

Flux Balance Analysis

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INTRODUCTION

In this tutorial, Flux Balance Analysis (FBA) is introduced using the E. coli core model, with functions in the COBRA Toolbox v3.0 [2].

E. coli core model

A map of the E. coli core model is shown in Figure 1.

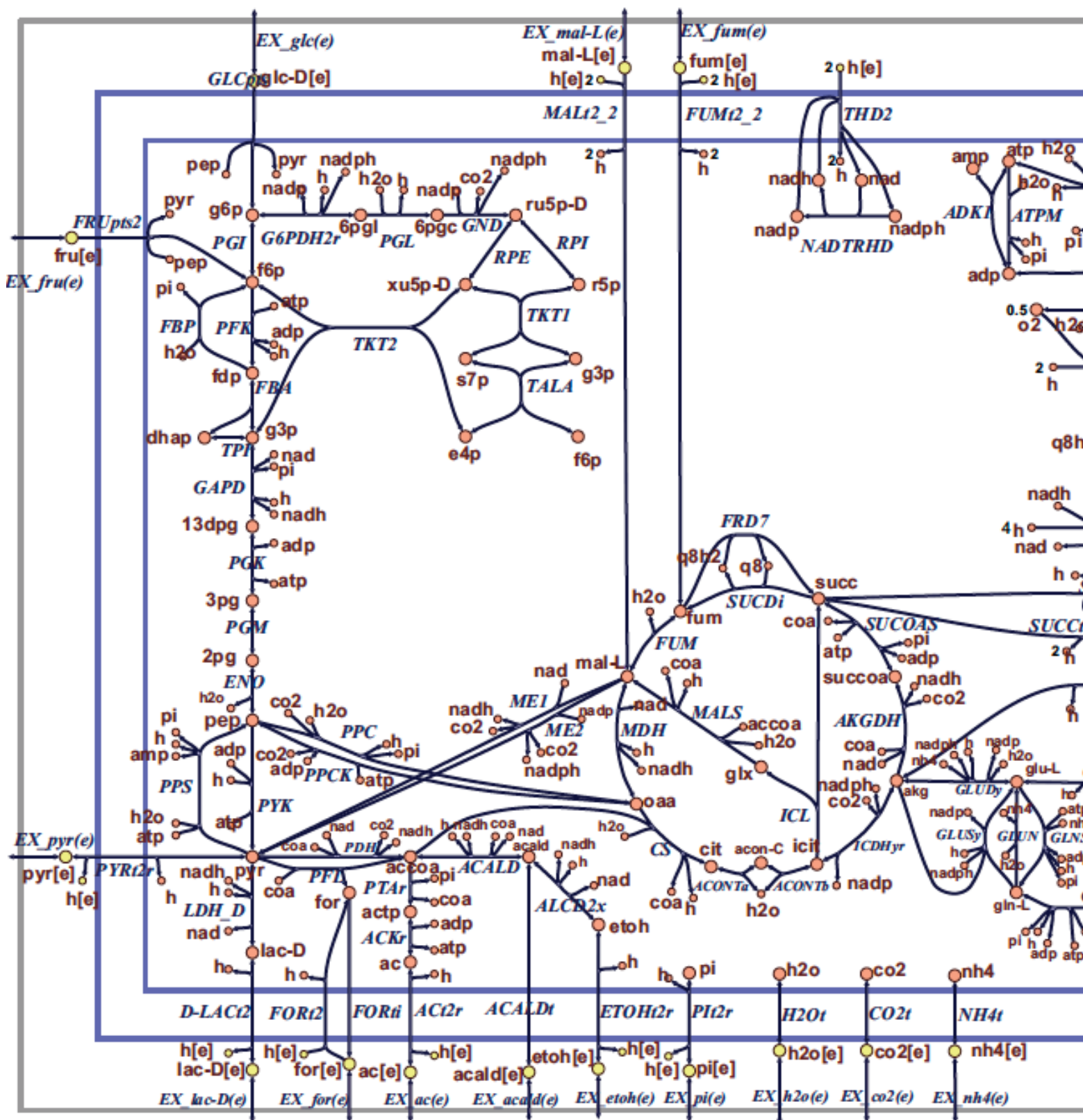


Figure 1 Map of the core *E. coli* metabolic network. Orange circles represent cytosolic metabolites, yellow circles represent extracellular metabolites, and the blue arrows represent reactions. Reaction name abbreviations are uppercase (blue) and metabolite name abbreviations are lowercase (rust colour). This flux map was drawn using SimPheny and edited for clarity with Adobe Illustrator.

MATERIALS - EQUIPMENT SETUP

Please ensure that all the required dependencies (e.g. , `git` and `curl`) of The COBRA Toolbox have been properly installed by following the installation guide [here](#). Please ensure that the COBRA Toolbox has been initialised (`tutorial_initialize.mlx`) and verify that the pre-packaged LP and QP solvers are functional (`tutorial_verify.mlx`).

PROCEDURE


























Load E. coli core model

The most direct way to load a model into The COBRA Toolbox is to use the `readCbModel` function. For example, to load a model from a MAT-file, you can simply use the filename (with or without file extension).

```
fileName = 'ecoli_core_model.mat';
if ~exist('modelOri','var')
    modelOri = readCbModel(fileName);
end
%backward compatibility with primer requires relaxation of upper bound on
%ATPM
modelOri = changeRxnBounds(modelOri,'ATPM',1000,'u');
model = modelOri;
```

model

1x1 struct with 28 fields

Field ▲	Value	Size
 S	72x95 sparse do...	72x95
 mets	72x1 cell	72x1
 b	72x1 double	72x1
 csense	72x1 char	72x1
 rxns	95x1 cell	95x1
 lb	95x1 double	95x1
 ub	95x1 double	95x1
 c	95x1 double	95x1
 osenseStr	'max'	1x3
 genes	137x1 cell	137x1
 rules	95x1 cell	95x1
 metCharges	72x1 int32	72x1
 metFormulas	72x1 cell	72x1
 metNames	72x1 cell	72x1
 metInChIString	72x1 cell	72x1
 metKEGGID	72x1 cell	72x1
 metChEBIID	72x1 cell	72x1
 metPubChemID	72x1 cell	72x1
 grRules	95x1 cell	95x1
 rxnGeneMat	95x137 sparse d...	95x137
 rxnConfidence...	95x1 double	95x1
 rxnNames	95x1 cell	95x1
 rxnNotes	95x1 cell	95x1
 rxnECNumbers	95x1 cell	95x1
 rxnReferences	95x1 cell	95x1
subSystems	95x1 cell	95x1

The meaning of each field in a standard model is defined in the [standard COBRA model field definition](#).

