

# KombSøg Eksamensnoter 2017

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## Contents

|          |  |           |
|----------|--|-----------|
| <b>1</b> | <b>P, NP and NPC.</b>  | <b>3</b>  |
| 1.1      | Beslutningsproblemer og stand-in sprog . . . . .             | 3         |
| 1.2      | P, NP, NPC . . . . .   | 3         |
| 1.3      | Reduktioner . . . . .  | 4         |
| 1.4      | 3SAT $\leq$ HAMILTONIAN PATH . . . . .                       | 4         |
| <b>2</b> | <b>Cook's theorem and the complexity of variants of SAT.</b> | <b>7</b>  |
| 2.1      | Beslutningsproblemer og stand-in sprog . . . . .             | 7         |
| 2.2      | P, NP, NPC . . . . .   | 7         |
| 2.3      | Varianter af SAT . . . . .                                   | 7         |
| 2.4      | Cook: $L \in NP \leq \text{CircuitSAT}$ . . . . .            | 7         |
| 2.5      | Circuit SAT $\leq$ SAT . . . . .                             | 7         |
| 2.6      | Circuit SAT $\leq$ NAESAT . . . . .                          | 8         |
| 2.7      | SAT $\leq$ 3SAT . . . . .                                    | 9         |
| 2.8      | 2SAT $\in$ P . . . . .                                       | 9         |
| 2.9      | 3SAT $\leq$ MAX2SAT . . . . .                                | 10        |
| <b>3</b> | <b>NP-complete graph problems.</b>                           | <b>11</b> |
| 3.1      | Beslutningsproblemer og stand-in sprog . . . . .             | 11        |
| 3.2      | P, NP, NPC . . . . .   | 11        |
| 3.3      | Reduktioner . . . . .  | 11        |
| 3.4      | 3SAT $\leq$ HAMILTONIAN PATH . . . . .                       | 11        |
| 3.5      | HAMILTONIAN PATH $\leq$ TSP . . . . .                        | 14        |
| 3.6      | 3SAT $\leq$ INDEPENDENT SET . . . . .                        | 14        |
| 3.7      | INDEPENDENT SET $\leq$ CLIQUE . . . . .                      | 16        |
| 3.8      | INDEPENDENT SET $\leq$ VERTEX COVER . . . . .                | 17        |
| <b>4</b> | <b>NP-complete problems involving sets and numbers.</b>      | <b>18</b> |
| 4.1      | Beslutningsproblemer og stand-in sprog . . . . .             | 18        |
| 4.2      | P, NP, NPC . . . . .   | 18        |
| 4.3      | Reduktioner . . . . .  | 18        |
| 4.4      | 3SAT $\leq$ TRIPARTITE MATCHING . . . . .                    | 18        |

|          |  |           |
|----------|--|-----------|
| 4.5      | Corollary: EXACT COVER BY 3-SETS, SET COVERING AND SET PACKING ARE NP COMPLETE . . . . . | 20        |
| 4.5.1    | TRIPARTITE MATCHING $\leq$ EXACT COVER BY 3-SETS . . . . .                               | 20        |
| 4.5.2    | EXACT COVER BY 3-SETS $\leq$ SET COVERING . . . . .                                      | 20        |
| 4.5.3    | NODE COVER $\leq$ SET COVERING . . . . .   | 20        |
| 4.5.4    | EXACT COVER BY 3-SETS $\leq$ SET PACKING . . . . .                                       | 20        |
| 4.6      | EXACT COVER BY 3-SETS $\leq$ KNAPSACK . . . . .  | 21        |
| <b>5</b> | <b>Approximation algorithms.</b>   | <b>22</b> |
| 5.1      | Disposition . . . . .  | 22        |
| 5.2      | P, NP, NPC . . . . .   | 23        |
| 5.3      | Løsninger af NPC problemer . . . . .   | 23        |
| 5.4      | Approx. algoritmer . . . . .   | 23        |
| 5.5      | Approx. schemes . . . . .  | 23        |
| 5.6      | Design . . . . .   | 23        |
| 5.7      | Vertex cover . . . . .   | 23        |
| 5.8      | Metric TSP . . . . .   | 24        |
| 5.9      | Generel TSP approx? . . . . .  | 25        |
| <b>6</b> | <b>Problemer og flere reduktioner</b>  | <b>27</b> |
| 6.1      | INDEPENDENT SET . . . . .  | 27        |
| 6.2      | CLIQUE . . . . .   | 27        |
| 6.3      | VERTEX COVER . . . . .   | 27        |
| 6.4      | MAX CUT . . . . .  | 28        |
| 6.5      | MAX BISECTION . . . . .  | 28        |
| 6.6      | BISECTION WIDTH . . . . .  | 28        |
| 6.7      | HAMILTONIAN PATH . . . . .   | 28        |
| 6.8      | TSP . . . . .  | 28        |
| 6.9      | SET COVERING . . . . .   | 28        |
| 6.10     | EXACT COVER BY 3-SETS . . . . .  | 28        |
| 6.11     | TRIPARTITE MATCHING . . . . .  | 28        |
| 6.12     | SET PACKING . . . . .  | 29        |
| 6.13     | KNAPSACK . . . . .   | 29        |
| 6.14     | SUBSET SUM (SPECIAL CASE OF KNAPSACK) . . . . .  | 29        |
| 6.15     | BIN PACKING . . . . .  | 29        |
| 6.16     | NAESAT $\leq$ MAX CUT . . . . .  | 29        |
| 6.17     | NAESAT $\leq$ 3-COLORING . . . . .   | 31        |

