From the biochemical pieces to the nutritional puzzle: using meta-reactions in teaching and research

Jaap van Milgen

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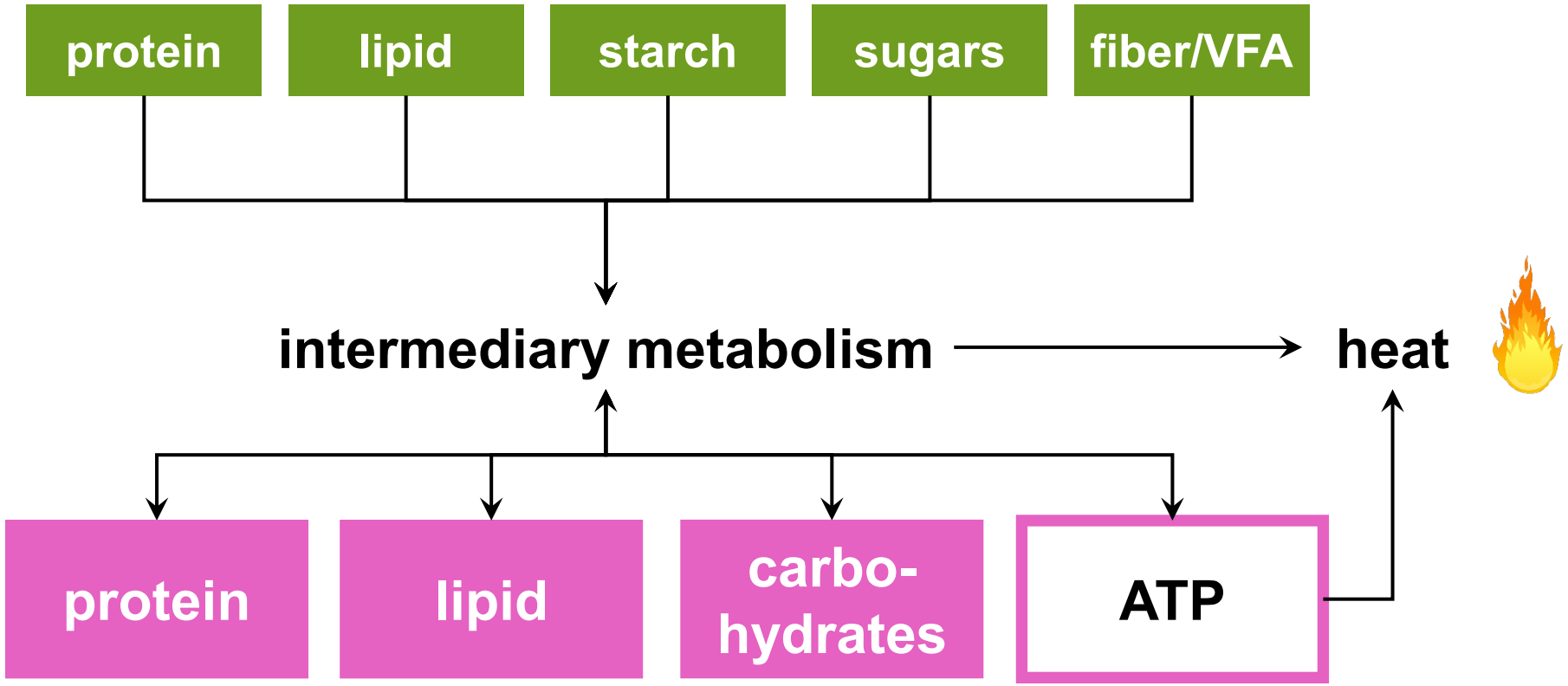
From nutrient intake to nutrient utilization



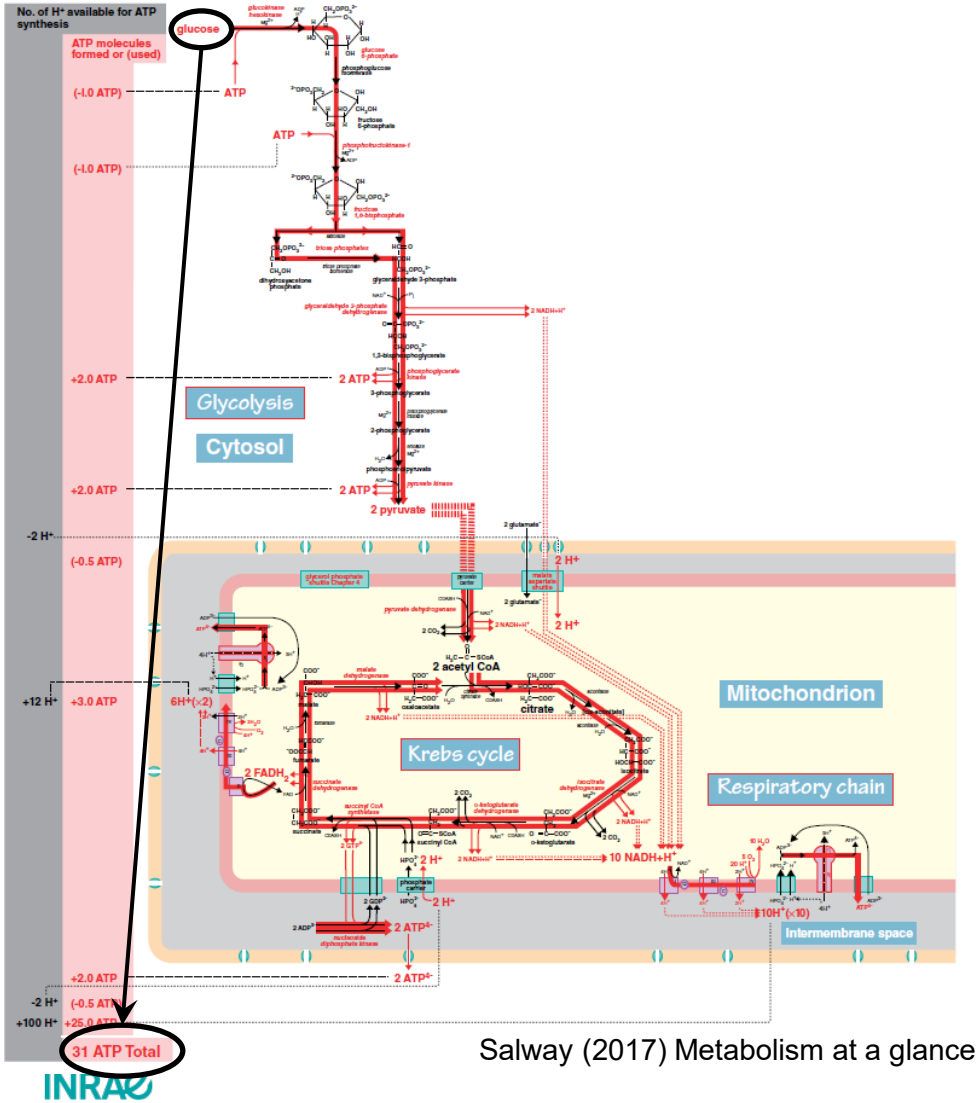
The catabolism of glucose

$$1\ \text{glucose} + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{heat}$$

$$1\ \text{glucose} + 6\ O_2 + 31\ (ADP+P_i) \rightarrow 31\ ATP + 6\ CO_2 + 6\ H_2O + \text{heat}$$

"work" → heat

Finding your way in metabolism



Salway (2017) Metabolism at a glance

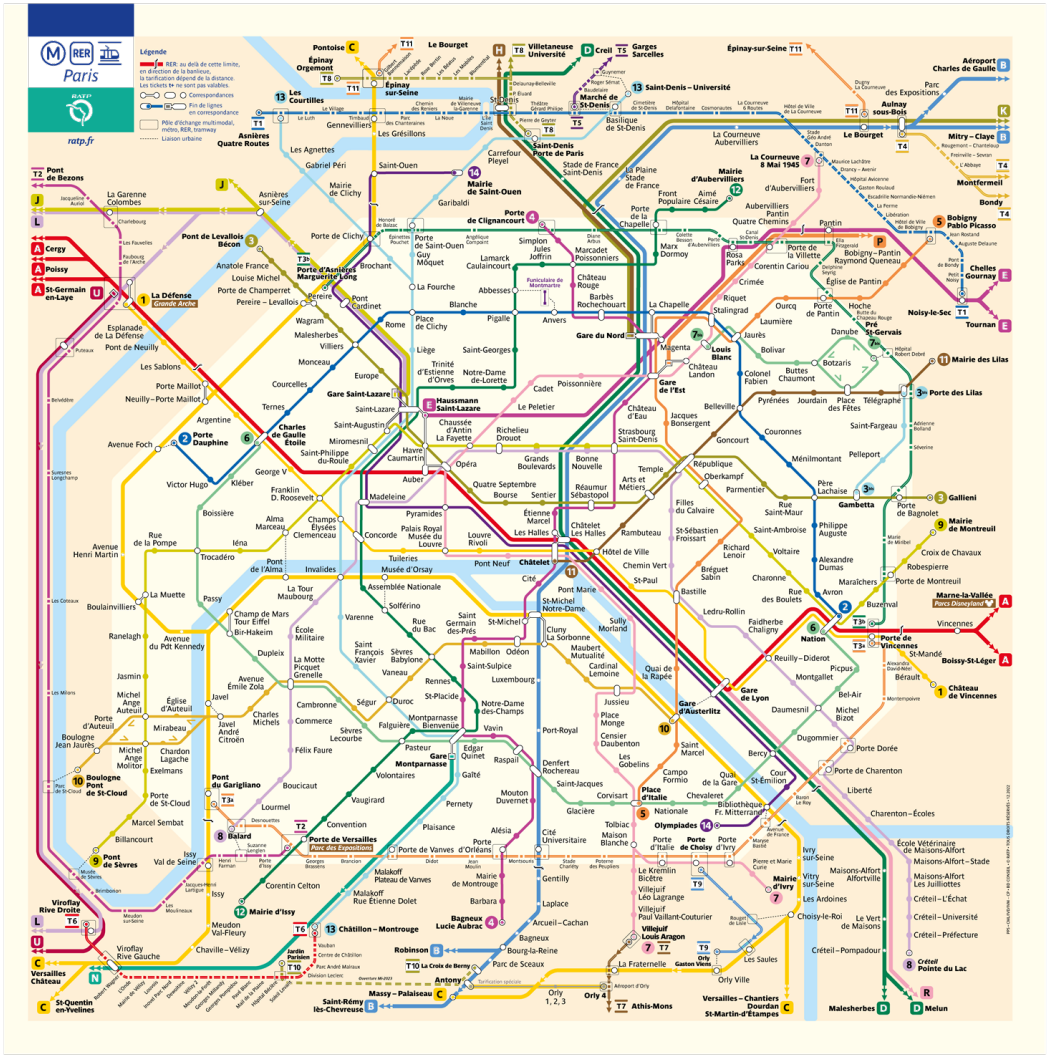
- 20 “carbon” metabolites involved:

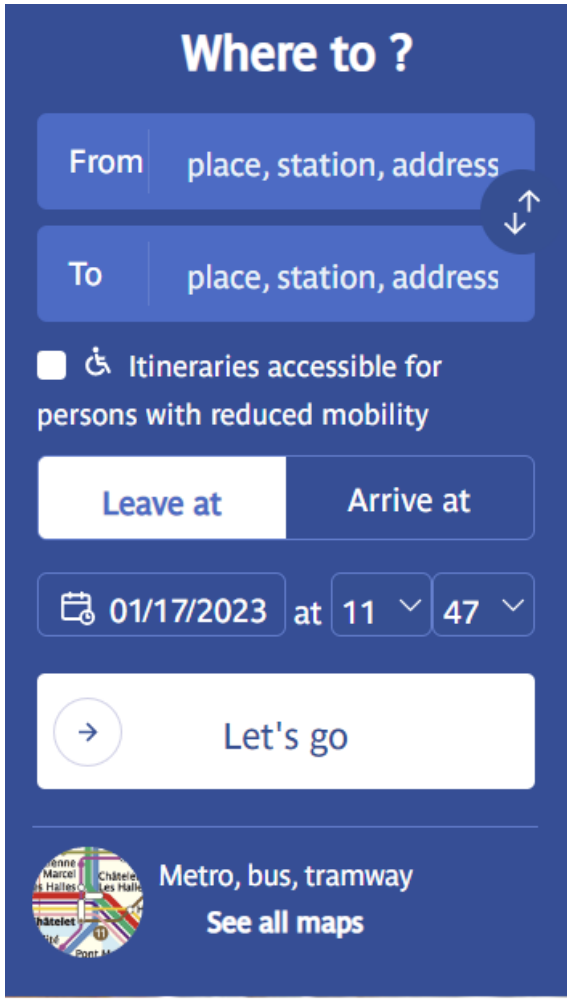
  glucose, glucose 6-phosphate, fructose 6-phosphate, fructose 1,6-bisphosphate, dihydroxyacetone phosphate, glyceraldehyde 3-phosphate, 1,3-bisphosphoglycerate, 3-phosphoglycerate, 2-phosphoglycerate, phosphoenolpyruvate, pyruvate, acetyl-CoA, citrate, isocitrate, α-ketoglutarate, succinyl CoA, succinate, fumarate, malate, oxaloacetate

- And also:

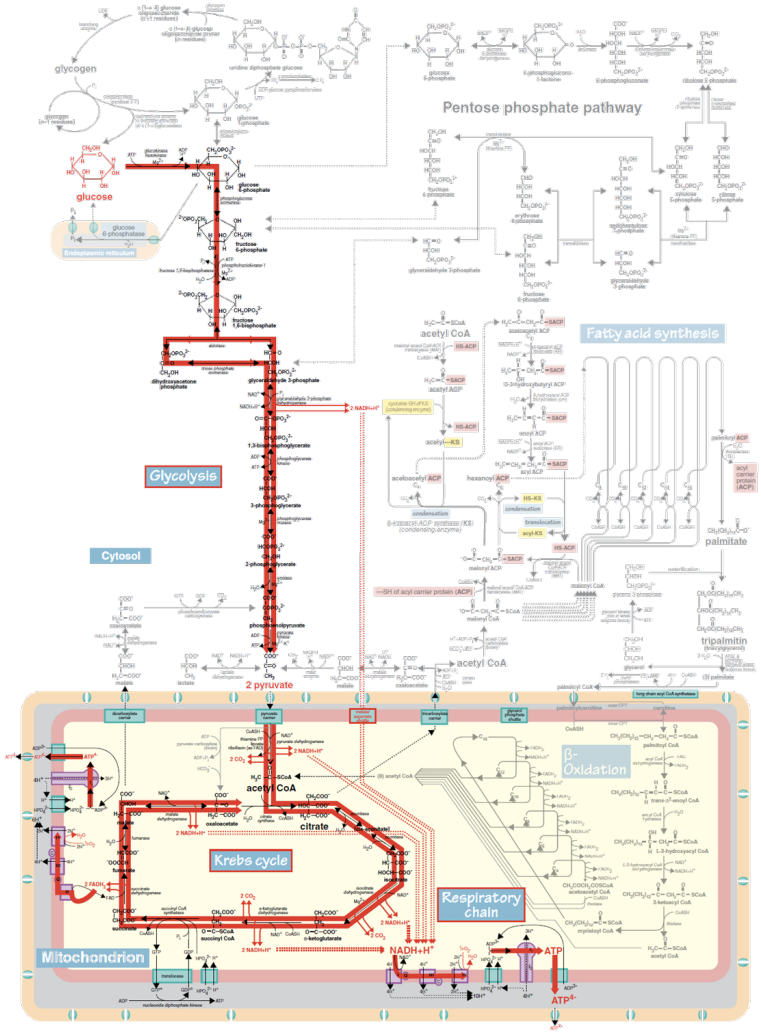
  ATP, GTP, NADH, $FADH_2$, H^+ (proton motive force), O_2, CO_2
  Other cofactors
  Enzymes