In general, the following fields should always be present:

- **S**, the stoichiometric matrix
- **mets**, the identifiers of the metabolites
- **b**, Accumulation (positive) or depletion (negative) of the corresponding metabolites. 0 Indicates no concentration change.
- **csense**, indicator whether the b vector is a lower bound ('G'), upper bound ('L'), or hard constraint 'E' for the metabolites.
- **rxns**, the identifiers of the reactions
- **lb**, the lower bounds of the reactions
- **ub**, the upper bounds of the reactions
- **c**, the linear objective
- **genes**, the list of genes in your model
- **rules**, the Gene-protein-reaction rules in a computer readable format present in your model.
- **osenseStr**, the objective sense either 'max' for maximisation or 'min' for minimisation

Checking the non-trivial constraints on a model

What are the default constraints on the model?

Hint: `printConstraints`

```
printConstraints(model, -1000, 1000)
```

```
MinConstraints:
ATPM      8.39
EX_glc(e) -10
maxConstraints:
```

Example 1: Calculating growth rates

Growth of *E. coli* on glucose can be simulated under aerobic conditions.

What is the growth rate of *E. coli* on glucose (uptake rate = 18.5 mmol/gDW/h) under aerobic and anaerobic conditions?

Hint: `changeRxnBounds`, `changeObjective`, `optimizeCbModel`, `printFluxVector`

To set the maximum glucose uptake rate to 18.5 mmol gDW⁻¹ hr⁻¹ (millimoles per gram dry cell weight per hour, the default flux units used in the COBRA Toolbox), enter:

```
model = changeRxnBounds(model, 'EX_glc(e)', -18.5, 'l');
```

This changes the lower bound ('l') of the glucose exchange reaction to -18.5, a biologically realistic uptake rate. By convention, exchange reactions are written as export reactions (e.g. 'glc[e] <==>'), so import of a metabolite is a negative flux.

To allow unlimited oxygen uptake, enter:

```
model = changeRxnBounds(model, 'EX_o2(e)', -1000, 'l');
```

By setting the lower bound of the oxygen uptake reaction to such a large number, it is practically unbounded. Next, to ensure that the biomass reaction is set as the objective function, enter:

```
model = changeObjective(model, 'Biomass_Ecoli_core_N(w/GAM)-Nmet2');
```

To perform FBA with maximization of the biomass reaction as the objective, enter:

```
FBAsolution = optimizeCbModel(model, 'max')
```

```
FBAsolution = struct with fields:
    full: [95x1 double]
    obj: 1.6065
    rcost: [95x1 double]
    dual: [72x1 double]
    slack: [72x1 double]
    solver: 'pdco'
    algorithm: 'default'
    stat: 1
    origStat: 0
    time: 0.0119
    basis: []
    f: 1.6065
    x: [95x1 double]
    v: [95x1 double]
    w: [95x1 double]
    y: [72x1 double]
    s: [72x1 double]
```

FBAsolution.f then give the value of the objective function, which should be 1.6531 mmol gDW-1 hr-1

```
FBAsolution.f
```

```
ans = 1.6065
```

This is the same as

```
model.c'*FBAsolution.v
```

```
ans = 1.6065
```

This means that the model predicts a growth rate of 1.6531 hr-1. Inspection of the flux distribution vector FBAsolution.v shows that there is high flux in the glycolysis, pentose phosphate, TCA cycle, and oxidative phosphorylation pathways, and that no organic by-products are secreted (Figure 2a).

```
FBAsolution.v
```

```
ans = 95x1
-0.1013
-0.0547
-0.0884
10.4868
10.4868
-0.0884
0.2152
5.2801
-0.0316
-0.0466
```

⋮

Inspection of the flux distribution is more convenient with the printFluxVector function

```
fluxData = FBAsolution.v;
nonZeroFlag = 1;
printFluxVector(model, fluxData, nonZeroFlag)
```

ACALD	-0.1013	
ACALDt	-0.05467	
ACKr	-0.08843	
ACONTa	10.49	
ACONTb	10.49	
Act2r	-0.08843	
ADK1	0.2152	
AKGDH	5.28	
AKGt2r	-0.03165	
ALCD2x	-0.04665	
ATPM	8.673	
ATPS4r	79.98	
Biomass_Ecoli_core_N(w/GAM)-Nmet2		1.607
CO2t	-40.89	
CS	10.49	
CYTBD	78.59	
D-LAct2	-0.04574	
ENO	26.88	
ETOHt2r	-0.04665	
EX_ac(e)	0.08843	
EX_acald(e)	0.05467	
EX_akg(e)	0.03165	
EX_co2(e)	40.89	
EX_etoh(e)	0.04665	
EX_for(e)	0.5022	
EX_fru(e)	2.128e-05	
EX_fum(e)	2.036e-05	
EX_glc(e)	-18.48	
EX_gln-L(e)	2.084e-05	
EX_glu-L(e)	0.02723	
EX_h2o(e)	52.75	
EX_h(e)	33.11	
EX_lac-D(e)	0.04574	
EX_mal-L(e)	2.03e-05	
EX_nh4(e)	-8.787	
EX_o2(e)	-39.3	
EX_pi(e)	-5.91	
EX_pyr(e)	0.05553	
EX_succ(e)	0.03619	
FBA	13.48	
FBP	0.2126	
FORT2	2.176	
FORTi	2.678	
FRD7	104.1	
FRUpts2	2.397e-05	
FUM	8.658	
FUMt2_2	2.431e-05	
G6PDH2r	10.21	
GAPD	29.29	
GLCpts	18.48	
GLNS	1.144	
GLNabc	2.413e-05	
GLUDy	-8.01	
GLUN	0.3662	

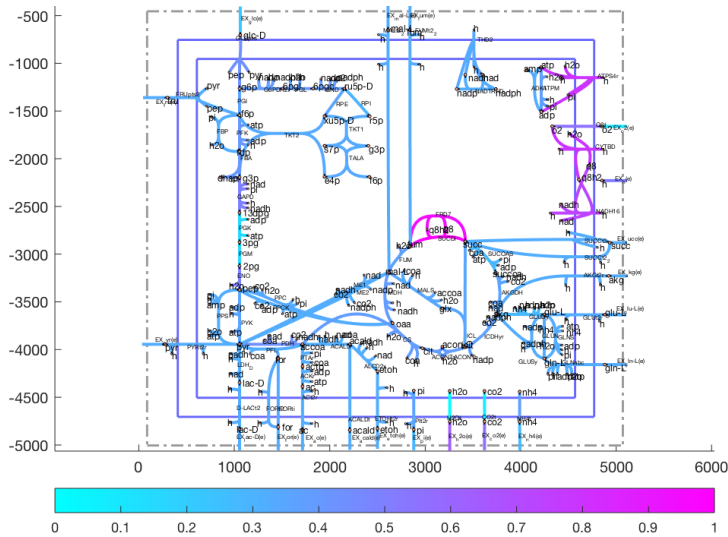
GLUSy	0.3666
GLUt2r	-0.02723
GND	10.21
H2Ot	-52.75
ICDHyr	7.072
ICL	3.415
LDH_D	-0.04574
MALs	3.415
MALt2_2	2.438e-05
MDH	11.13
ME1	0.3326
ME2	0.6087
NADH16	69.93
NADTRHD	0.7396
NH4t	8.787
O2t	39.3
PDH	19.61
PFK	13.69
PFL	0.5022
PGI	7.943
PGK	-29.29
PGL	10.21
PGM	-26.88
PIt2r	5.91
PPC	2.39
PPCK	0.1647
PPS	0.2152
PTAr	0.08843
PYK	5.559
PYRt2r	-0.05553
RPE	5.65
RPI	-4.557
SUCct2_2	0.7464
SUCct3	0.7826
SUCDi	112.7
SUCOAS	-5.28
TALA	3.115
THD2	1.951
TKT1	3.115
TKT2	2.535
TPI	13.48

Display an optimal flux vector on a metabolic map

Which reactions/pathways are in use (look at the flux vector and flux map)?