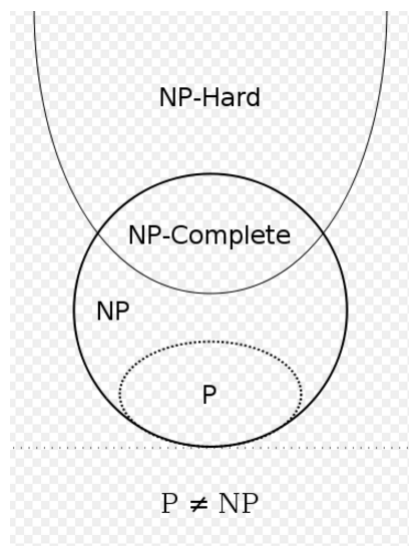
# 1 P, NP and NPC.

## 1.1 Beslutningsproblemer og stand-in sprog

I dette kursus har vi fokuseret på beslutningsproblemer, dvs. problemer hvor outputtet er yes/no.

Og vi har indført såkaldte stand-in sprog for de oprindelige sprog. Eksempelvis max cut, som er et optimerings problem hvor vi leder efter det største cut. I stand-in problemet får vi udover grafen også givet et target  $k$ , og vi spørger om der findes et cut af størrelse mindst  $k$ . Ideen er så at vi kan vise at stand-in sproget ikke har en effektiv algoritme, og dermed har det originale problem heller ikke stand-in sproget ikke er sværere end det originale (Hvis nogen påstår at det er nemmere så kan vi bruge algoritmen for det og sammenligne med vores target  $k$ , og dermed få et rigtigt svar).

## 1.2 P, NP, NPC



**P** er klassen af problemer som kan løses i poly-tid af en TM. Og når vi skal argumentere for at et problem er i P, så beskriver vi en effektiv algoritme og refererer til **Polynomial Church-Turing thesis** som siger noget om at noget kan løses af en TM i poly-tid hvis og kun hvis det kan i poly-tid af en "fornuftig beregningsmodel".

**NP** er klassen af problemer hvor løsninger kan verificeres i poly-tid. P er en delmængde af NP: hvis vi kan finde en løsning i polynomiell tid så kan en given løsning tjekkes ved blot at løse problemet i poly-tid og ignorere et eventuelt certifikat. Når vi skal argumentere for at et problem er i NP skal vi således blot beskrive en poly-tids algoritme som verificerer løsninger.

**NP**C er klassen af problemer som er i NP og som samtidig er NP-hard. At et problem er NP-Hard vil sige, at alle problemer i NP kan reduceres til dette. NPC er en særlig interessant klasse da den indeholder mange problemer som vi gerne vil løse, men også fordi at vi kan bruge den til at vise at nogle problemer bare ikke har en effektiv algoritme (under antagelse at  $P \neq NP$ ). Dette kan vi gøre med en reduktion fra et problem som vi allerede ved at i NPC.

### 1.3 Reduktioner

Vi har talt meget om reduktioner i kurset. Reduktioner bruges i dette kursus til at vise nogle ting om et sprog.