Finding your way in Paris

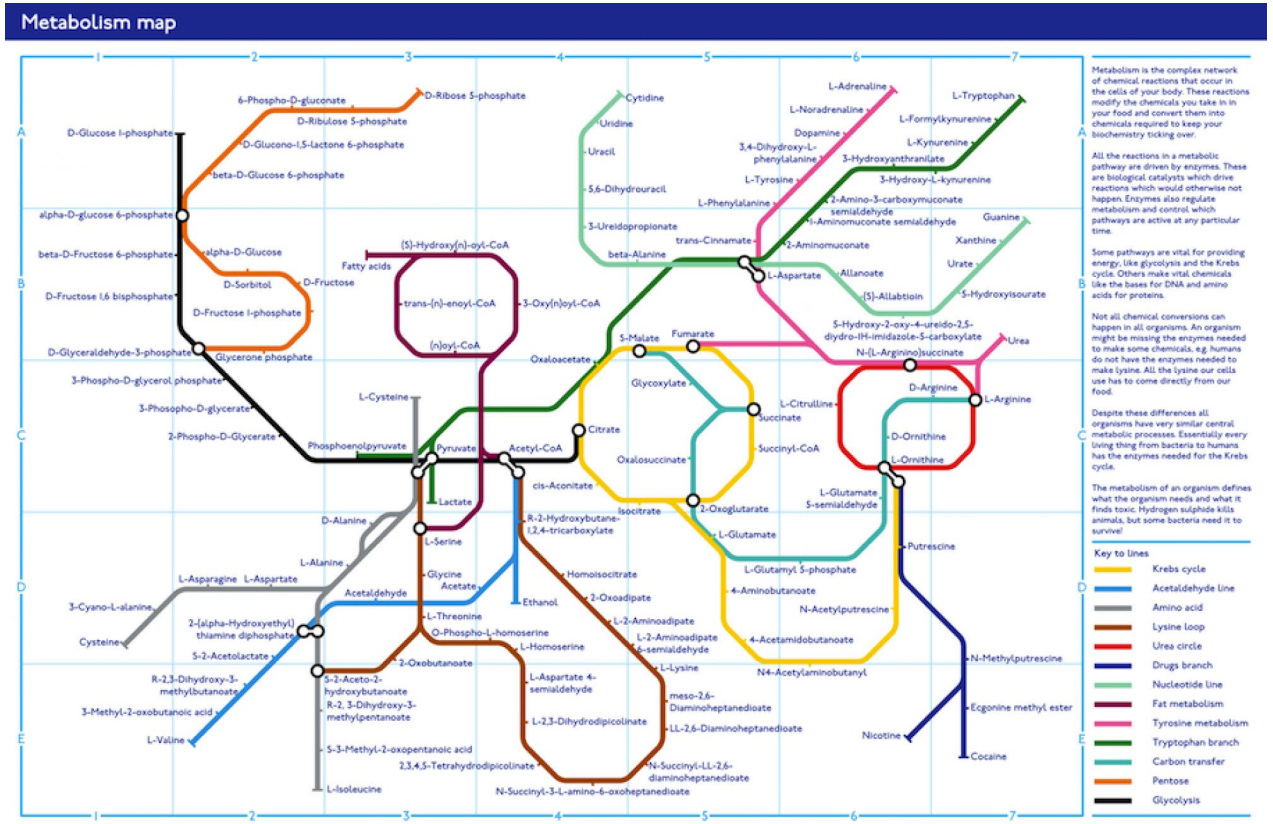




Finding your way in metabolism



Salway (2017). Metabolism at a glance, 4th edition. Wiley Blackwell



Richard Wheeler

Databases of metabolic pathways

KEGG Kyoto Encyclopedia of Genes and Genomes

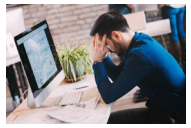
METACYC

reactome

Rhea

What a lockdown can do to people …

COVID-19 Coronavirus



Animal 15 (2021) 100213

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J. van Milgen

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From the biochemical pieces to the nutritional puzzle: using meta-reactions in teaching and research

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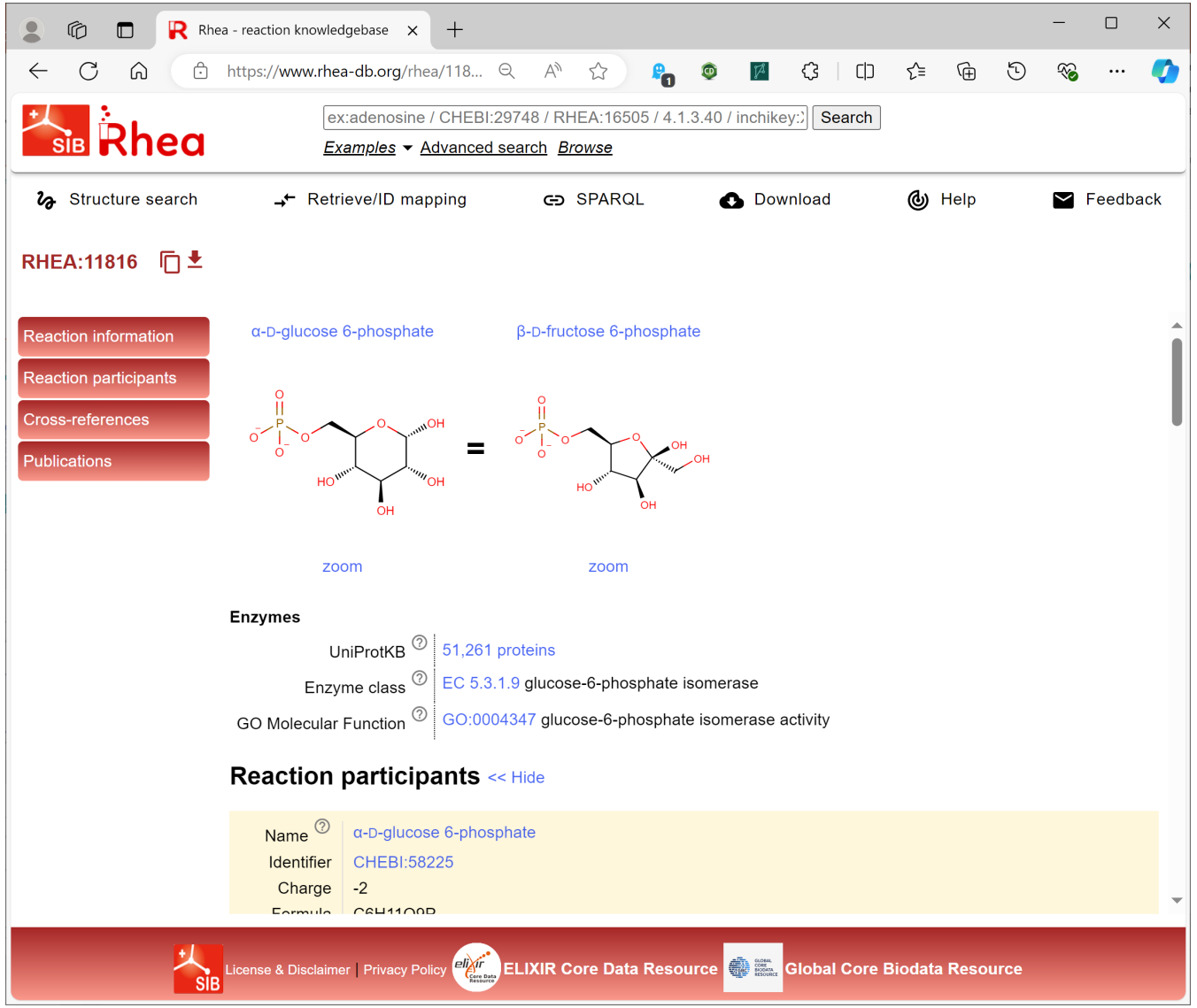
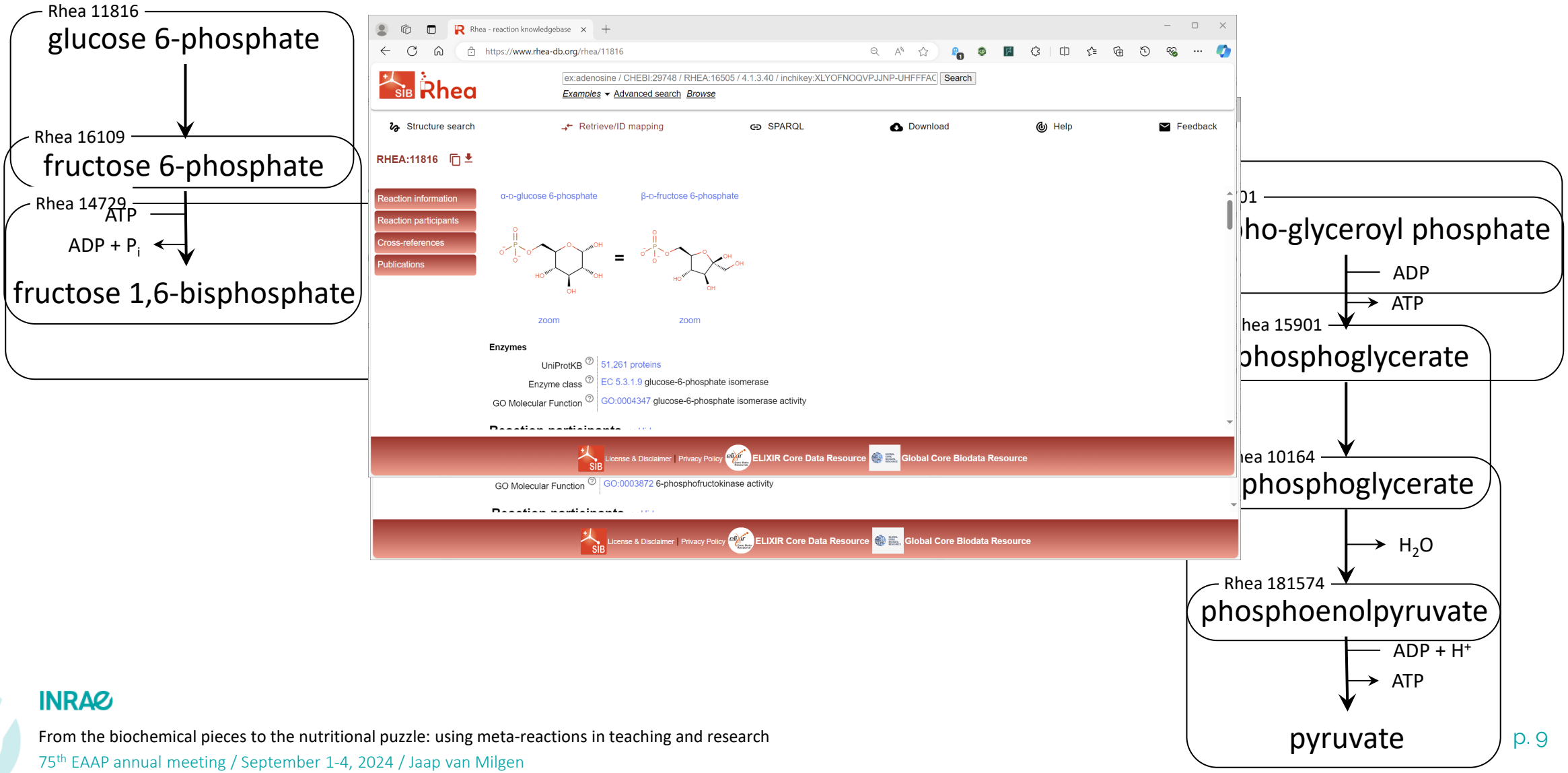
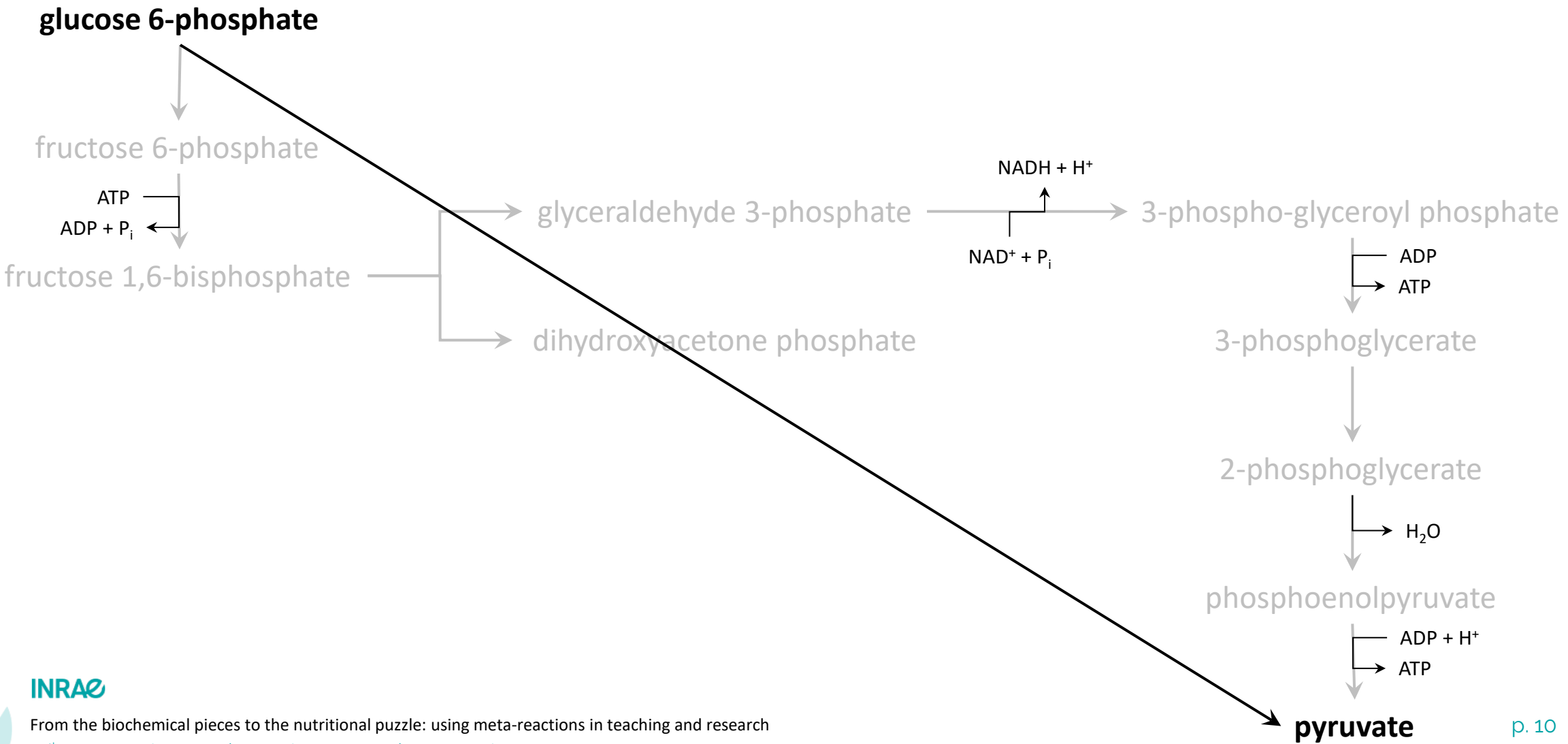
Rhea, an open database with curated chemical and transport reactions