Hint: drawFlux

```
outputFormatOK = changeCbMapOutput('matlab');
map=readCbMap('ecoli_core_map');
options.zeroFluxWidth = 0.1;
options.rxnDirMultiplier = 10;
drawFlux(map, model, FBAsolution.v, options);
```



Next, the same simulation is performed under anaerobic conditions. With the same model:

```
model = changeRxnBounds(model, 'EX_o2(e)', 0, '1');
```

The lower bound of the oxygen exchange reaction is now 0, so oxygen may not enter the system. When `optimizeCbModel` is used as before, the resulting growth rate is now much lower, 0.4706 hr⁻¹.

```
FBAsolution2 = optimizeCbModel(model, 'max');
FBAsolution2.f
```

```
ans = 0.4148
```

What reactions of oxidative phosphorylation are active in anaerobic conditions?

Hint: `printFluxVector` `drawFlux`

The flux distribution shows that oxidative phosphorylation is not used in these conditions, and that acetate, formate, and ethanol are produced by fermentation pathways (Figure 2b). Inspection of both flux vectors for comparison:

```
fluxData = [FBAsolution.v, FBAsolution2.v];
nonZeroFlag = 1;
excFlag = 1;
printFluxVector(model, fluxData, nonZeroFlag, excFlag)
```

Biomass_Ecoli_core_N(w/GAM)-Nmet2	1.607	0.4148
EX_ac(e)	0.08843	11.16
EX_acald(e)	0.05467	0.3076
EX_akg(e)	0.03165	0.07803
EX_co2(e)	40.89	2.057
EX_etoh(e)	0.04665	16.53
EX_for(e)	0.5022	29.05
EX_fru(e)	2.128e-05	2.195e-05
EX_fum(e)	2.036e-05	1.963e-05
EX_glc(e)	-18.48	-18.43

EX_gln-L(e)	2.084e-05	2.077e-05
EX_glu-L(e)	0.02723	0.06891
EX_h2o(e)	52.75	-10.22
EX_h(e)	33.11	50.97
EX_lac-D(e)	0.04574	0.5303
EX_mal-L(e)	2.03e-05	1.984e-05
EX_nh4(e)	-8.787	-2.331
EX_o2(e)	-39.3	3.626e-05
EX_pi(e)	-5.91	-1.526
EX_pyr(e)	0.05553	0.2642
EX_succ(e)	0.03619	0.6749

```
%drawFlux(map, model, FBAsolution2.v, options);
```

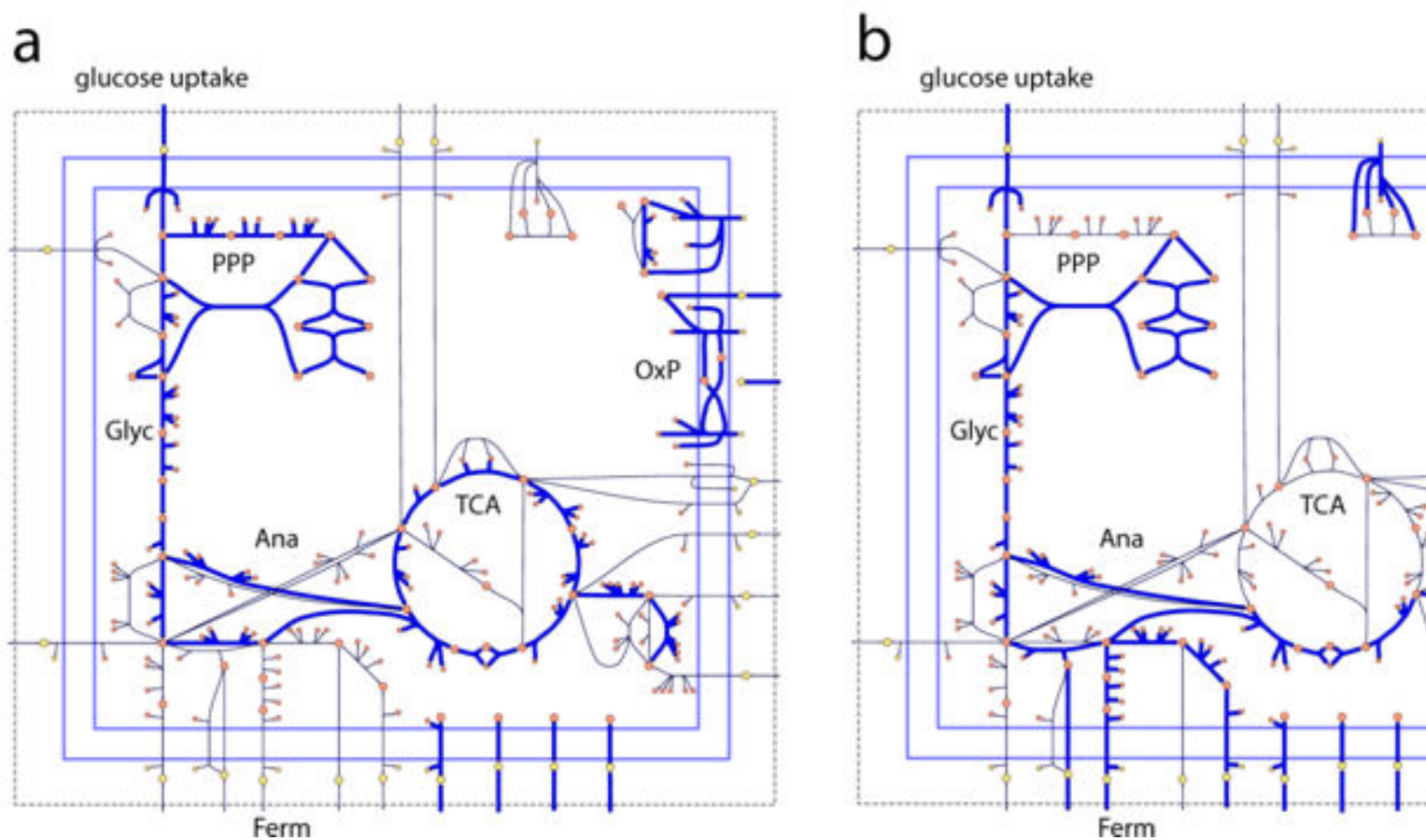


Figure 2 Flux vectors computed by FBA can be visualized on network maps. In these two examples, the thick blue arrows represent reactions carrying flux, and the thin black arrows represent unused reactions. These maps show the state of the E. coli core model with maximum growth rate as the objective (Z) under aerobic (a) and anaerobic (b) conditions. Reactions that are in use have thick blue arrows, while reactions that carry 0 flux have thin black arrows. The metabolic pathways shown in these maps are glycolysis (Glyc), pentose phosphate pathway (PPP), TCA cycle (TCA), oxidative phosphorylation (OxP), anaplerotic reactions (Ana), and fermentation pathways (Ferm).