En reduktion  $r$  mapper instanser fra et sprog til et andet, og vi skriver  $L_1 \leq L_2$  hvis vi kan beskrive en valid reduktion. Den er gyldig hvis udførselstiden er polynomiel, og hvis der gælder at  $\forall x : x \in L_1 \iff r(x) \in L_2$ . Vi bruger dette til at vise at nogle problemer er NP-complete. Ideen er, at hvis vi ved at der ikke findes en effektiv algoritme som løser  $L_1$  (under antagelse at  $P \neq NP$ ), og vi samtidig kan reducere  $L_1$  til  $L_2$ , så kan der heller ikke findes en effektiv algoritme til at løse  $L_2$  (da vi ellers lige har beskrevet en poly tids algoritme til  $L_1$ .)

### 1.4 3SAT $\leq$ HAMILTONIAN PATH

**Theorem 9.7:** HAMILTONIAN PATH is NP-Complete

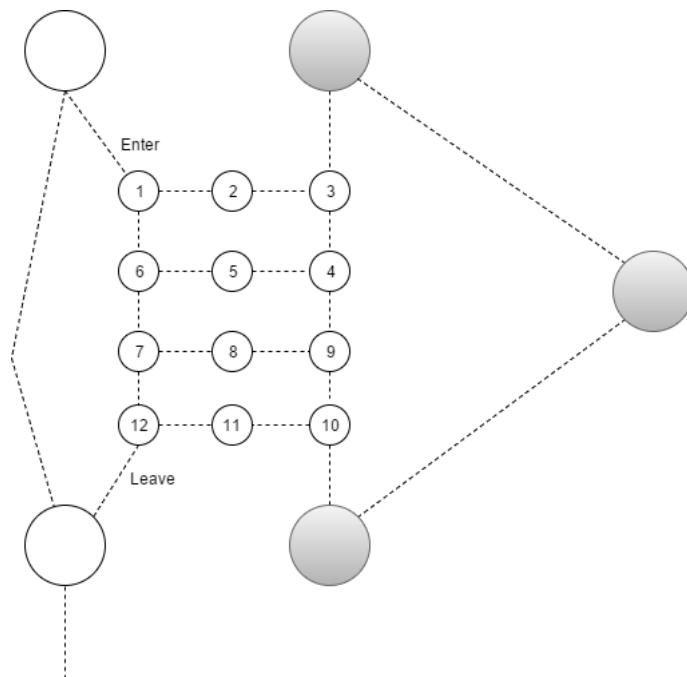
We prove this by reducing from 3SAT, which we know is NP-complete.

We construct a graph  $G$  such that  $G$  has a Hamiltonian path if and only if the input 3sat formula has a satisfying assignment.

For each variable we add a choice gadget and join them. For each clause we add a triangle where each edge corresponds to a literal in the clause. For each edge in the triangle, we add a consistency gadget from the edge, to the edge in the corresponding choice gadget. All nodes in all triangles belong to a clique together with the edge following the last choice gadget, and some other node which is the only one adjacent to the last edge in our path (see figure 6.)

The important thing is that all triangle have at least one edge visited (or actually the 4 nodes on the edges) by the time we get to the clique member after the last choice gadget. If this is not the case then we cannot visit all nodes in a triangle without visiting one of the clique members twice. Recall that edges in the triangles represent literals in the clause - the edges we visit via the choice gadgets are the one for which the corresponding literal make the clause true, and so if no edge is visited, then the clause is false. This is consistent with the fact that we cannot make a hamiltonian cycle.

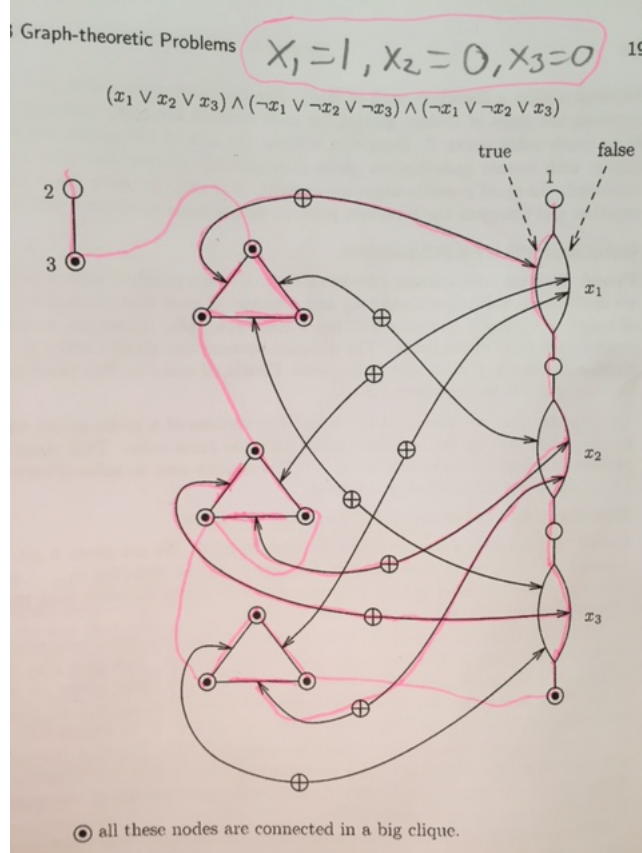
Figure 5 show exactly what happens with the consistency gadget. Our path goes through nodes 1,2,3,4... and leaves at 12. It is clear that none of the black nodes are visited.