A meta-reaction is the outcome reaction of a series of coupled individual (Rhea) reactions

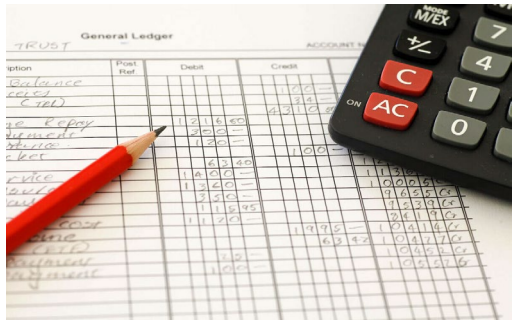


A meta-reaction is the outcome reaction of a series of coupled individual (Rhea) reactions



A meta-reaction is the outcome reaction of a series of coupled individual (Rhea) reactions

Meta-reaction	ReactionID	Flux	*Reaction*
2	11816	1	*glucose 6-phosphate → beta-D-fructose 6-phosphate*
2	16109	1	*ATP + beta-D-fructose 6-phosphate → ADP + H^+ + beta-D-fructose 1,6-bisphosphate*
2	14729	1	*beta-D-fructose 1,6-bisphosphate → dihydroxyacetone phosphate + D-glyceraldehyde 3-phosphate*
2	18585	-1	*D-glyceraldehyde 3-phosphate ← dihydroxyacetone phosphate*
2	10300	2	*P_i + NAD^+ + D-glyceraldehyde 3-phosphate → NADH + H^+ + (2R)-3-phospho-glyceroyl phosphate*
2	14801	-2	*ATP + (2R)-3-phosphoglycerate ← ADP + (2R)-3-phospho-glyceroyl phosphate*
2	15901	-2	*(2R)-2-phosphoglycerate ← (2R)-3-phosphoglycerate*
2	10164	2	*(2R)-2-phosphoglycerate → phosphoenolpyruvate + H_2O*
2	18157	-2	*pyruvate + ATP ← ADP + H^+ + phosphoenolpyruvate*



1 glucose 6-phosphate + 2 NAD^+ + 3 ADP + 2 P_i → 2 pyruvate + 3 ATP + 2 NADH + 1 H^+ + 2 H_2O

A pathway is the outcome reaction of a series of coupled meta-reactions

cytosol

ATP

glucose → glucose 6-phosphate

ATP
NADH

pyruvate

mitochondrion

CO_2
NADH

NADH

acetyl-CoA

NADH
$FADH_2$
O_2 → ATP

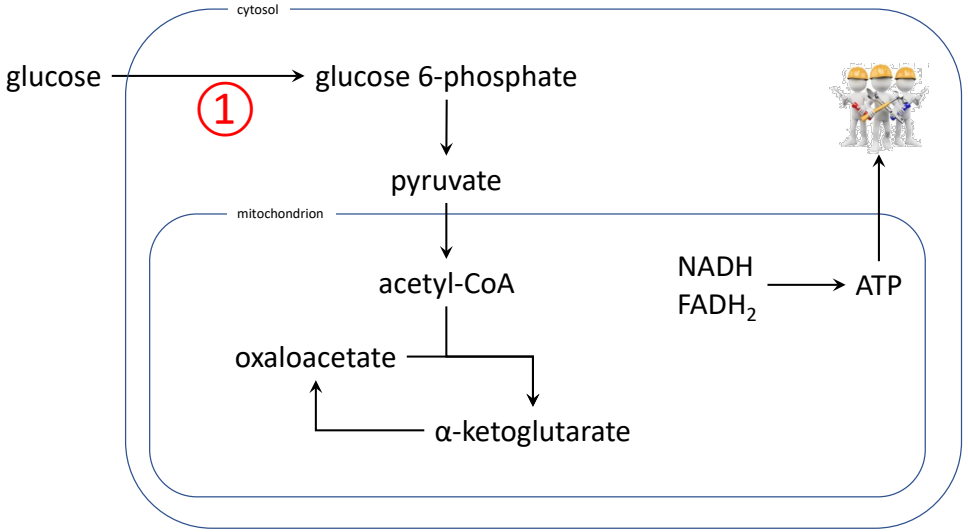
oxaloacetate

CO_2
NADH

CO_2
NADH
$FADH_2$
ATP

α-ketoglutarate

Constructing pathways using the Excel tool

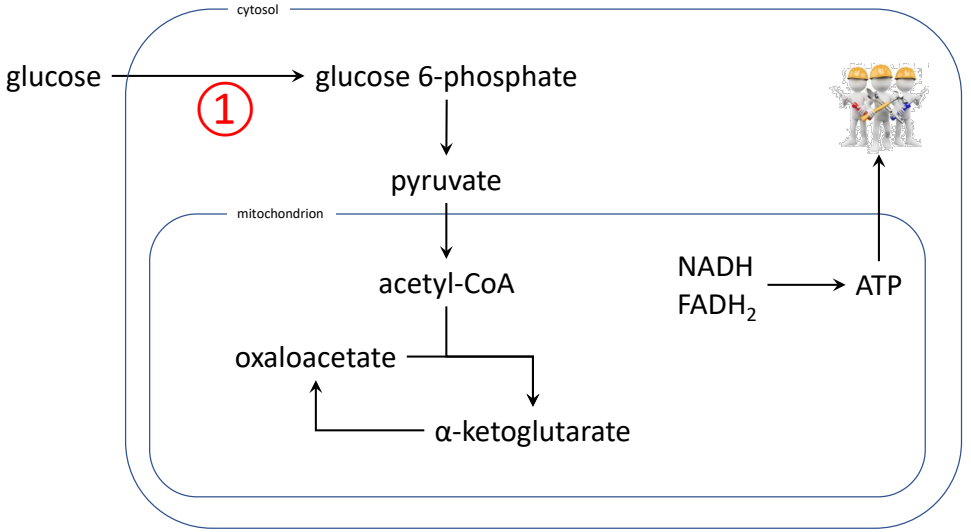


No meta-reactions selected yet

Type	Metabolite	As a ...	To/From ...	Meta-reaction	Flux

carbohydrates
amino acids, peptides, and polyamines
fatty acids and lipids
volatile fatty acids and ketones
other organic metabolites
intermediate metabolites
electron transport and ATP metabolism
1-carbon metabolism

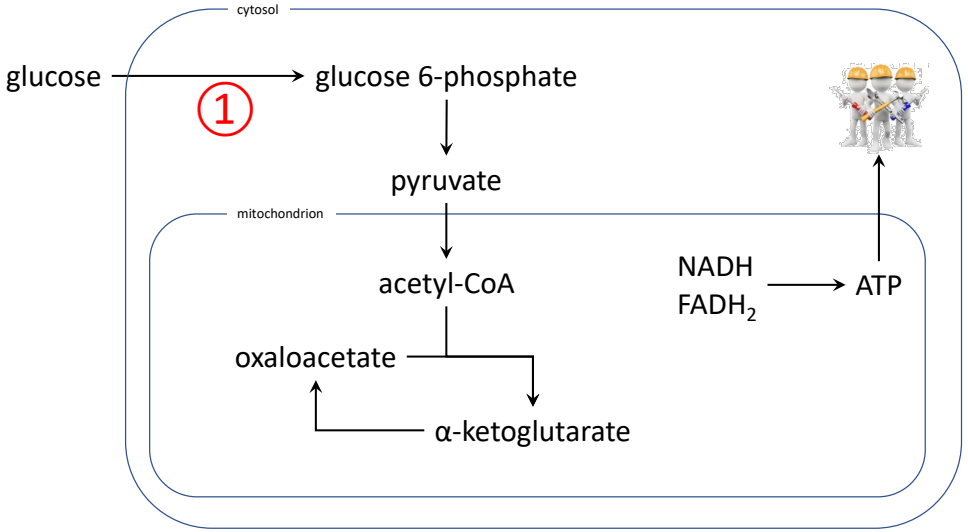
Constructing pathways using the Excel tool



No meta-reactions selected yet

Type	Metabolite	As a ...	To/From ...	Meta-reaction	Flux
carbohydrates					
	fructose				
	galactose				
	glucose				
	glycogen				
	lactose				
	sucrose				

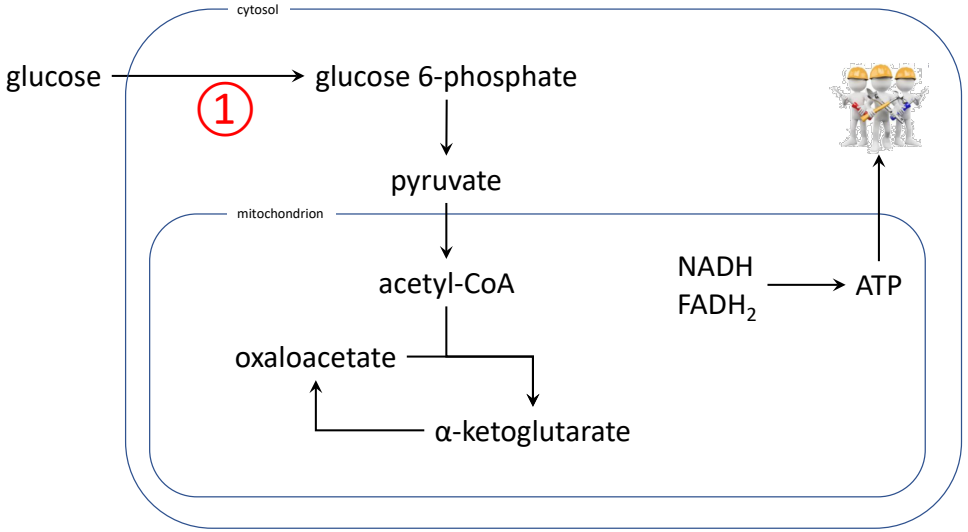
Constructing pathways using the Excel tool



No meta-reactions selected yet

Type	Metabolite	As a ...	To/From ...	Meta-reaction	Flux
carbohydrates	glucose				
		substrate			
		product			

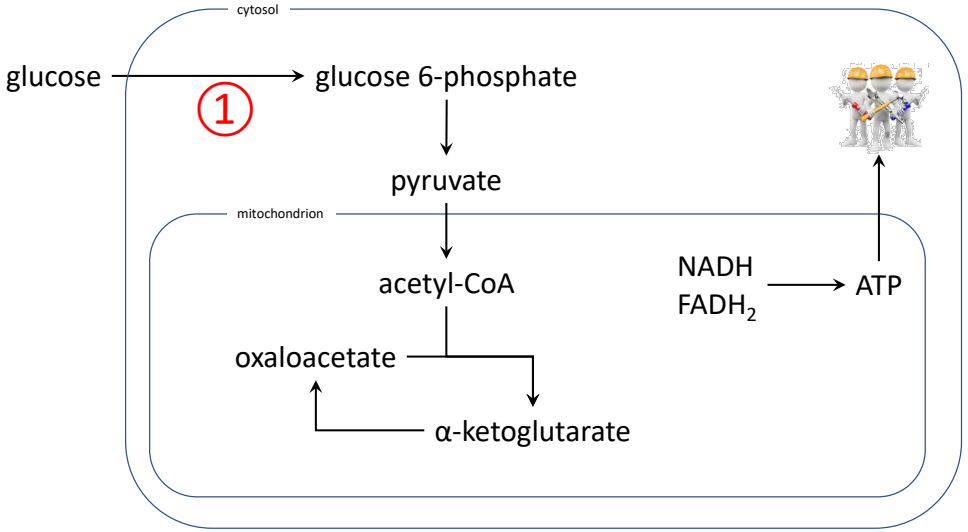
Constructing pathways using the Excel tool



No meta-reactions selected yet

Type	Metabolite	As a ...	To/From ...	Meta-reaction	Flux
carbohydrates	glucose	substrate			
			glucose 6-phosphate		
			with glucose 6-phosphate → lactose		

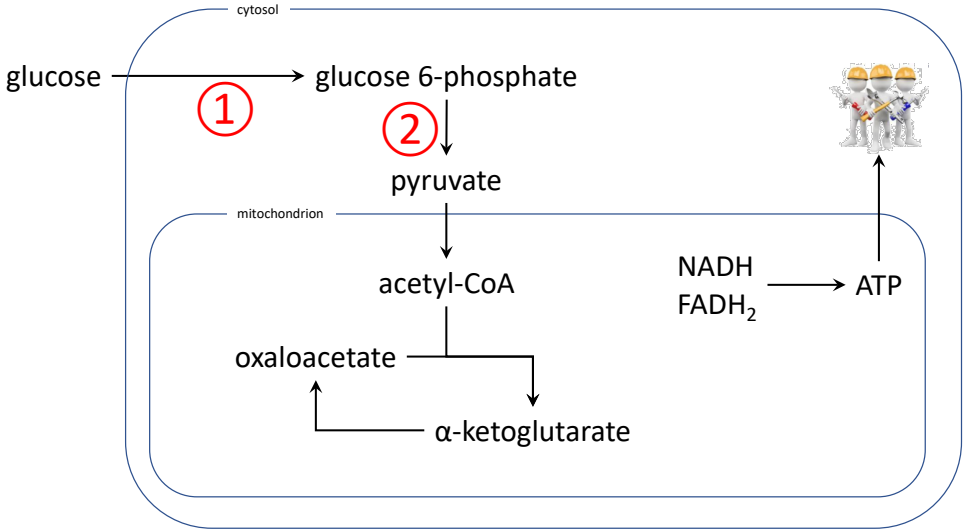
Constructing pathways using the Excel tool



No "Flux" indicated yet

Type	Metabolite	As a ...	To/From ...	Meta-reaction	Flux
carbohydrates	glucose	substrate	glucose 6-phosphate	glucose + ATP → glucose 6-phosphate + ADP + H^+	