Example 2: Growth on alternate substrates

Just as FBA was used to calculate growth rates of *E. coli* on glucose, it can also be used to simulate growth on other substrates. The core *E. coli* model contains exchange reactions for 13 different organic compounds, each of which can be used as the sole carbon source under aerobic conditions.

What is the growth rate of *E. coli* on succinate?

Hint: `changeRxnBounds`

Before trying out new boundary conditions on a model, make sure one's starting point is appropriate.

```
model = modelOri;
```

For example, to simulate growth on succinate instead of glucose, first use the `changeRxnBounds` function to set the lower bound of the glucose exchange reaction (`EX_glc(e)`) to 0.

```
model = changeRxnBounds(model, 'EX_glc(e)', 0, 'l');
```

Then use `changeRxnBounds` to set the lower bound of the succinate exchange reaction (`EX_succ(e)`) to -20 mmol gDW⁻¹ hr⁻¹ (an arbitrary uptake rate).

```
model = changeRxnBounds(model, 'EX_succ(e)', -20, 'l');
```

As in the glucose examples, make sure that the biomass reaction is set as the objective (the function `checkObjective` can be used to identify the objective reaction(s)),

```
checkObjective(model);
```

```
summaryT = 23x5 table
```

	Coefficient	Metabolite	metID	Reaction	RxnID
1	-1.4960	3pg[c]	3	Biomass_Ecoli...	13
2	-3.7478	accoa[c]	10	Biomass_Ecoli...	13
3	59.8100	adp[c]	13	Biomass_Ecoli...	13
4	4.1182	akg[c]	14	Biomass_Ecoli...	13
5	-59.8100	atp[c]	17	Biomass_Ecoli...	13
6	3.7478	coa[c]	21	Biomass_Ecoli...	13
7	-0.3610	e4p[c]	23	Biomass_Ecoli...	13
8	-0.0709	f6p[c]	26	Biomass_Ecoli...	13
9	-0.1290	g3p[c]	33	Biomass_Ecoli...	13
10	-0.2050	g6p[c]	34	Biomass_Ecoli...	13
11	-0.2557	gln-L[c]	36	Biomass_Ecoli...	13
12	-4.9414	glu-L[c]	38	Biomass_Ecoli...	13
13	-59.8100	h2o[c]	41	Biomass_Ecoli...	13
14	59.8100	h[c]	43	Biomass_Ecoli...	13

```
⋮
```

Use `optimizeCbModel` to perform FBA, then the growth rate, given by `FBAsolution.f`, will be 0.8401 hr⁻¹.

```
FBAsolution = optimizeCbModel(model, 'max');  
FBAsolution.f
```

```
ans = 0.8087
```

```
changeCobraSolver('pdco', 'QP')
```

```
> pdco interface added to MATLAB path.  
> The solver compatibility is not tested with MATLAB R2019b.  
ans = logical  
1
```

```
FBAsolution = optimizeCbModel(model, 'max', 1e-6);
```

```
Warning: Using only diagonal part of hess from pdObj
```

Growth can also be simulated under anaerobic conditions with any substrate by using `changeRxnBounds` to set the lower bound of the oxygen exchange reaction (`EX_o2(e)`) to 0 mmol gDW⁻¹ hr⁻¹, so no oxygen can enter the system. When this constraint is applied and succinate is the only organic substrate, `optimizeCbModel` returns a growth rate of 0 hr⁻¹

```
model = changeRxnBounds(model, 'EX_o2(e)', 0, 'l');  
FBAsolution = optimizeCbModel(model, 'max');  
FBAsolution.f
```

```
ans = 1.0633e-10
```

In this case, FBA predicts that growth is not possible on succinate under anaerobic conditions. Because the maximum amount of ATP that can be produced from this amount of succinate is less than the minimum bound of 8.39 mmol gDW⁻¹ hr⁻¹ of the ATP maintenance reaction, ATPM, there is no feasible solution.

Example 3. Alternate optimal solutions

The flux distribution calculated by FBA is often not unique. In many cases, it is possible for a biological system to achieve the same objective value by using alternate pathways, so phenotypically different alternate optimal solutions are possible. A method that uses FBA to identify alternate optimal solutions is Flux Variability Analysis (FVA)[13]. This is a method that identifies the maximum and minimum possible fluxes through a particular reaction with the objective value constrained to be close to or equal to its optimal value. Performing FVA on a single reaction using the basic COBRA Toolbox functions is simple. First, use functions `changeRxnBounds`, `changeObjective`, and `optimizeCbModel` to perform FBA as described in the previous examples. Get the optimal objective value (`FBAsolution.f`), and then set both the lower and upper bounds of the objective reaction to exactly this value. Next, set the reaction of interest as the objective, and use FBA to minimize and maximize this new objective in two separate steps. This will give the minimum and maximum possible fluxes through this reaction while contributing to the optimal objective value.

What reactions vary their optimal flux in the set of alternate optimal solutions to maximum growth of *E. coli* on succinate? Are there any reactions that are not used in one optimal solution but used in another

optimal solution? What are the computational and biochemical aspects to consider when interpreting these alternate optimal solutions?

Hint: fluxVariability

Consider the variability of the malic enzyme reaction (ME1) in E. coli growing on succinate. The minimum possible flux through this reaction is 0 mmol gDW⁻¹ hr⁻¹ and the maximum is 6.49 mmol gDW⁻¹ hr⁻¹. In one alternate optimal solution, the ME1 reaction is used, but in another, it is not used at all. The full code to set the model to these conditions and perform FVA on this reaction is:

```
model = modelOri;
model = changeRxnBounds(model, 'EX_glc(e)', 0, 'l');
model = changeRxnBounds(model, 'EX_succ(e)', -20, 'l');
model = changeRxnBounds(model, 'EX_o2(e)', -1000, 'l');
FBAsolution = optimizeCbModel(model, 'max');
model = changeRxnBounds(model, 'Biomass_Ecoli_core_N(w/GAM)-Nmet2', FBAsolution.f, 'b');
model_ME1 = changeObjective(model, 'ME1');
FBAsolution_ME1_Min = optimizeCbModel(model_ME1, 'min');
FBAsolution_ME1_Max = optimizeCbModel(model_ME1, 'max');
FBAsolution_ME1_Min.f
```

```
ans = 0.0013
```

```
FBAsolution_ME1_Max.f
```

```
ans = 16.6408
```