**Figure 5:** Zooming in on the consistency gadget between the choice gadget and the triangle.

**Example:**

Given a 3SAT formula  $f = (x_1 \vee x_2 \vee x_3) \wedge (\neg x_1 \vee \neg x_2 \vee x_3) \wedge (\neg x_1 \vee \neg x_2 \vee x_3)$  We can construct a graph similar to the one in figure 6. For the satisfying assignment  $x_1 = 1, x_2 = 0, x_3 = 0$ , we can obtain a hamiltonian path by starting at 1, and following the pink line to 2.



**Figure 6:** Graph  $r(f)$  corresponding to the formula  $f$

**Polynomial time reduction:**

For each variable we make one choice gadget, and for each clause we make one triangle and 3 consistency gadgets.

$\implies$  :

Given a satisfying assignment to the input formula  $f$  we can show that  $r(f)$  has a hamiltonian path: Simply follow the path through the choice gadgets which corresponds to the truth value of the variables. When reaching the clique node after the last choice gadget, we just jump around in the clique and traverse the missing edges in each triangle and finally jump to node 3 and then finally 2.

$\Leftarrow$  :

Given that the graph has a hamiltonian path, we show that the input formula is satisfiable: Since there is only two nodes with degree one we can assume the path starts at node 1. Since we know the structure of the graph and the given hamiltonian path, a truth assignment  $T$  is defined by the way the path traverses the choice gadgets and the consistency gadgets along the way.  $T$  satisfies the input formula since it makes sure one edge is visited in each triangle.

## 2 Cook's theorem and the complexity of variants of SAT.

### 2.1 Beslutningsproblemer og stand-in sprog

### 2.2 P, NP, NPC

### 2.3 Varianter af SAT

1.  $SAT \in NPC$
2.  $2SAT \in P$
3.  $3SAT \in NPC$
4.  $NAESAT \in NPC$
5.  $MAX2SAT \in NPC$

### 2.4 Cook: $L \in NP \leqslant CircuitSAT$

### 2.5 Circuit SAT $\leqslant$ SAT

SAT er et slags special case af Circuit SAT hvor det boolske circuit har en helt særlig struktur: En masse AND gates i toppen forbinder alle clauses og resultatet af disse AND gates går til en enkelt OUTPUT gate. Hver clause er OR af dens literals. Og hver literal er en ukendt INPUT gate eller negeringen af en.

Givet en boolean circuit C konstruerer vi en CNF formula  $r(C)$  som følger:  
Vi ser på hver gate  $g$  og dens inputgates  $h_1$  og  $h_2$ . Afhængig af gate typen laver vi følgende forskellige formler:

1. AND: Følgende clauses som er logisk ækvivalente med  $g \iff (h_1 \wedge h_2)$

$$(\neg g \vee h_1)(\neg g \vee h_2)(g \vee \neg h_1 \vee \neg h_2)$$

Første og anden clause tvinger  $g$  til at være 0 hvis  $h_1$  eller  $h_2$  er 0. Den sidste tvinger  $g$  til at være 1 hvis både  $h_1$  og  $h_2$  er 1.

2. OR: Følgende clauses som er logisk ækvivalente med  $g \iff (h_1 \vee h_2)$

$$(g \vee \neg h_1)(g \vee \neg h_2)(\neg g \vee h_1 \vee h_2)$$

Første og anden clause tvinger  $g$  til at være 1 hvis  $h_1$  eller  $h_2$  er 1. Sidste clause tvinger  $g$  til at være 0 hvis  $h_1$  og  $h_2$  er 0.

3. NOT: Følgende clauses som er logisk ækvivalente med  $g \iff \neg h$

$$(g \vee h)(\neg g \vee \neg h)$$

Første clause sikrer at  $g$  er 1 hvis  $h$  er 0, og anden clause sikrer at  $g$  er 0 hvis  $h$  er 1.