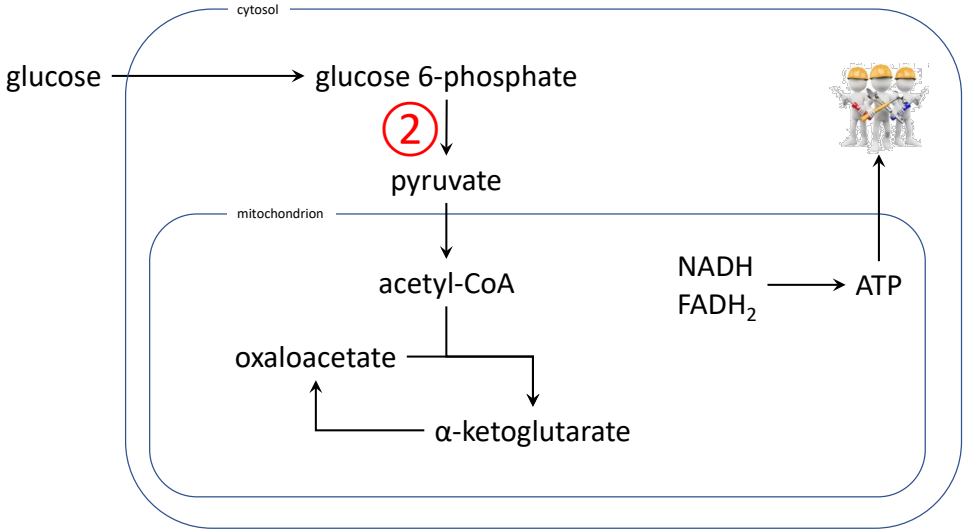
Constructing pathways using the Excel tool



glucose + ATP → glucose 6-phosphate + ADP + H^+ (Q = 30 kJ)

Type	Metabolite	As a …	To/From …	Meta-reaction	Flux
carbohydrates	glucose	substrate	glucose 6-phosphate	glucose + ATP → glucose 6-phosphate + ADP + H^+	1

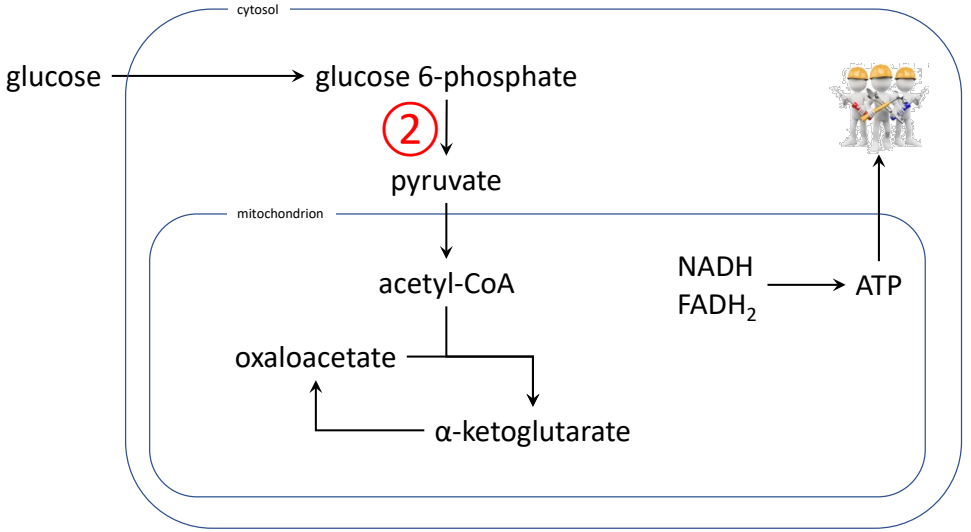
Constructing pathways using the Excel tool



glucose + ATP → glucose 6-phosphate + ADP + H^+ (Q = 30 kJ)

Type	Metabolite	As a …	To/From …	Meta-reaction	Flux
carbohydrates	glucose	substrate	glucose 6-phosphate	glucose + ATP → glucose 6-phosphate + ADP + H^+	1
intermediate metabolites	glucose 6-phosphate	substrate	pyruvate (glycolysis)	glucose 6-phosphate + 3 ADP + 2 P_i + 2 NAD^+ → 2 pyruvate + 3 ATP + 2 NADH + H^+ + 2 H_2O (glycolysis)	

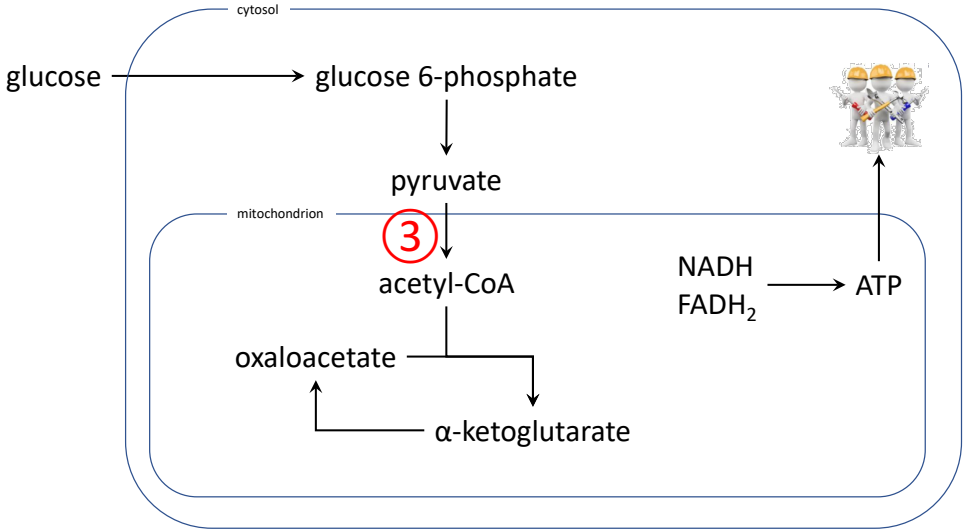
Constructing pathways using the Excel tool



glucose + 2 ADP + 2 P_i + 2 NAD^+ → 2 pyruvate + 2 ATP + 2 NADH + 2 H^+ + 2 H_2O (Q = -63 kJ)

Type	Metabolite	As a …	To/From …	Meta-reaction	Flux
carbohydrates	glucose	substrate	glucose 6-phosphate	glucose + ATP → glucose 6-phosphate + ADP + H^+	1
intermediate metabolites	glucose 6-phosphate	substrate	pyruvate (glycolysis)	glucose 6-phosphate + 3 ADP + 2 P_i + 2 NAD^+ → 2 pyruvate + 3 ATP + 2 NADH + H^+ + 2 H_2O (glycolysis)	1

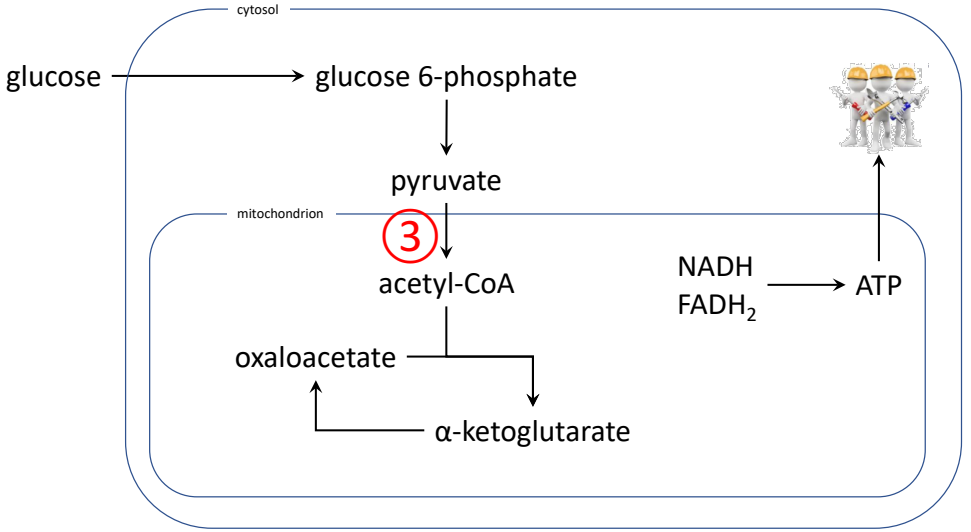
Constructing pathways using the Excel tool



glucose + 2 ADP + 2 P_i + 2 NAD^+ → 2 pyruvate + 2 ATP + 2 NADH + 2 H^+ + 2 H_2O (Q = -63 kJ)

Type	Metabolite	As a …	To/From …	Meta-reaction	Flux
carbohydrates	glucose	substrate	glucose 6-phosphate	glucose + ATP → glucose 6-phosphate + ADP + H^+	1
intermediate metabolites	glucose 6-phosphate	substrate	pyruvate (glycolysis)	glucose 6-phosphate + 3 ADP + 2 P_i + 2 NAD^+ → 2 pyruvate + 3 ATP + 2 NADH + H^+ + 2 H_2O (glycolysis)	1
intermediate metabolites	pyruvate	substrate	acetyl-CoA	pyruvate + NAD^+ + CoA → acetyl-CoA + NADH + CO_2	

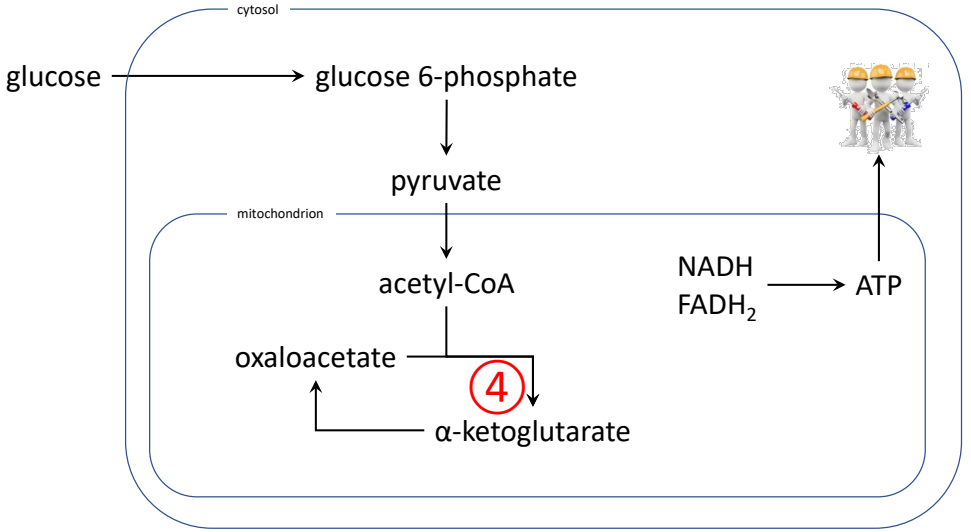
Constructing pathways using the Excel tool



glucose + 2 ADP + 2 P_i + 2 CoA + 4 NAD^+ → 2 acetyl-CoA + 2 ATP + 4 NADH + 2 H^+ + 2 H_2O + 2 CO_2 (Q not available)

Type	Metabolite	As a …	To/From …	Meta-reaction	Flux
carbohydrates	glucose	substrate	glucose 6-phosphate	glucose + ATP → glucose 6-phosphate + ADP + H^+	1
intermediate metabolites	glucose 6-phosphate	substrate	pyruvate (glycolysis)	glucose 6-phosphate + 3 ADP + 2 P_i + 2 NAD^+ → 2 pyruvate + 3 ATP + 2 NADH + H^+ + 2 H_2O (glycolysis)	1
intermediate metabolites	pyruvate	substrate	acetyl-CoA	pyruvate + NAD^+ + CoA → acetyl-CoA + NADH + CO_2	2

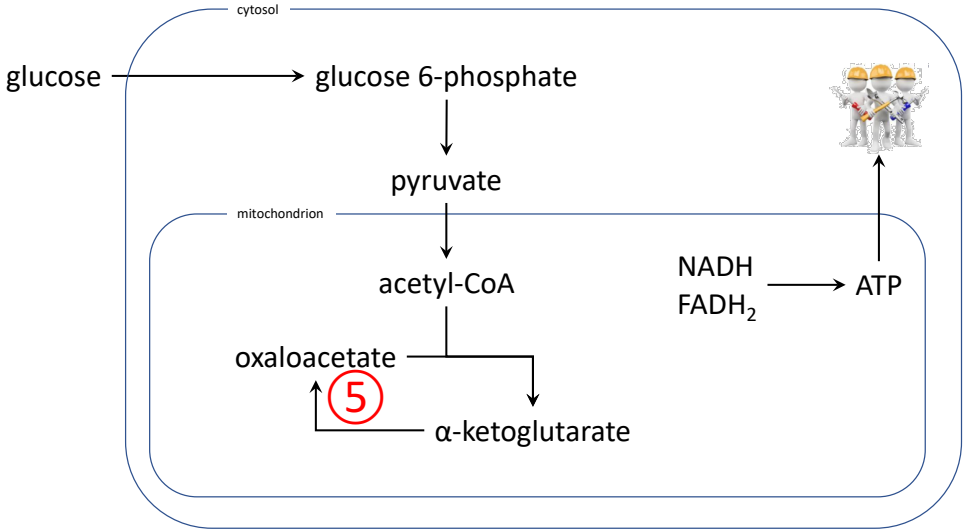
Constructing pathways using the Excel tool



glucose + 2 oxaloacetate + 2 ADP + 2 P_i + 6 NAD^+ → 2 α-ketoglutarate + 2 ATP + 6 NADH + 4 H^+ + 4 CO_2 (Q = 42 kJ)

Type	Metabolite	As a …	To/From …	Meta-reaction	Flux
carbohydrates	glucose	substrate	glucose 6-phosphate	glucose + ATP → glucose 6-phosphate + ADP + H^+	1
intermediate metabolites	glucose 6-phosphate	substrate	pyruvate (glycolysis)	glucose 6-phosphate + 3 ADP + 2 P_i + 2 NAD^+ → 2 pyruvate + 3 ATP + 2 NADH + H^+ + 2 H_2O (glycolysis)	1
intermediate metabolites	pyruvate	substrate	acetyl-CoA	pyruvate + NAD^+ + CoA → acetyl-CoA + NADH + CO_2	2
intermediate metabolites	acetyl-CoA	substrate	with oxaloacetate → α-ketoglutarate (TCA cycle)	acetyl-CoA + oxaloacetate + NAD^+ + H_2O → α-ketoglutarate + NADH + H^+ + CoA + CO_2 (TCA cycle)	2

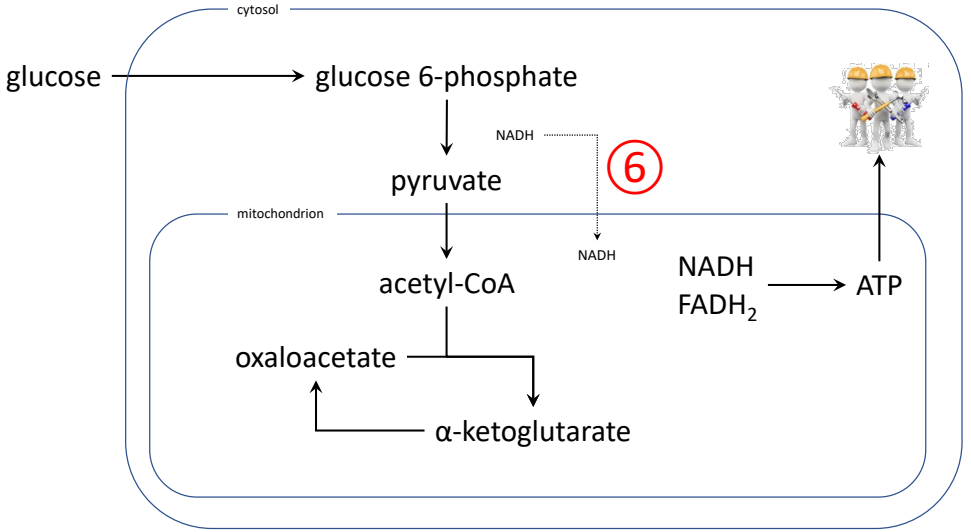
Constructing pathways using the Excel tool



glucose + 3.5 ADP + 2.5 H_2O + 3.5 P_i + 2 FAD + 10 NAD^+ → 3.5 ATP + 2 $FADH_2$ + 10 NADH + 4.5 H^+ + 6 CO_2 (Q not available)