The COBRA Toolbox includes a built in function for performing FVA called `fluxVariability`. This function is useful because it performs FVA on every reaction in a model. When FVA is performed on every reaction in the E. coli core model for growth on succinate, eight reactions are found to be variable (Table 5). Inspection of the variable reactions shows that conversion of L-malate to pyruvate may occur through several different pathways, each leading to the same maximum growth rate. Flux vectors using combinations of these pathways are also valid solutions. Two of these alternate solutions are shown in Figure 4.

```
FVAresults=cell(size(model.S,2)+1,1);
FVAresults{1,1}='Reaction';
FVAresults{1,2}='Minimum Flux';
FVAresults{1,3}='Maximum Flux';
FVAresults(2:end,1)=model.rxns;
[minFlux, maxFlux, ~, ~] = fluxVariability(model, 100, 'max', [], 0, 1, 'FBA');
for n=1:size(model.S,2)
    FVAresults{n+1,2}=minFlux(n);
    FVAresults{n+1,3}=maxFlux(n);
end
bool=abs(maxFlux-minFlux)>=1e-6;
bool=[true;bool];
FVAresults=FVAresults(bool,:)
```

```
FVAresults = 85x3 cell
```

	1	2	3
1	'Reaction'	'Minimum Flux'	'Maximum Flux'

	1	2	3
2	'ACALD'	-0.8811	-0.0028
3	'ACALDt'	-0.8815	-0.0014
4	'ACKr'	-1.3587	-0.0013
5	'ACONTa'	5.9996	8.5689
6	'ACONTb'	5.9996	8.5689
7	'ACT2r'	-1.3587	-0.0013
8	'ADK1'	0.0011	5.8265
9	'AKGDH'	1.8799	7.6935
10	'AKGt2r'	-0.4687	-0.0015
11	'ALCD2x'	-0.7612	-0.0014
12	'ATPM'	8.3911	14.2266
13	'ATPS4r'	55.2285	62.9699
14	'CO2t'	-45.5731	-41.7011
	⋮		

Table 5 Variable reactions for growth on succinate (uptake rate = 20 mmol gDW⁻¹ hr⁻¹) under aerobic conditions. The minimum and maximum possible flux for every reaction was calculated at the maximum growth rate and only reactions with variable fluxes are shown here. FRD7 (fumarate reductase) and SUCDi (succinate dehydrogenase) always have highly variable fluxes in this model because they form a cycle that can carry any flux. Physiologically, these fluxes are not relevant. The other variable reactions are MDH (malate dehydrogenase), ME1 (malic enzyme (NAD)), ME2 (malic enzyme (NADP)), NADTRHD (NAD transhydrogenase), PPCK (phosphoenolpyruvate carboxykinase), and PYK (pyruvate kinase).

```
model_ME1 = changeObjective(model, 'ME1');
FBAsolution_ME1_Max = optimizeCbModel(model_ME1, 'max');
drawFlux(map, model, FBAsolution_ME1_Max.v, options);
```

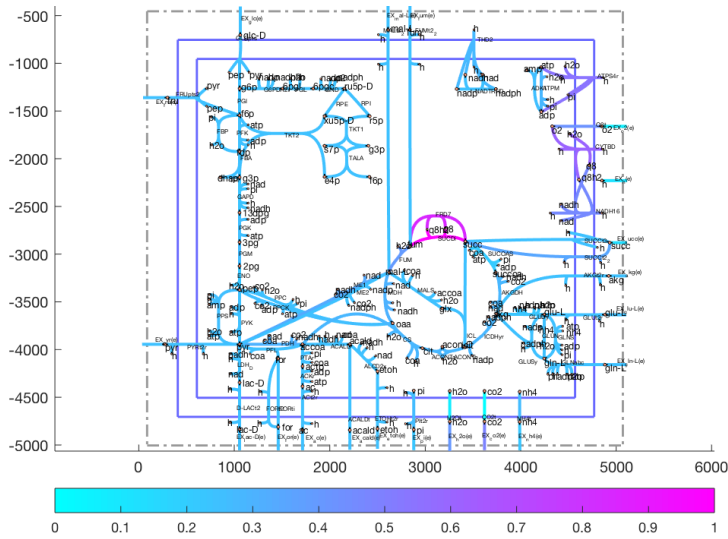


Figure 4a Flux maps for an alternate solutions for maximum aerobic growth on succinate. The reaction ME1 is used to convert L-malate to pyruvate.

```
model_PYK = changeObjective(model, 'PYK');
FBASolution_PYK_Max = optimizeCbModel(model_PYK, 'max');
drawFlux(map, model, FBASolution_PYK_Max.v, options);
```

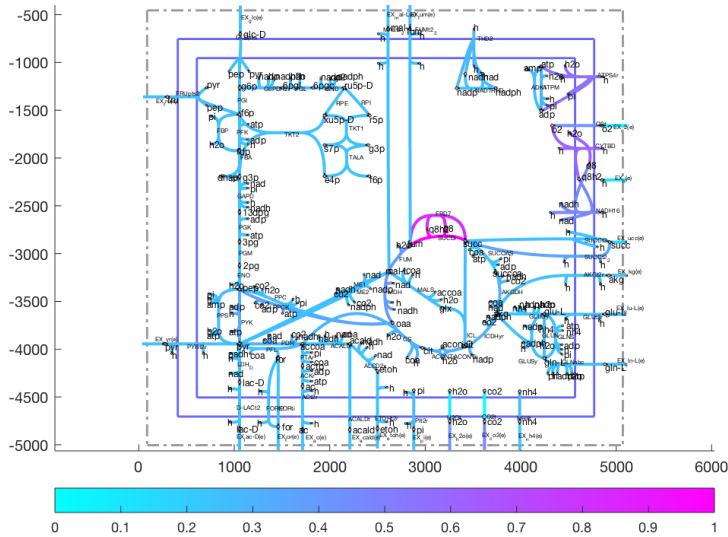


Figure 4b Flux maps for an alternate solutions for maximum aerobic growth on succinate. ME1 is is not used at all, and the reaction PYK is used. **The two alternative reactions are highlighted in red.**

Example 4. Robustness analysis

Another method that uses FBA to analyze network properties is robustness analysis [14]. In this method, the flux through one reaction is varied and the optimal objective value is calculated as a function of this flux. This reveals how sensitive the objective is to a particular reaction. There are many insightful combinations of reaction and objective that can be investigated with robustness analysis. One example is examination of the effects of nutrient uptake on growth rate.

What is the effect of varying glucose uptake rate on growth? At what uptake rates does glucose alone constrain growth?

