 149, 229–30
- Walras, Leon 2, 143, 170
- Walrasian economics 1, 2, 3, 10, 140, 142–3, 159
- Warr, Benjamin 24, 168, 198, 200, 253, 263, 293
- wars
 - and crisis-driven radical innovation 26, 31–3, 34, 58
- and production function estimation for US and Japan 201, 203, 205, 206, 207, 208, 209, 210, 211, 213, 214
- and production functions 175–6
- waste disposal and treatment 63, 64, 141, 168, 170
- waste flows 63, 64–5, 141, 144, 168–9
- wastes
 - and disequilibrium paradigm 10
 - and entropy law 168, 169, 170, 171
 - and exergy 141, 170
 - and mass flows 68, 69, 70, 71–2
 - and materials life-cycle 65, 66, 67
 - and neoclassical paradigm 64, 136, 144, 261
 - and Solow-Swan model of economic growth 150
 - ‘stylized facts’ about economic growth 258
 - and Walrasian equilibrium 10
 - see also* pollution and harmful wastes; recycling; waste disposal and treatment; waste flows
- water 79, 307–8
- water heating 112, 117
- water vapor 68, 69
- wealth 62–3, 134–5, 299, 300–302, 303, 309
- welfare 21, 62, 134–5, 303–4
- Winter, Sidney G. 11, 42, 166, 167–8, 259
- wood products 70
- work 89, 296
 - see also* useful work
- World Bank 264, 306–8
- young countries 280–82, 293
- zero emissions 171