Type	Metabolite	As a …	To/From …	Meta-reaction	Flux
carbohydrates	glucose	substrate	glucose 6-phosphate	glucose + ATP → glucose 6-phosphate + ADP + H^+	1
intermediate metabolites	glucose 6-phosphate	substrate	pyruvate (glycolysis)	glucose 6-phosphate + 3 ADP + 2 P_i + 2 NAD^+ → 2 pyruvate + 3 ATP + 2 NADH + H^+ + 2 H_2O (glycolysis)	1
intermediate metabolites	pyruvate	substrate	acetyl-CoA	pyruvate + NAD^+ + CoA → acetyl-CoA + NADH + CO_2	2
intermediate metabolites	acetyl-CoA	substrate	with oxaloacetate → α-ketoglutarate (TCA cycle)	acetyl-CoA + oxaloacetate + NAD^+ + H_2O → α-ketoglutarate + NADH + H^+ + CoA + CO_2 (TCA cycle)	2
intermediate metabolites	α-ketoglutarate	substrate	oxaloacetate (TCA cycle)	α-ketoglutarate + 0.75 ADP + 0.75 P_i + 2 NAD^+ + FAD + 1.25 H_2O → oxaloacetate + 0.75 ATP + 2 NADH + 0.25 H^+ + $FADH_2$ + CO_2 (TCA cycle)	2

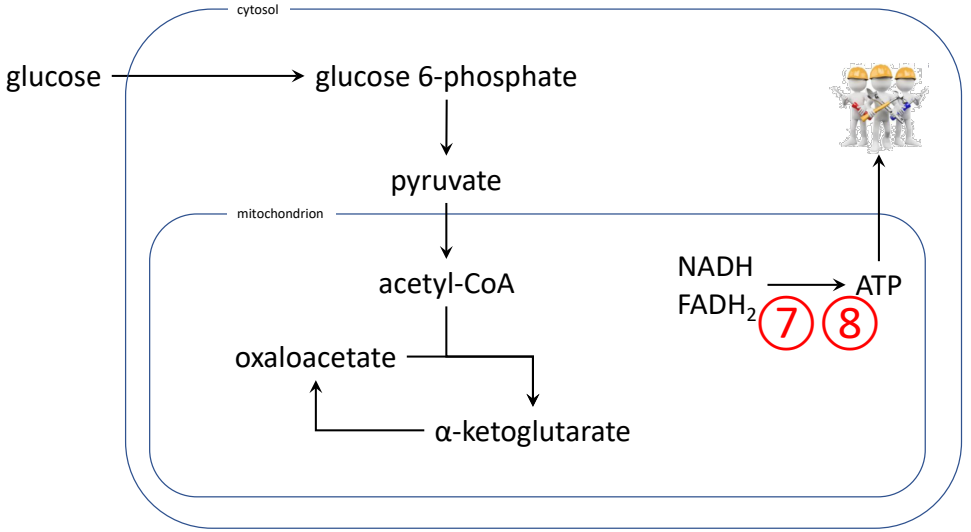
Constructing pathways using the Excel tool



glucose + 3 ADP + 3 H_2O + 3 P_i + 2 FAD + 10 NAD^+ → 3 ATP + 2 $FADH_2$ + 10 NADH + 5 H^+ + 6 CO_2 (Q not available)

Type	Metabolite	As a …	To/From …	Meta-reaction	Flux
carbohydrates	glucose	substrate	glucose 6-phosphate	glucose + ATP → glucose 6-phosphate + ADP + H^+	1
intermediate metabolites	glucose 6-phosphate	substrate	pyruvate (glycolysis)	glucose 6-phosphate + 3 ADP + 2 P_i + 2 NAD^+ → 2 pyruvate + 3 ATP + 2 NADH + H^+ + 2 H_2O (glycolysis)	1
intermediate metabolites	pyruvate	substrate	acetyl-CoA	pyruvate + NAD^+ + CoA → acetyl-CoA + NADH + CO_2	2
intermediate metabolites	acetyl-CoA	substrate	with oxaloacetate → α-ketoglutarate (TCA cycle)	acetyl-CoA + oxaloacetate + NAD^+ + H_2O → α-ketoglutarate + NADH + H^+ + CoA + CO_2 (TCA cycle)	2
intermediate metabolites	α-ketoglutarate	substrate	oxaloacetate (TCA cycle)	α-ketoglutarate + 0.75 ADP + 0.75 P_i + 2 NAD^+ + FAD + 1.25 H_2O → oxaloacetate + 0.75 ATP + 2 NADH + 0.25 H^+ + $FADH_2$ + CO_2 (TCA cycle)	2
electron transport and ATP metabolism	NADH	substrate	NADH cytosol → NADH mitochondrion	0.25 ATP + 0.25 H_2O → 0.25 ADP + 0.25 P_i + 0.25 H^+ (malate - aspartate shuttle)	2

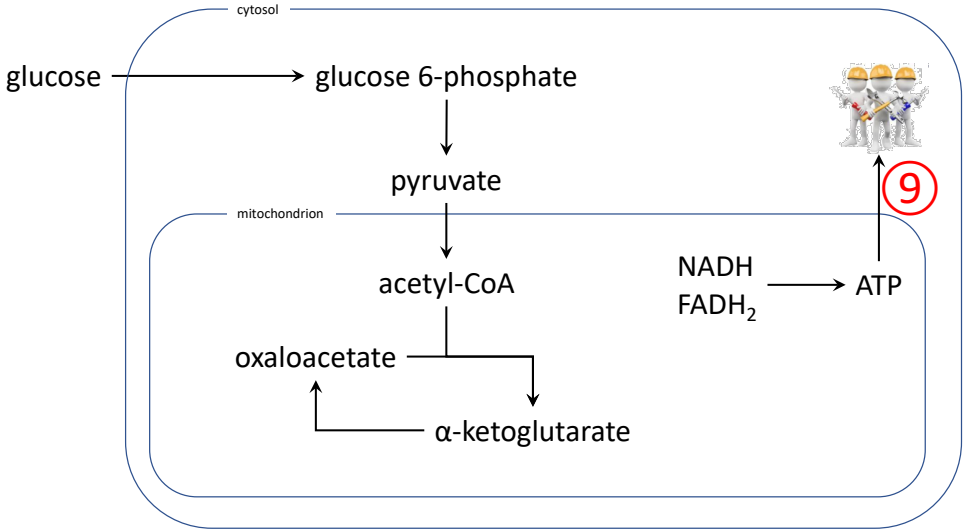
Constructing pathways using the Excel tool



glucose + 31 ADP + 31 H^+ + 31 P_i + 6 O_2 → 31 ATP + 37 H_2O + 6 CO_2 (Q = 1,927 kJ)

Type	Metabolite	As a …	To/From …	Meta-reaction	Flux
carbohydrates	glucose	substrate	glucose 6-phosphate	glucose + ATP → glucose 6-phosphate + ADP + H^+	1
intermediate metabolites	glucose 6-phosphate	substrate	pyruvate (glycolysis)	glucose 6-phosphate + 3 ADP + 2 P_i + 2 NAD^+ → 2 pyruvate + 3 ATP + 2 NADH + H^+ + 2 H_2O (glycolysis)	1
intermediate metabolites	pyruvate	substrate	acetyl-CoA	pyruvate + NAD^+ + CoA → acetyl-CoA + NADH + CO_2	2
intermediate metabolites	acetyl-CoA	substrate	with oxaloacetate → α-ketoglutarate (TCA cycle)	acetyl-CoA + oxaloacetate + NAD^+ + H_2O → α-ketoglutarate + NADH + H^+ + CoA + CO_2 (TCA cycle)	2
intermediate metabolites	α-ketoglutarate	substrate	oxaloacetate (TCA cycle)	α-ketoglutarate + 0.75 ADP + 0.75 P_i + 2 NAD^+ + FAD + 1.25 H_2O → oxaloacetate + 0.75 ATP + 2 NADH + 0.25 H^+ + $FADH_2$ + CO_2 (TCA cycle)	2
electron transport and ATP metabolism	NADH	substrate	NADH cytosol → NADH mitochondrion	0.25 ATP + 0.25 H_2O → 0.25 ADP + 0.25 P_i + 0.25 H^+ (malate - aspartate shuttle)	2
electron transport and ATP metabolism	NADH	substrate	ATP (oxidative phosphorylation)	2.5 ADP + 2.5 P_i + NADH + 3.5 H^+ + 0.5 O_2 → 2.5 ATP + NAD^+ + 3.5 H_2O (oxidative phosphorylation)	10
electron transport and ATP metabolism	$FADH_2$	substrate	ATP (oxidative phosphorylation)	1.5 ADP + 1.5 P_i + 0.5 H^+ + $FADH_2$ + 0.5 O_2 → 1.5 ATP + FAD + 2.5 H_2O (oxidative phosphorylation)	2

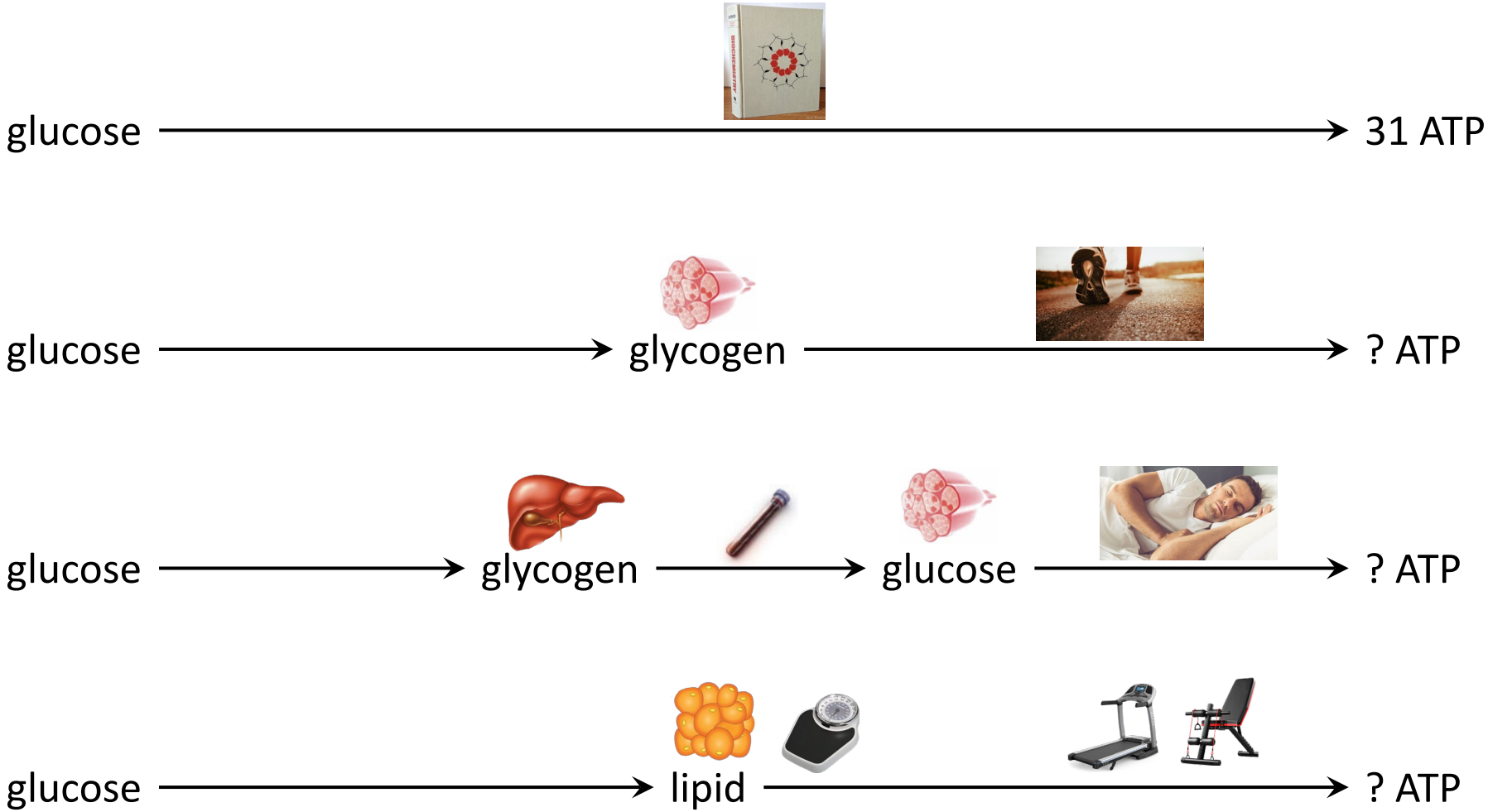
Constructing pathways using the Excel tool



glucose + 6 O_2 → 6 H_2O + 6 CO_2 Q = 2,814 kJ

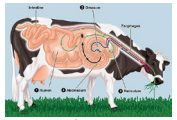
Type	Metabolite	As a …	To/From …	Meta-reaction	Flux
carbohydrates	glucose	substrate	glucose 6-phosphate	glucose + ATP → glucose 6-phosphate + ADP + H^+	1
intermediate metabolites	glucose 6-phosphate	substrate	pyruvate (glycolysis)	glucose 6-phosphate + 3 ADP + 2 P_i + 2 NAD^+ → 2 pyruvate + 3 ATP + 2 NADH + H^+ + 2 H_2O (glycolysis)	1
intermediate metabolites	pyruvate	substrate	acetyl-CoA	pyruvate + NAD^+ + CoA → acetyl-CoA + NADH + CO_2	2
intermediate metabolites	acetyl-CoA	substrate	with oxaloacetate → α-ketoglutarate (TCA cycle)	acetyl-CoA + oxaloacetate + NAD^+ + H_2O → α-ketoglutarate + NADH + H^+ + CoA + CO_2 (TCA cycle)	2
intermediate metabolites	α-ketoglutarate	substrate	oxaloacetate (TCA cycle)	α-ketoglutarate + 0.75 ADP + 0.75 P_i + 2 NAD^+ + FAD + 1.25 H_2O → oxaloacetate + 0.75 ATP + 2 NADH + 0.25 H^+ + $FADH_2$ + CO_2 (TCA cycle)	2
electron transport and ATP metabolism	NADH	substrate	NADH cytosol → NADH mitochondrion	0.25 ATP + 0.25 H_2O → 0.25 ADP + 0.25 P_i + 0.25 H^+ (malate - aspartate shuttle)	2
electron transport and ATP metabolism	NADH	substrate	ATP (oxidative phosphorylation)	2.5 ADP + 2.5 P_i + NADH + 3.5 H^+ + 0.5 O_2 → 2.5 ATP + NAD^+ + 3.5 H_2O (oxidative phosphorylation)	10
electron transport and ATP metabolism	$FADH_2$	substrate	ATP (oxidative phosphorylation)	1.5 ADP + 1.5 P_i + 0.5 H^+ + $FADH_2$ + 0.5 O_2 → 1.5 ATP + FAD + 2.5 H_2O (oxidative phosphorylation)	2
electron transport and ATP metabolism	ATP	substrate	e.g., maintenance, peptide synthesis	ATP + H_2O → ADP + P_i + H^+	31