Hint: fix the oxygen uptake rate to 17 mmol gDW-1 hr-1

To determine the effect of varying glucose uptake on growth, first use `changeRxnBounds` to set the oxygen uptake rate (`EX_o2(e)`) to 17 mmol gDW-1 hr-1, a realistic uptake rate. Then, use a for loop to set both the upper and lower bounds of the glucose exchange reaction to values between 0 and -20 mmol gDW-1 hr-1, and use `optimizeCbModel` to perform FBA with each uptake rate. Be sure to store each growth rate in a vector or other type of Matlab list. The COBRA Toolbox also contains a function for performing robustness analysis (`robustnessAnalysis`) that can perform these functions. The full code to perform this robustness analysis is:

```
model = modelOri;
model = changeRxnBounds(model, 'EX_o2(e)', -17, 'b');
glucoseUptakeRates = zeros(21,1);
growthRates = zeros(21,1);
for i = 0:20
    model = changeRxnBounds(model, 'EX_glc(e)', -i, 'b');
    glucoseUptakeRates(i+1) = -i;
    FBASolution = optimizeCbModel(model, 'max');
    growthRates(i+1) = FBASolution.f;
end
```

The results can then be plotted:

```
figure;
plot(-glucoseUptakeRates, growthRates, '-')
xlabel('Glucose Uptake Rate (mmol gDW-1 hr-1)')
ylabel('Growth Rate (mmol gDW-1 hr-1)')
```

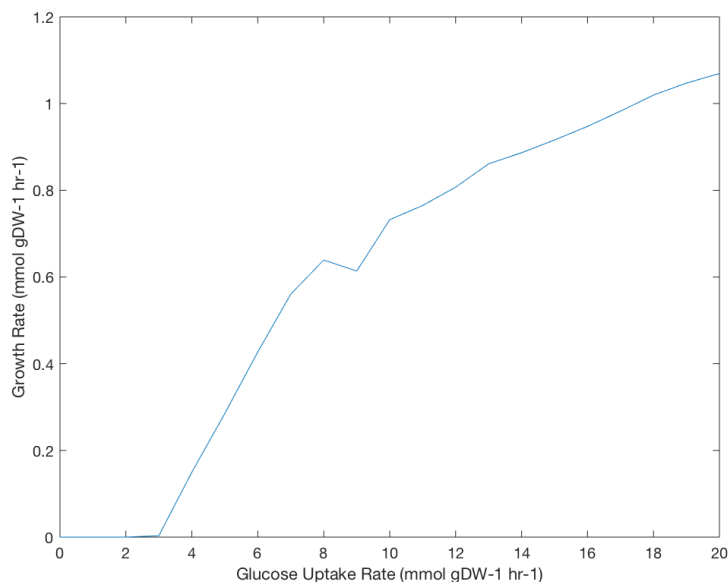


Figure 5 Robustness analysis for maximum growth rate while varying glucose uptake rate with oxygen uptake fixed at 17 mmol gDW-1 hr-1.

As expected, with a glucose uptake of 0 mmol gDW-1 hr-1, the maximum possible growth rate is 0 hr-1. Growth remains at 0 hr-1 until a glucose uptake rate of about 2.83 mmol gDW-1 hr-1, because with such a small amount of glucose, the system cannot make 8.39 mmol gDW-1 hr-1 ATP to meet the default lower bound of the ATP maintenance reaction (ATPM). This reaction simulates the consumption of ATP by non-growth associated processes such as maintenance of electrochemical gradients across the cell membrane. Once enough glucose is available to meet this ATP requirement, growth increases rapidly as glucose uptake increases. At an uptake rate of about 7.59 mmol gDW-1 hr-1, growth does not increase as rapidly. It is at this point that oxygen and not glucose limits growth. Excess glucose cannot be fully oxidized, so the fermentation pathways are used.

What is the growth rate as a function of oxygen uptake rate with glucose uptake held constant?

Hint: fix glucose uptake at 10 mmol gDW-1 hr-1

The oxygen uptake rate can also be varied with the glucose uptake rate held constant. With glucose uptake fixed at 10 mmol gDW-1 hr-1, growth rate increases steadily as oxygen uptake increases (Figure 6). At an oxygen uptake of about 21.80 mmol gDW-1 hr-1, growth actually begins to decrease as oxygen uptake increases. This is because glucose becomes limiting at this point, and glucose that would have been used to produce biomass must instead be used to reduce excess oxygen. In the previous example, growth rate continues to increase once oxygen become limiting because *E. coli* can grow on glucose without oxygen. In this example, *E. coli* cannot grow with oxygen but not glucose (or another carbon source), so growth decreases when excess oxygen is added.

```
model = modelOri;
model = changeRxnBounds(model, 'EX_glc(e)', -10, 'b');
oxygenUptakeRates = zeros(25,1);
growthRates = zeros(25,1);
for i = 0:25
    model = changeRxnBounds(model, 'EX_o2(e)', -i, 'b');
    oxygenUptakeRates(i+1)=-i;
```

```

FBAsolution = optimizeCbModel(model, 'max');
growthRates(i+1) = FBAsolution.f;
end
figure;
plot(-oxygenUptakeRates, growthRates, '-')
xlabel('Oxygen Uptake Rate (mmol gDW-1 hr-1)')
ylabel('Growth Rate (mmol gDW-1 hr-1)')

```

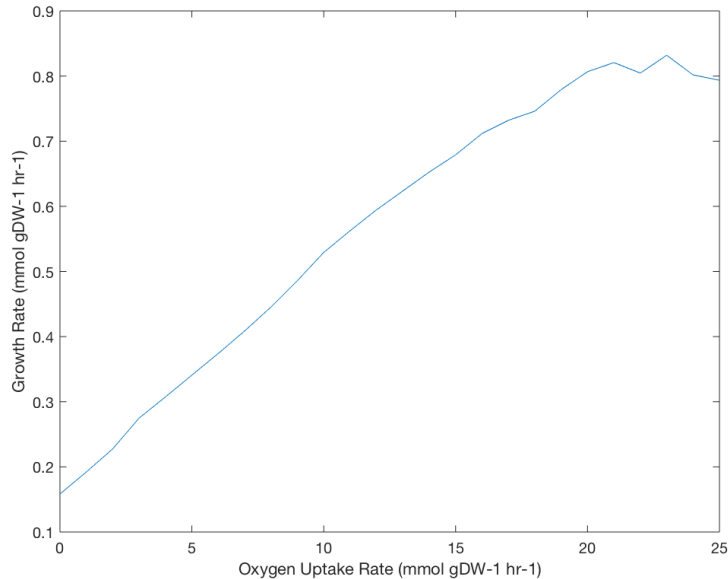


Figure 6 Robustness analysis for maximum growth rate while varying oxygen uptake rate with glucose uptake fixed at 10 mmol gDW-1 hr-1.

Example 6. Simulating gene knockouts

Just as growth in different environments can be simulated with FBA, gene knockouts can also be simulated by changing reaction bounds. To simulate the knockout of any gene, its associated reaction or reactions can simply be constrained to not carry flux. By setting both the upper and lower bounds of a reaction to 0 mmol gDW-1 hr-1, a reaction is essentially knocked out, and is restricted from carrying flux. The E. coli core model, like many other constraint-based models, contains a list of gene-protein-reaction interactions (GPRs), a list of Boolean rules that dictate which genes are connected with each reaction in the model. When a reaction is catalyzed by isozymes (two different enzymes that catalyze the same reaction), the associated GPR contains an “or” rule, where either of two or more genes may be knocked out but the reaction will not be constrained.

Which genes are required to be knocked out to eliminate flux through the phosphofructokinase (PFK) reaction?

Hint: study the model

The GPR for phosphofructokinase (PFK) is “b1723 (pfkB) or b3916 (pfkA),” so according to this Boolean rule, both pfkB and pfkA must be knocked out to restrict this reaction. When a reaction is catalyzed by a protein with multiple essential subunits, the GPR contains an “and” rule, and if any of the genes are knocked out the reaction will be constrained to 0 flux. Succinyl-CoA synthetase (SUCCOAS), for example, has the GPR “b0728 (sucC) and b0729 (sucD),” so knocking out either of these genes will restrict this reaction. Some reactions are catalyzed by a single gene product, while others may be associated with ten or more genes in complex associations.

What is the growth rate of *E. coli* when the gene b1852 (zwf) is knocked out?

Hint: `deleteModelGenes`

The COBRA Toolbox contains a function called `deleteModelGenes` that uses the GPRs to constrain the correct reactions. Then FBA may be used to predict the model phenotype with gene knockouts. For example, growth can be predicted for *E. coli* growing aerobically on glucose with the gene b1852 (zwf), corresponding to the reaction glucose-6-phosphate dehydrogenase (G6PDH2r), knocked out. The FBA predicted growth rate of this strain is 1.6329 hr⁻¹, which is slightly lower than the growth rate of 1.6531 hr⁻¹ for wild-type *E. coli* because the cell can no longer use the oxidative branch of the pentose phosphate pathway to generate NADPH. Using FBA to predict the phenotypes of gene knockouts is especially useful in predicting essential genes. When the gene b2779 (eno), corresponding to the enolase reaction (ENO), is knocked out, the resulting growth rate on glucose is 0 hr⁻¹. Growth is no longer possible because there is no way to convert glucose into TCA cycle intermediates without this glycolysis reaction, so this gene is predicted to be essential. Because FBA can compute phenotypes very quickly, it is feasible to use it for large scale computational screens for gene essentiality, including screens for two or more simultaneous knockouts.

Knockout every pairwise combination of the 136 genes in the *E. coli* core model and display the results.

Hint: `doubleGeneDeletion`

Figure 8 shows the results of a double knockout screen, in which every pairwise combination of the 136 genes in the *E. coli* core model were knocked out. The code to produce this figure is:

```
model = modelOri;
[grRatio,grRateKO,grRateWT] = doubleGeneDeletion(model);
```

```
Single deletion analysis to remove lethal genes
100%      [.....]
131 non-lethal genes
Double gene deletion analysis
Total of 8515 pairs to analyze
Double gene deletion analysis in progress ...
Perc complete      CPU time
```

```
figure;
imagesc(grRatio);
colormap('hsv')
xlabel('gene knockout 1')
ylabel('gene knockout 2')
```

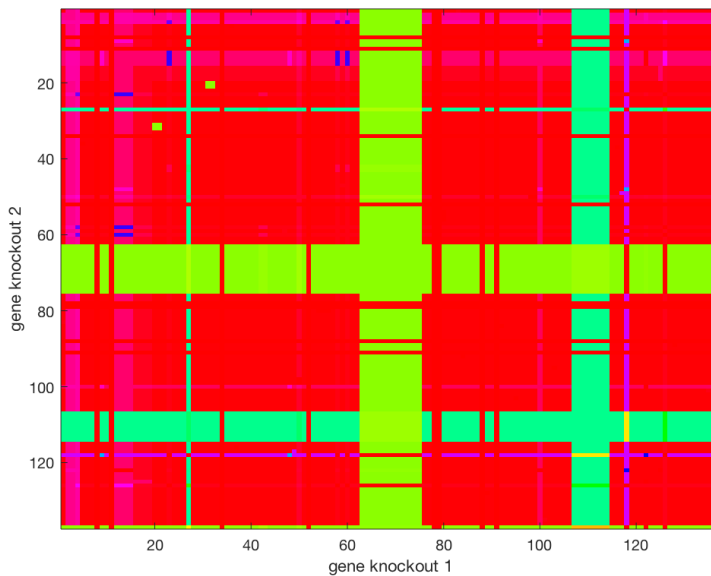


Figure 8 Gene knockout screen on glucose under aerobic conditions. Each of the 136 genes in the core E. coli model were knocked out in pairs, and the resulting relative growth rates were plotted. In this figure, genes are ordered by their b number. Some genes are always essential, and result in a growth rate of 0 when knocked out no matter which other gene is also knocked out. Other genes form synthetic lethal pairs, where knocking out only one of the genes has no effect on growth rate, but knocking both out is lethal. Growth rates in this figure are relative to wild-type.

Example 7. Which genes are essential for which biomass precursor?

Earlier, we saw how to determine essential genes for growth. Here we will repeat the same analysis but instead of optimizing for the biomass production, we will optimize for the synthesis of all biomass precursors individually.

Which genes are essential for synthesis of each biomass precursor?

Hint: `addDemandReaction`

Therefore, we have to add a demand reaction for each biomass precursor to the model and perform a gene deletion study for each demand reaction. First, the components of the biomass reaction can be identified and demand reactions can be added by using the `addDemandReaction` function:

```
model = modelOri;
bool=model.S(:,strcmp(model.rxns,'Biomass_Ecoli_core_N(w/GAM)-Nmet2'))~=0;
biomassComponents=model.mets(bool);
[modelBiomass,rxnNames] = addDemandReaction(model,biomassComponents);
```

Adding the following reactions to the model:

```
DM_3pg[c]    3pg[c]    ->
DM_accoa[c]  accoa[c]  ->
DM_adp[c]    adp[c]    ->
DM_akg[c]    akg[c]    ->
DM_atp[c]    atp[c]    ->
DM_coa[c]    coa[c]    ->
DM_e4p[c]    e4p[c]    ->
DM_f6p[c]    f6p[c]    ->
```

DM_g3p[c]	g3p[c]	->
DM_g6p[c]	g6p[c]	->
DM_gln-L[c]	gln-L[c]	->
DM_glu-L[c]	glu-L[c]	->
DM_h2o[c]	h2o[c]	->
DM_h[c]	h[c]	->
DM_nad[c]	nad[c]	->
DM_nadh[c]	nadh[c]	->
DM_nadp[c]	nadp[c]	->
DM_nadph[c]	nadph[c]	->
DM_oaa[c]	oaa[c]	->
DM_pep[c]	pep[c]	->
DM_pi[c]	pi[c]	->
DM_pyr[c]	pyr[c]	->
DM_r5p[c]	r5p[c]	->

Next, gene knockout screens can be performed with each of these demand reactions set as the objective, one at a time:

```
for i = 1:length(rxnNames)
    modelBiomass = changeObjective(modelBiomass,rxnNames{i});
    [grRatio,grRateKO,grRateWT,hasEffect,delRxns,fluxSolution] = singleGeneDeletion(modelBiomass,rxnNames{i});
    biomassPrecursorGeneEss(:,i) = grRateKO;
    biomassPrecursorGeneEssRatio(:,i) = grRatio;
end
```

```
11111111111111111111111100%    [ ..... ]
```

```
%biomassPrecursorGeneEssRatio(~isfinite(biomassPrecursorGeneEssRatio))=0;
```