Using meta-reactions to teach nutritional biochemistry

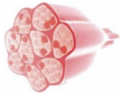
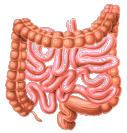


Using meta-reactions to teach nutritional biochemistry


glucose → lactose → glucose (+ galactose) → ? ATP



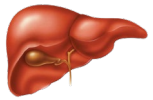

propionate → glucose → lactose → glucose (+ galactose) → ? ATP

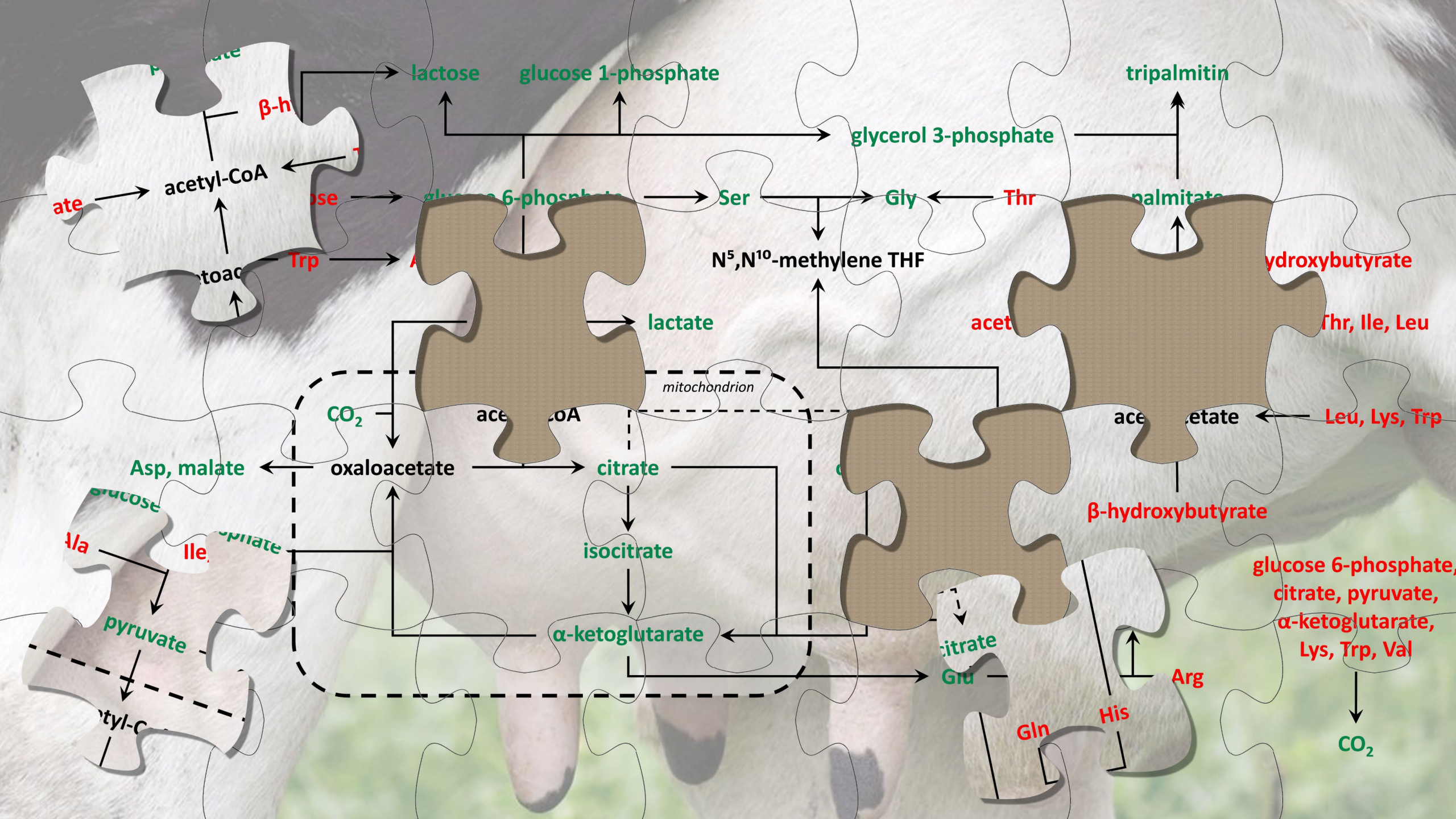
glucose → glutamine

glutamine → ? ATP

glucose → ? ATP




lactate ← lactate


lactose
glucose 1-phosphate
tripalmitin
β-h
acetyl-CoA
glycerol 3-phosphate
ate
Ser
Gly
Thr
Trp
N5,N10-methylene THF
lactate
Thr, Ile, Leu
mitochondrion
CO2
Leu, Lys, Trp
Asp, malate
oxaloacetate
citrate
β-hydroxybutyrate
isocitrate
pyruvate
α-ketoglutarate
Glu
Arg
Gln
His
glucose 6-phosphate,
citrate, pyruvate,
α-ketoglutarate,
Lys, Trp, Val
CO2

Using meta-reactions to balance metabolites in the mammary gland

J. Dairy Sci. 92:6068–6082
doi:10.3168/jds.2009-2018

Whole-body glucose metabolism and mammary energetic nutrient metabolism in lactating dairy cows receiving digestive infusions of casein and propionic acid

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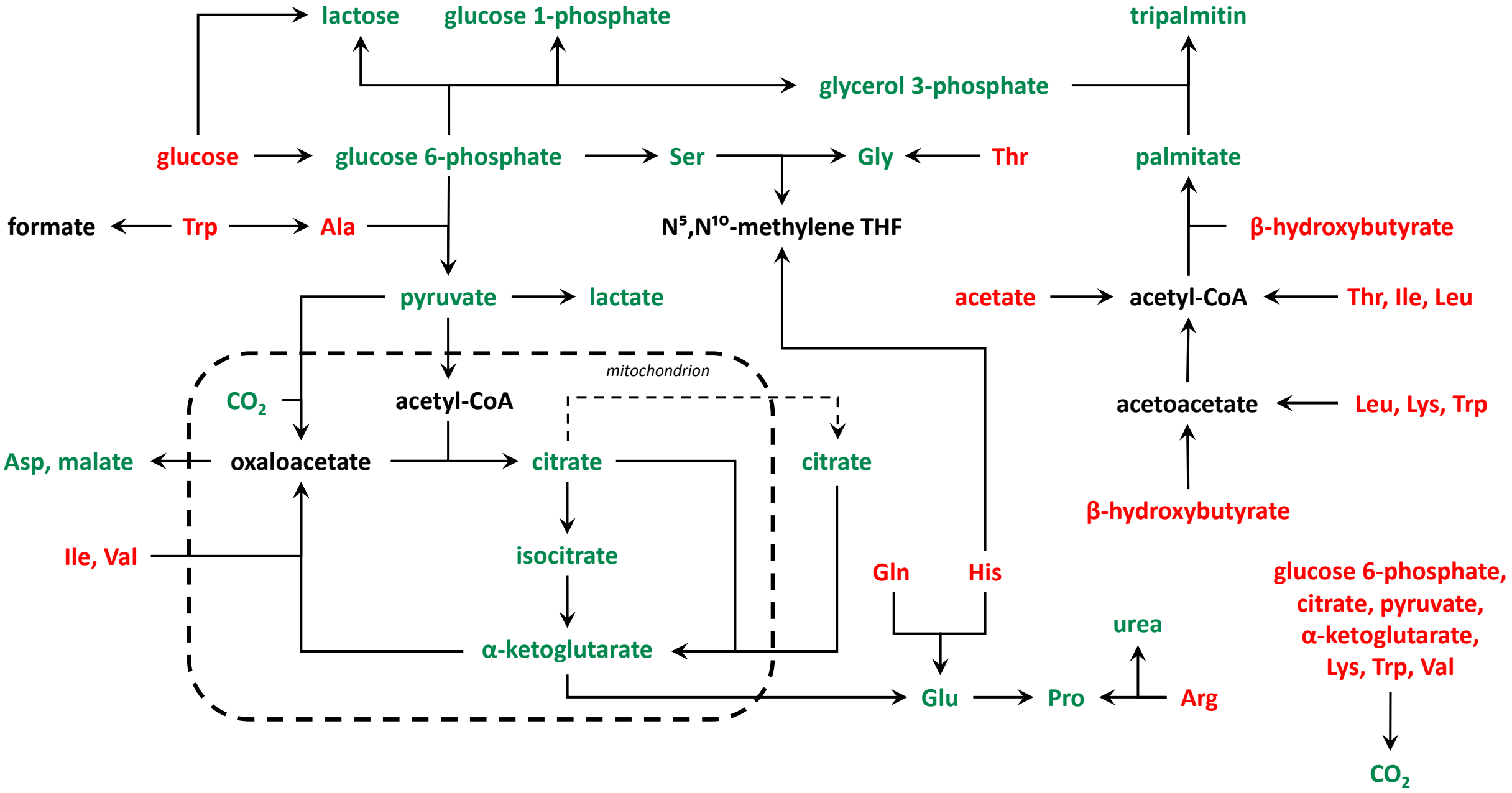
*INRA, UMR1080 Dairy Production, F-35590 Saint Gilles, France
†Agrocampus Ouest, UMR1080 Dairy Production, F-35000 Rennes, France
‡Organic Dairy Research Centre, Guelph University, Alfred campus, 31 rue St-Paul, PO Box 580, Alfred, Ontario K0B 1A0, Canada
§Rowett Institute of Nutrition and Health, University of Aberdeen, Aberdeen AB21 9SB, United Kingdom
#Dairy and Swine Research and Development Centre, Agriculture and Agri-Food Canada, STN Lennoxville, Sherbrooke, Québec J1M 1Z3, Canada

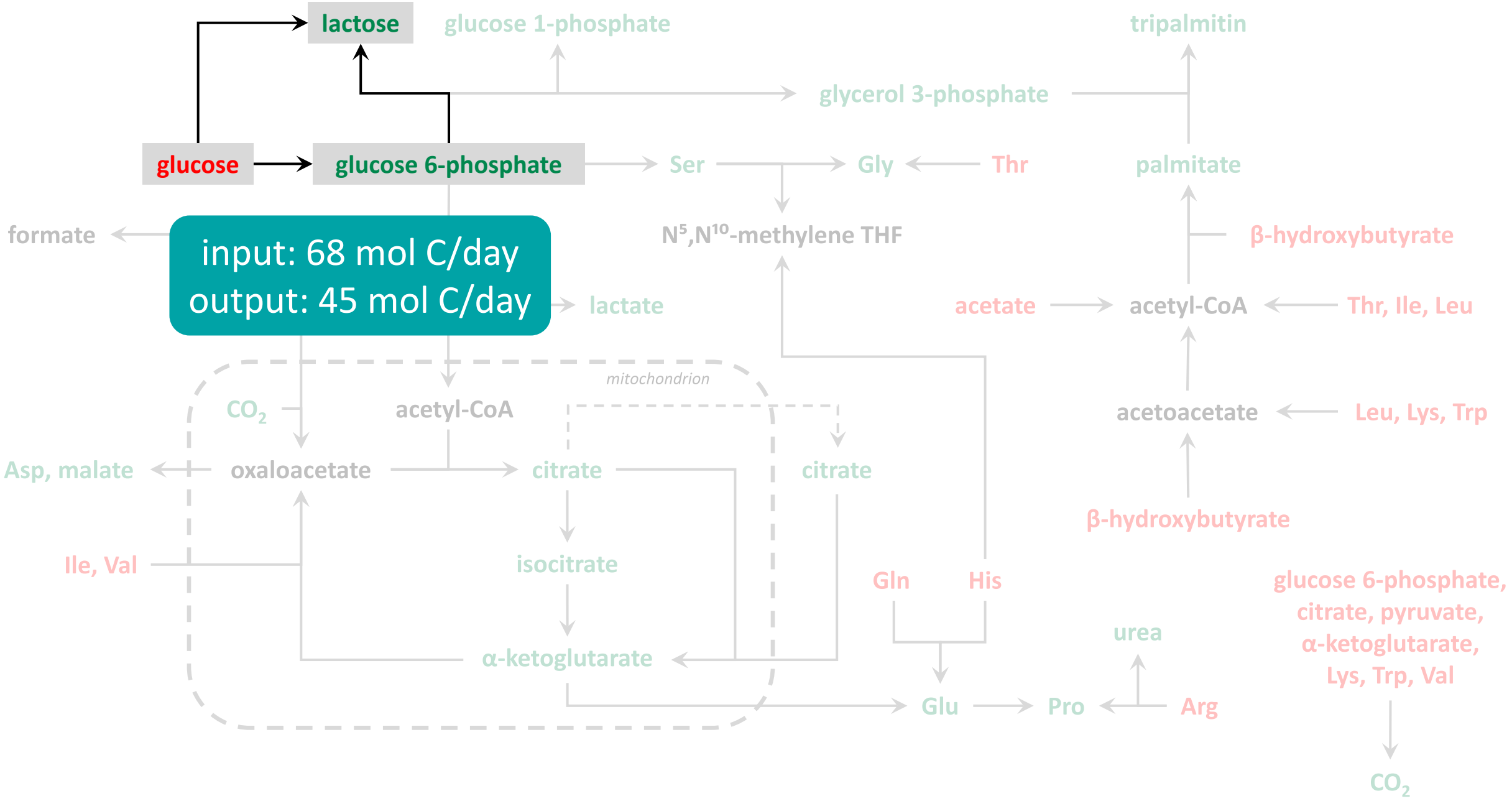
J. Dairy Sci. 89:4340–4351

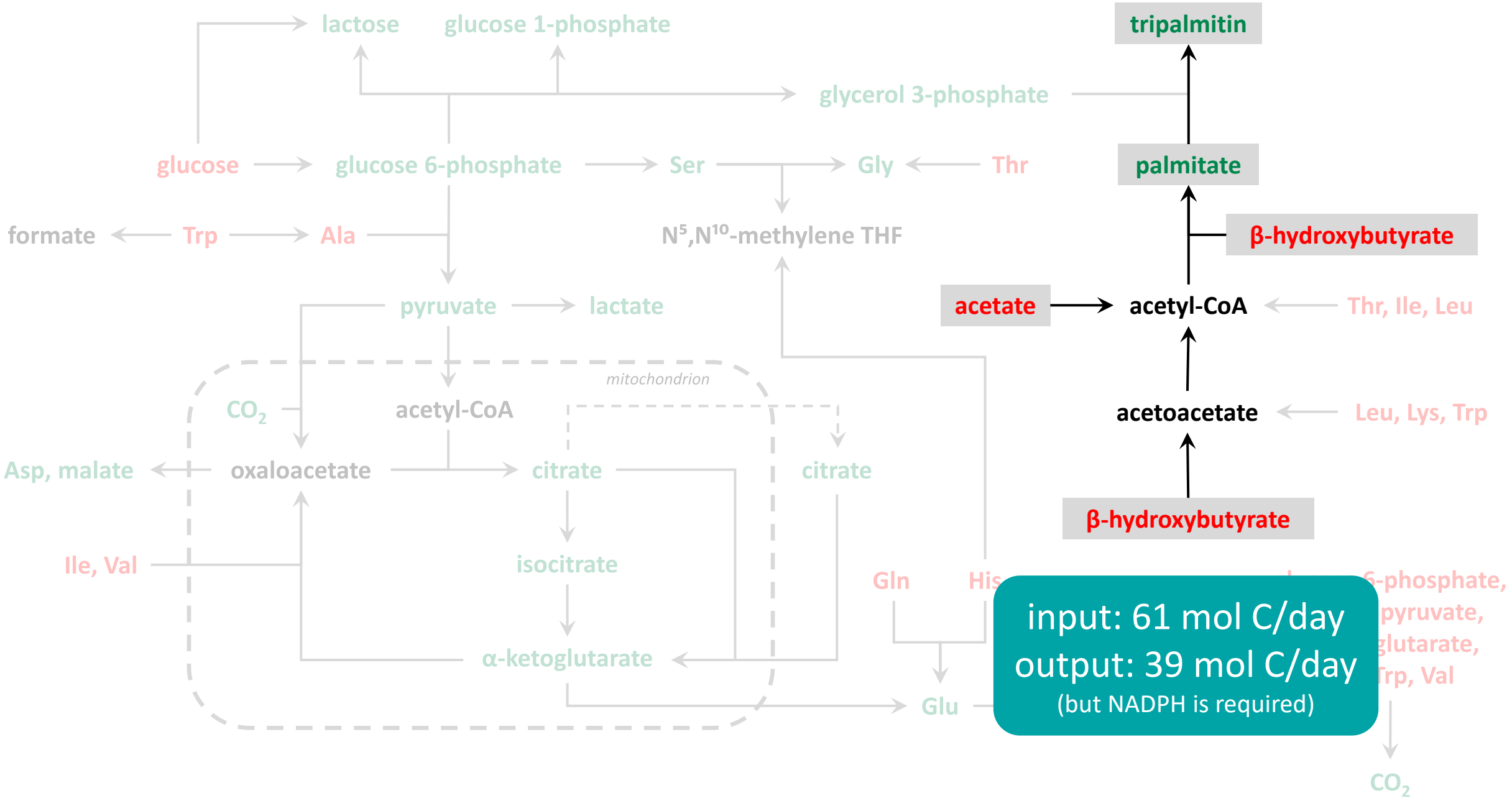
Effect of Casein and Propionate Supply on Mammary Protein Metabolism in Lactating Dairy Cows

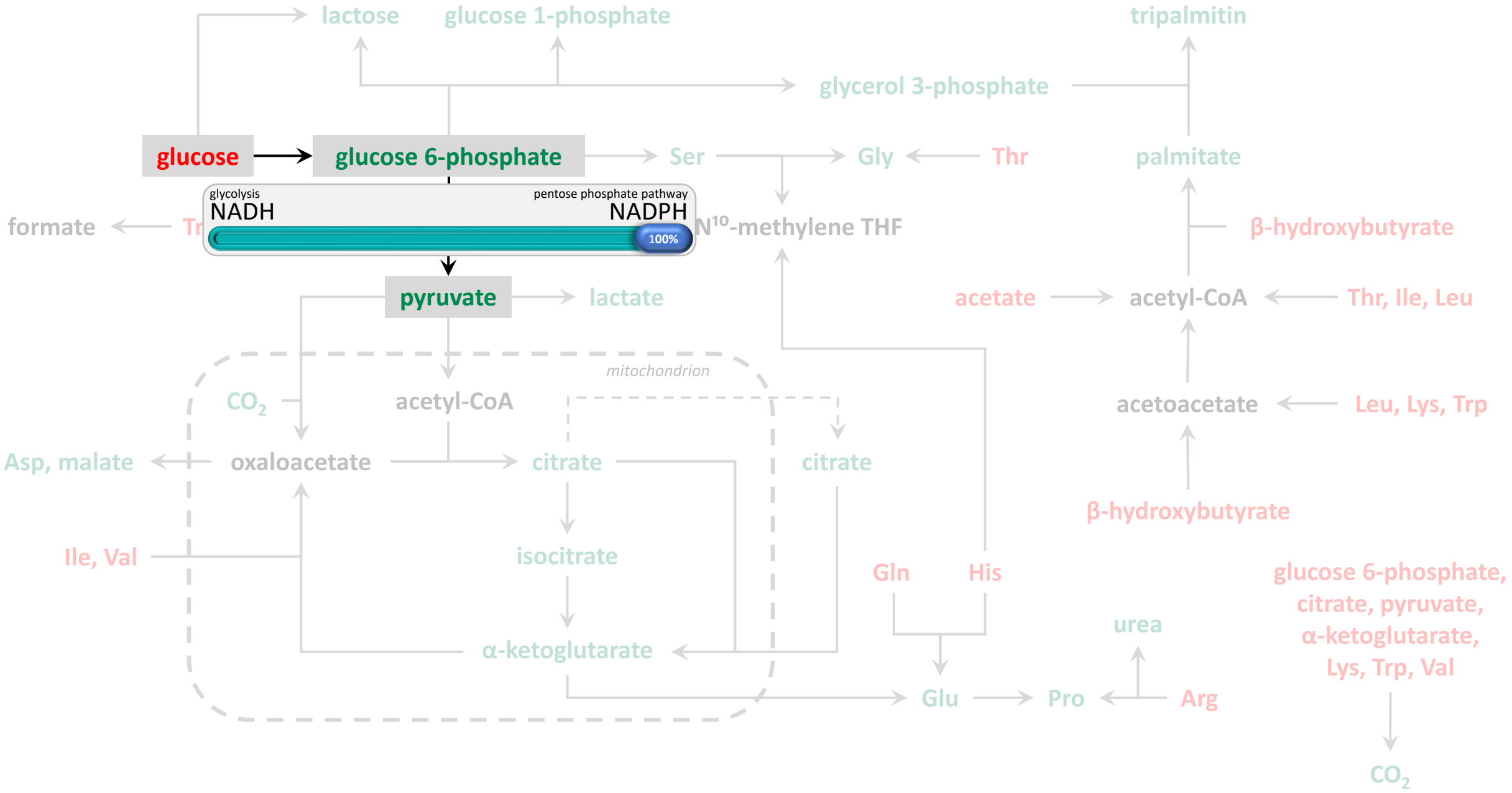
G. Raggio,* S. Lemosquet,† G. E. Lobley,‡ H. Rulquin,† and H. Lapierre§[1]
*Department of Animal Science, Université Laval, Québec, Québec, Canada, G1K 7P4
†Institut National de la Recherche Agronomique, Unité Mixte de Recherches Production du Lait, 35590 Saint-Gilles, France
‡Rowett Research Institute, Aberdeen, UK, AB21 9SB
§Dairy and Swine Research & Development Centre, Agriculture and Agri-Food Canada, Sherbrooke, Quebec, Canada, J1M 1Z3

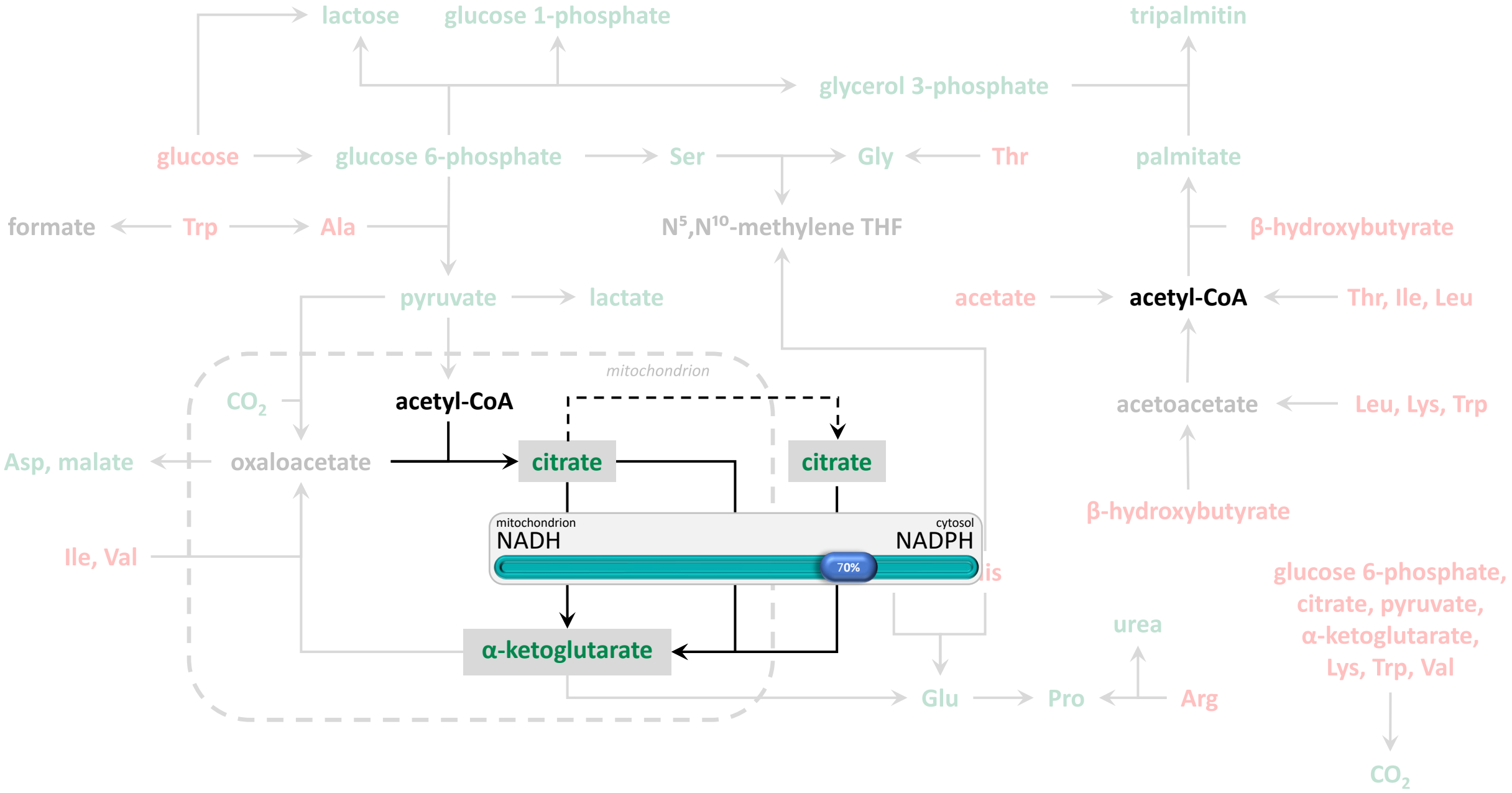
Substrate (input)	mol/d	Product (output)	mol/d
Glucose	11.36	Lactose	3.73
Acetate	24.48	Tripalmitin (C16:0)	0.73
β-Hydroxybutyrate	4.03	Palmitate (C16:0)	0.12
Alanine	0.02	Aspartate	0.16
Arginine	0.21	Cysteine	0.01
Glutamine	0.04	Glutamate	0.04
Histidine	0.01	Glycine	0.22
Isoleucine	0.10	Proline	0.54
Leucine	0.10	Serine	0.38
Lysine	0.12	Lactate	0.29
Threonine	0.01	Citrate	0.27
Tryptophan	0.001	Isocitrate	0.01
Valine	0.12	Glucose 1-phosphate	0.001
O_2	31.68	Glucose 6-phosphate	0.001
		Glycerol 3-phosphate	0.001
		Malate	0.01
		Pyruvate	0.001
		α-Ketoglutarate	0.002
		Urea (blood)	0.02
		Non-protein nitrogen (milk)	0.39
		CO_2	44.64

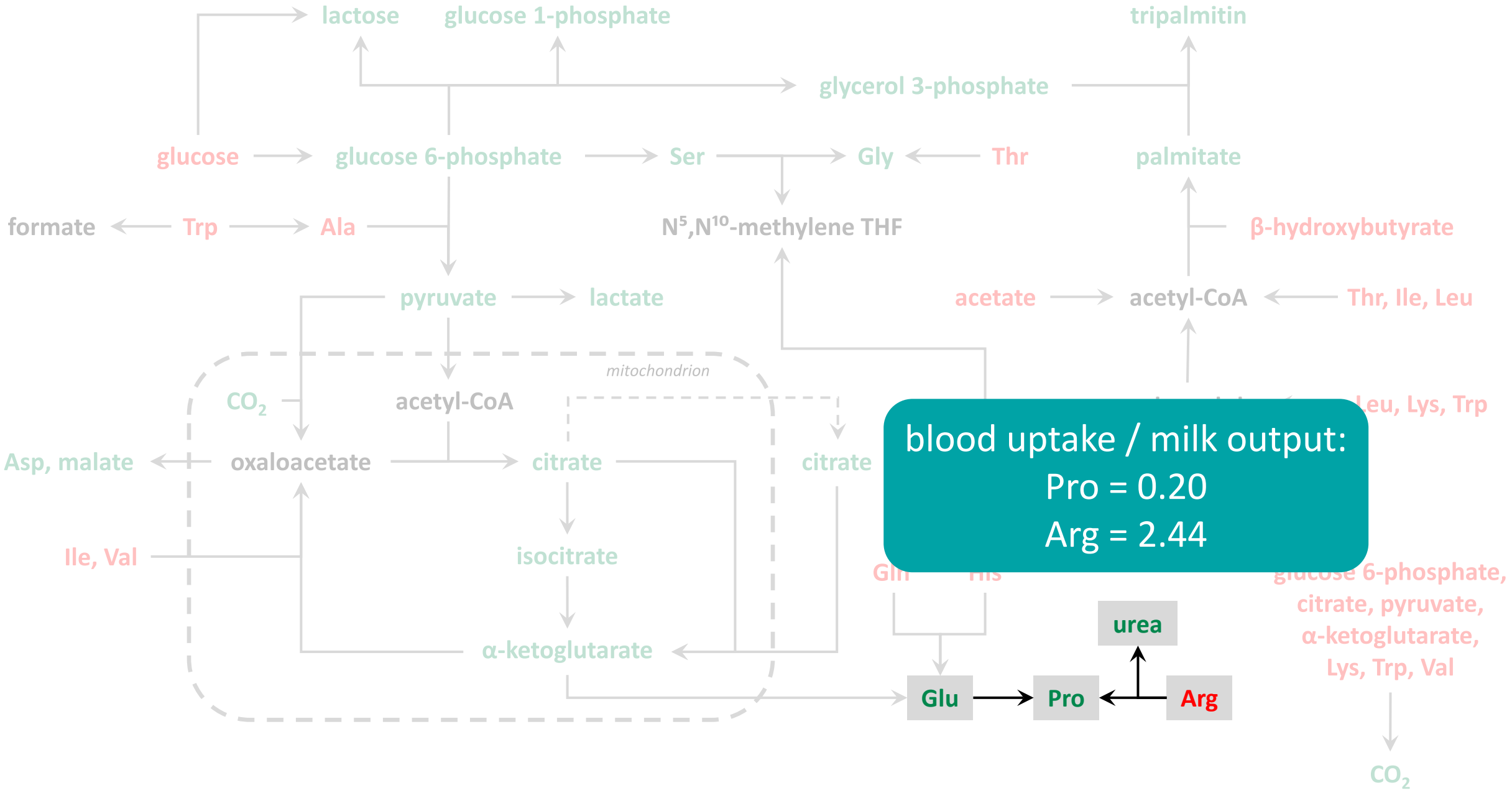

lactose
glucose 1-phosphate
tripalmitin
glycerol 3-phosphate
glucose
glucose 6-phosphate
Ser
Gly
Thr
palmitate
formate
Trp
Ala
N5,N10-methylene THF
β-hydroxybutyrate
pyruvate
lactate
acetate
acetyl-CoA
Thr, Ile, Leu
mitochondrion
CO2
acetyl-CoA
acetoacetate
Leu, Lys, Trp
Asp, malate
oxaloacetate
citrate
citrate
β-hydroxybutyrate
Ile, Val
isocitrate
Gln
His
glucose 6-phosphate,
citrate, pyruvate,
α-ketoglutarate,
Lys, Trp, Val
urea
α-ketoglutarate
Glu
Pro
Arg
CO2