The resulting matrix `biomassPrecursorGeneEssRatio` is plotted with the `imagesc` function in Figure 9, and indicate which biomass precursors become blocked by certain gene knockouts.

```
figure;  
imagesc(biomassPrecursorGeneEssRatio);  
colormap('hsv')  
yticks(1:length(model.genes));  
yticklabels(model.genes)
```

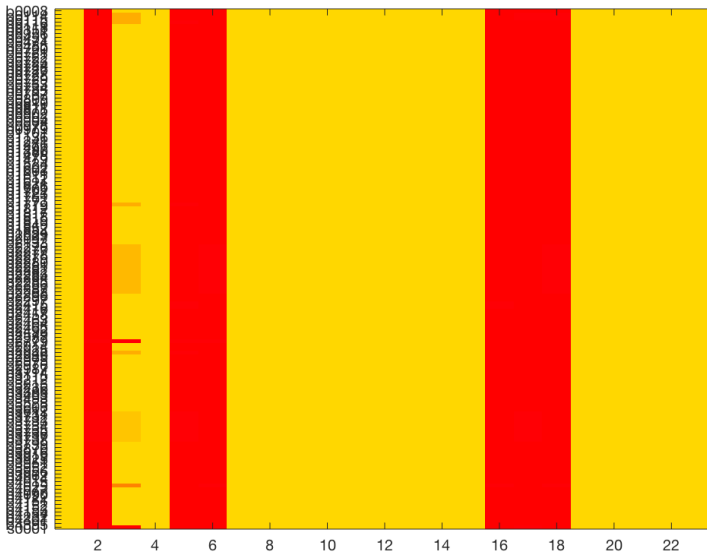


Figure 9 Gene essentiality for biomass precursor synthesis. Heat map shows the relative biomass precursor synthesis rate of mutant compared to wild-type. The 23 biomass precursors are 3pg, accoa, adp, akg, atp, coa, e4p, f6p, g3p, g6p, gln-L, glu-L, h2o, h, nad, nadh, nadp, nadph, oaa, pep, pi, pyr, r5p.

Which biomass precursors cannot be net synthesised by the E. coli core model? What does this say about the E. coli core model itself?

Hint: think about steady state versus mass balance

Some precursors (like atp[c]) cannot be net produced by any of the gene knockout strains because of the demand reactions that consume them and there are no set of reactions that de novo synthesise that precursor. The addDemandReaction function produces a demand reaction that does not regenerate ADP when ATP is consumed or NAD⁺ when NADH is consumed, so these reactions cannot carry flux at steady-state. The genome-scale E. coli model contains all the reactions for de novo synthesis of ATP.

Example 8. Which non-essential gene knockouts have the greatest effect on the network flexibility?

Another question one might be interested in asking is what are the consequences for the network of deleting a non-essential gene? Given an objective, the flux span is the difference between the maximum and minimum alternate optimal flux values for a reaction. A reaction is said to become more flexible if its flux span increases and less flexible if its flux span decreases.

What reactions are increased and decreased in flux span in response to deletion of these 6 genes? {'b0114', 'b0723', 'b0726', 'b0767', 'b1602', 'b1702'} With reference to a particular example, what is the biochemical interpretation of an increased flux span in response to a gene deletion?

Hint: fluxVariability, hist

To address this question, first delete the network genes individually (a single gene deletion study) and then perform FVA (Example 3) on non-essential gene deletion strains. In many cases one would expect that the deletion of a gene has only minor consequences to the network, especially if the deletion does not alter the maximal growth rate. In some cases however, the deletion may reduce the overall network flexibility or maybe even increase the flux range through specific reactions. In fact, this latter property is used to design optimal production strains (e.g., using OptKnock [9]), by redirecting fluxes through the network.

The absolute flux span is a measure of flux range for each reaction. It is calculated as $f_i = \text{abs}(v_{\text{max},i} - v_{\text{min},i})$, where $v_{\text{min},i}$ and $v_{\text{max},i}$ are the minimal and maximal flux rate as determined using FVA. First, calculate wild-type flux variability:

```
[minFluxAll(:,1),maxFluxAll(:,1)] = fluxVariability(model);
```

Next, calculate the knockout strain flux variabilities and flux spans:

```
genes=model.genes([2,14,16,23,42,48]);
for i = 1 : length(genes)
    [modelDel] = deleteModelGenes(model,genes{i});
    [minFluxAll(:,i+1),maxFluxAll(:,i+1)] = fluxVariability(modelDel);
end

fluxSpan = abs(maxFluxAll - minFluxAll);
for i = 1 : size(fluxSpan,2)
    fluxSpanRelative(:,i) = fluxSpan(:,i)./fluxSpan(:,1);
end
```

This example with six mutant strains shows that the majority of the network reactions have reduced flux span compared to wild-type (Figure 10). However, some of these knockout strains have a few reactions which have much higher flux span than wildtype. For example, in one of the knockout strains (*sucA*), the flux span is increased 14 times through the phosphoenolpyruvate carboxykinase reaction (PPCK).

Finally, histograms can be plotted to show how many reactions have increased or decreased flux spans for each knockout:

```
for i =2:7
    subplot(2,3,i-1)
    hist(fluxSpanRelative(:,i),20);
    title(genes{i-1});
end
```

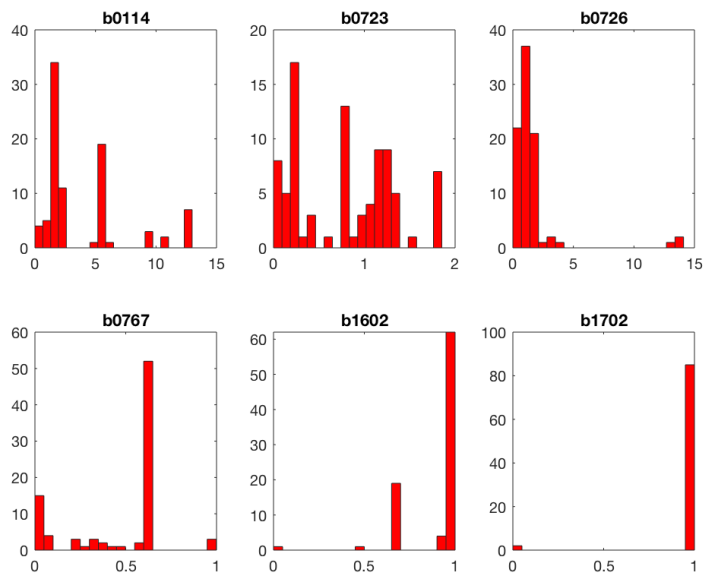



Figure 10 Histograms of relative flux spans for 6 gene knockout mutants.

TIMING

2 hrs

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