lactose
glucose 1-phosphate
tripalmitin
glycerol 3-phosphate
glucose
glucose 6-phosphate
Ser
Gly
Thr
palmitate
formate
input: 68 mol C/day
output: 45 mol C/day
N5,N10-methylene THF
β-hydroxybutyrate
lactate
acetate
acetyl-CoA
Thr, Ile, Leu
mitochondrion
CO2
acetyl-CoA
acetoacetate
Leu, Lys, Trp
Asp, malate
oxaloacetate
citrate
citrate
β-hydroxybutyrate
Ile, Val
isocitrate
Gln
His
glucose 6-phosphate,
citrate, pyruvate,
α-ketoglutarate,
Lys, Trp, Val
urea
α-ketoglutarate
Glu
Pro
Arg
CO2


lactose
glucose 1-phosphate
tripalmitin
glycerol 3-phosphate
glucose
glucose 6-phosphate
Ser
Gly
Thr
palmitate
formate
Trp
Ala
N5,N10-methylene THF
β-hydroxybutyrate
acetate
acetyl-CoA
Thr, Ile, Leu
pyruvate
lactate
mitochondrion
CO2
acetyl-CoA
acetoacetate
Leu, Lys, Trp
Asp, malate
oxaloacetate
citrate
citrate
β-hydroxybutyrate
Ile, Val
isocitrate
Gln
His
α-ketoglutarate
Glu
input: 61 mol C/day
output: 39 mol C/day
(but NADPH is required)
pyruvate,
Trp, Val
CO2


lactose
glucose 1-phosphate
tripalmitin
glycerol 3-phosphate
glucose
glucose 6-phosphate
Ser
Gly
Thr
palmitate
glycolysis
NADH
pentose phosphate pathway
NADPH
100%
formate
N10-methylene THF
β-hydroxybutyrate
pyruvate
lactate
acetate
acetyl-CoA
Thr, Ile, Leu
mitochondrion
CO2
acetyl-CoA
acetoacetate
Leu, Lys, Trp
Asp, malate
oxaloacetate
citrate
citrate
β-hydroxybutyrate
Ile, Val
isocitrate
Gln
His
glucose 6-phosphate,
citrate, pyruvate,
α-ketoglutarate,
Lys, Trp, Val
urea
α-ketoglutarate
Glu
Pro
Arg
CO2


lactose
glucose 1-phosphate
tripalmitin
glycerol 3-phosphate
glucose
glucose 6-phosphate
Ser
Gly
Thr
palmitate
formate
Trp
Ala
N5,N10-methylene THF
β-hydroxybutyrate
pyruvate
lactate
acetate
acetyl-CoA
Thr, Ile, Leu
mitochondrion
CO2
acetyl-CoA
acetoacetate
Leu, Lys, Trp
Asp, malate
oxaloacetate
citrate
citrate
β-hydroxybutyrate
mitochondrion
cytosol
NADH
NADPH
70%
Ile, Val
glucose 6-phosphate,
citrate, pyruvate,
α-ketoglutarate,
Lys, Trp, Val
urea
α-ketoglutarate
Glu
Pro
Arg
CO2


lactose
glucose 1-phosphate
tripalmitin
glycerol 3-phosphate
glucose
glucose 6-phosphate
Ser
Gly
Thr
palmitate
formate
Trp
Ala
N5,N10-methylene THF
β-hydroxybutyrate
pyruvate
lactate
acetate
acetyl-CoA
Thr, Ile, Leu
mitochondrion
CO2
acetyl-CoA
Leu, Lys, Trp
Asp, malate
oxaloacetate
citrate
citrate
blood uptake / milk output:
Pro = 0.20
Arg = 2.44
Ile, Val
isocitrate
Gln
His
glucose 6-phosphate,
citrate, pyruvate,
α-ketoglutarate,
Lys, Trp, Val
α-ketoglutarate
urea
Glu
Pro
Arg
CO2

Arginine metabolism in the mammary gland

Metabolism of Arginine and Ornithine in the Cow and Rabbit Mammary Tissue[1]

J. H. CLARK, R. G. DERRIG, C. L. DAVIS, and H. R. SPIRES
Department of Dairy Science
University of Illinois
Urbana 61801

The Importance of Ornithine as a Precursor for Proline in Mammalian Cells

ROBERT J. SMITH [1] AND JAMES M. PHANG [2]
Endocrinology Section, Metabolism Branch, National Cancer Institute, Bethesda, Maryland 20014

Animal (2019), **13:4**, pp 790–798 © The Animal Consortium 2018
doi:10.1017/S1751731118002069

animal

Dietary L-arginine supplementation increased mammary gland vascularity of lactating sows

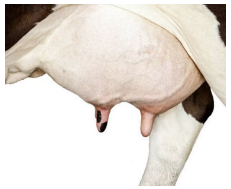
D. M. Holanda[1], C. S. Marcolla[1], S. E. F. Guimarães[1], M. M. Neves[2], G. J. Hausman[3], M. S. Duarte[1], M. L. T. Abreu[4] and A. Saraiva[1†]

[1]Department of Animal Sciences, Universidade Federal de Viçosa, Viçosa MG 36570-900, Brazil; [2]Department of Biology, Universidade Federal de Viçosa, Viçosa, MG 36570-900, Brazil; [3]United States Department of Agriculture, Agriculture Research Services, Athens, GA 30605, USA; [4]Department of Animal Sciences, Universidade Federal de Lavras, Lavras, MG 37200-000, Brazil

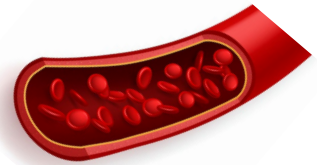
Local Secretion of Nitric Oxide and the Control of Mammary Blood Flow[1]

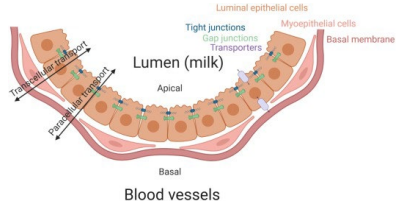
P. LACASSE,*,[2] V. C. FARR,† S. R. DAVIS,† and C. G. PROSSER†,[3]
*Agriculture and Agri-Food Canada, Dairy and Swine Research and Development Centre, PO Box 90, Lennoxville, QC, Canada J1M 1Z3
†Dairy Science Group, AgResearch, Ruakura Research Centre, Private Bag 3123, Hamilton, New Zealand

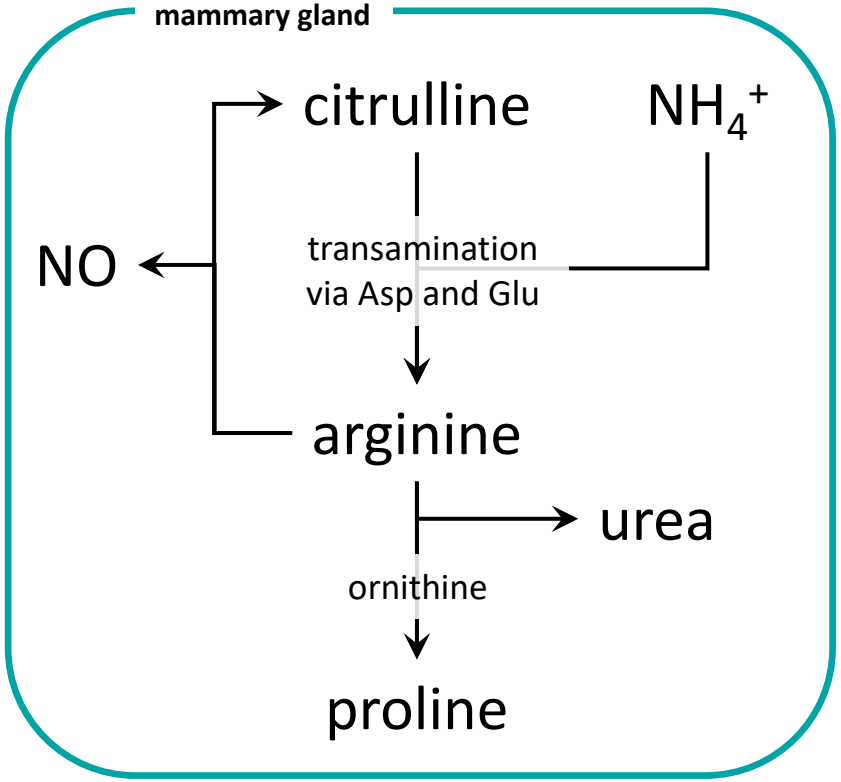
Arginine metabolism in the mammary gland

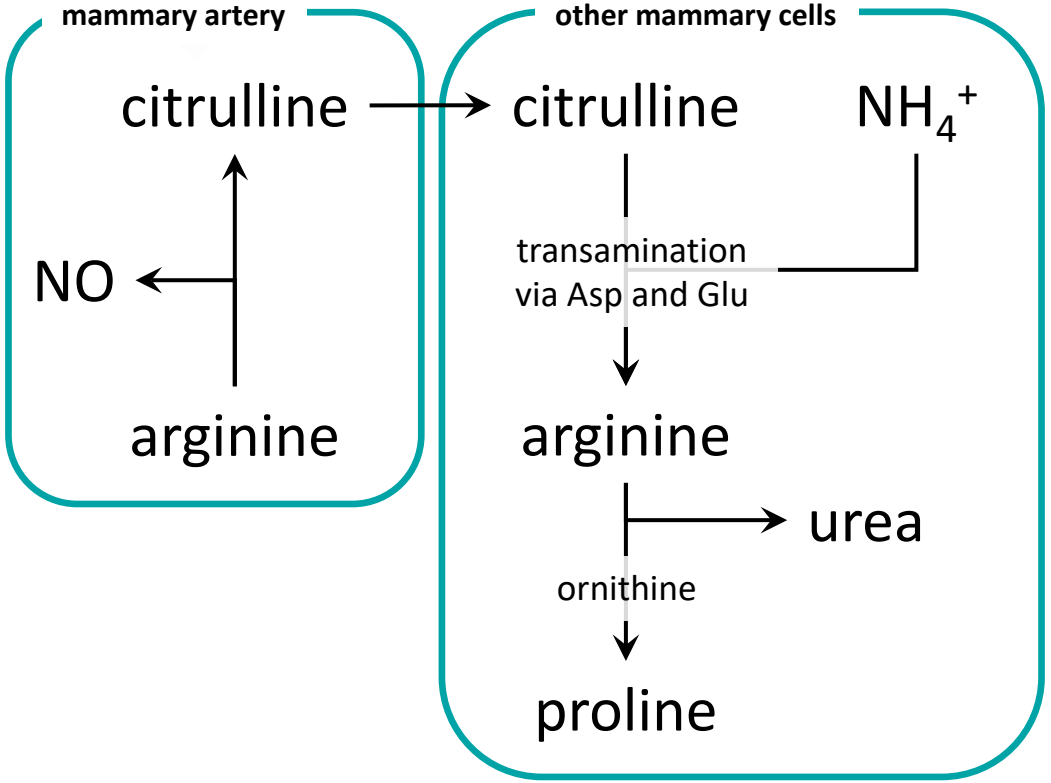


compartmentalization of metabolism









Conclusion

- Meta-reactions are useful to teach nutritional biochemistry
- Meta-reactions can be used to analyze nutritional balances
- Compartmentalization of metabolism has an impact on “efficiency”
- Meta-reactions can be developed for other domains

Further information

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Contents lists available at ScienceDirect

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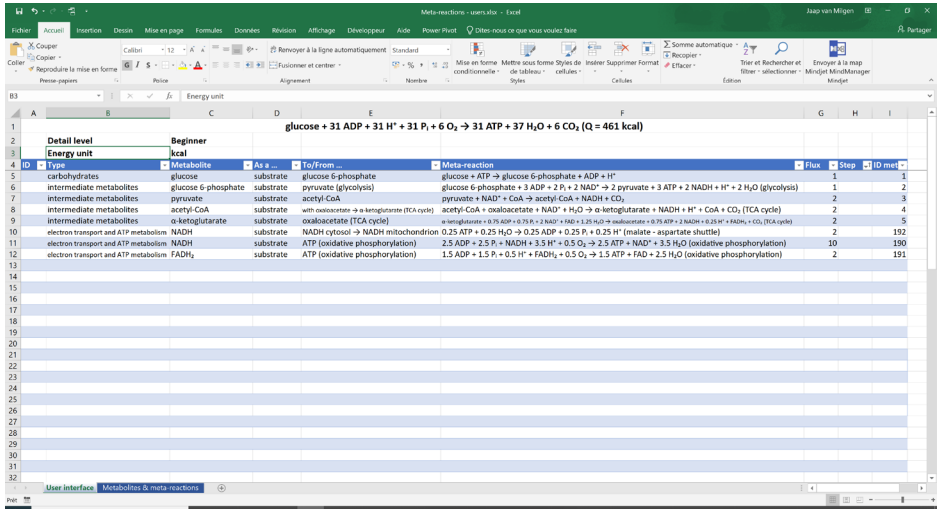
The international journal of animal biosciences

From the biochemical pieces to the nutritional puzzle: using meta-reactions in teaching and research

J. van Milgen

PEGASE, INRAE, Institut Agro, 35590 Saint Gilles, France



Two versions of the Excel tool:

- End-users: to teach nutritional biochemistry and for use in research
- Developers: to modify and add meta-reactions

Acknowledgements

- François Moreews and Sophie Lemosquet (UMR Pegase, INRAE)
- Student and staff:
  - Universidade Estadual Paulista “Júlio de Mesquita Filho” (UNESP), Jaboticabal (Brazil)
  - Guangdong Academy of Agricultural Science (GDAAS) in Guangzhou (China)
  - University of Illinois at Urbana-Champaign (USA)
- COVID-19 Coronavirus