4. COPY: Følgende clauses som er logisk ækvivalente med  $g \iff h$

$$(g \vee \neg h)(\neg g \vee h)$$

Første clause tvinger  $g$  til at være 1 hvis  $h$  er 1. Anden clause tvinger  $g$  til at være 0 hvis  $h$  er 0.

5. CONSTANT: For constant gates tilføjes blot clause  $(g)$  eller  $(\neg g)$  afhængig af om gaten er 1 eller 0 hhv.
6. OUTPUT: For output gaten tilføjes clause  $(g)$ . Dermed kan formelen kun være true hvis denne variable og dermed output gaten er true.

Poly tids reduktion da vi max laver 3 clauses for hver gate.

$\implies$  :

Givet et tilfredsstillende input til vores Circuit  $C$ , hvis vi evaluerer  $C$  på dette input, så kan vi sætte boolean variable  $g_j = G_j$  hvor  $G_j$  er output af den  $j$ 'te gate af  $C$ . Denne tildeling tilfredsstiller vores konstruerede formel.

$\impliedby$  :

Givet en tilfredsstillende assignment til formlen  $F$ , giv input til Circuit  $C$ , den del af  $F$  som svarer til input gates i  $C$ . Det kan vises med induktion at output for gat  $j$  i  $C$  er lig med  $g_j$  og dermed evaluerer  $C$  også til 1.

## 2.6 Circuit SAT $\leq$ NAESAT

Genbrug den forrige reduktion og "fyld op" med ny literal  $z$  i clauses med 1 og 2 literals. Denne reduktion opfylder nu at  $C \in \text{CircuitSAT} \iff r(C) \in \text{NAESAT}$ . De clauses med 3 literals vi har genereret opfylder allerede NAE-SAT predikatet, og i de andre clauses bruger vi  $z$  til at opfylde vores NAESAT constraint.

Tydeligvis i poly-tids reduktion.

$\implies$  :

Givet at  $C$  kan tilfredsstilles, så kan vi vise at  $r(C)$  også kan tilfredsstilles. Argumentet er delvist det samme som i forrige reduktion: "*Givet et tilfredsstillende input til vores Circuit  $C$ , hvis vi evaluerer  $C$  på dette input, så kan vi sætte boolean variable  $g_j = G_j$  hvor  $G_j$  er output af den  $j$ 'te gate af  $C$ .*" Dvs alle clauses har automatisk mindst én sand literal. Og i denne reduktion bruger vi variablen  $z = \text{false}$  til at sørge for at clauses med 1 og 2 literals også har mindst én falsk literale.

$\impliedby$  :



Hvis der er en tildeling af sandhedsværdier som tilfredsstiller  $r(C)$  (i NAESAT forstand), så er det tydeligt at den complementære tildeling også tilfredsstiller i NAESAT forstand. En af disse tildelinger - den hvor  $z = \text{false}$  - tilfredsstiller også den originale  $r(C)$  (den uden  $z$  variabelen), og dermed også det originale circuit  $C$ .

## 2.7 SAT $\leq$ 3SAT

Givet en CNF formel som har clauses med mere eller mindre end 3 literals skal være gøre følgende for hver clause:

1. Hvis en clause har 1 eller 2 literals, så kopierer vi bare en literal 2 eller 1 gang hhv. Eksempelvis  $(x \vee y)$  bliver til  $(x \vee y \vee y)$  dette ændrer ikke i semantikken af clausen.
2. Hvis en clause har mere end 3 literals gør følgende:  $F = (l_1 \vee l_2 \vee A) \dots$  hvor  $A$  er en OR af 2 eller flere literals. Vi indfører nu variabel  $y$  og laver nu  $F' = (l_1 \vee l_2 \vee y)(\neg y \vee A)$ . Sådan fortsætter vi til  $A$  består af en OR af kun 2 literals, da vi så er færdige.

Kører i polytid da vi for hver iteration mindsker en clause med 1 literal indtil vi er færdige.

$\implies$  : Givet en satisfying assignment for  $F$  skal vi vise at  $F'$  også er satisfied. Vi ser på hvilke dele af  $F$  som gøre den satisfied, hvis det er  $l_1$  eller  $l_2$  så sætter vi  $y = 0$  i  $F'$ . Hvis  $l_1$  og  $l_2$  ikke er variablerne som tilfredsstiller  $f$ , så må det være en af literals i  $A$ , så sætter vi  $y = 1$ .

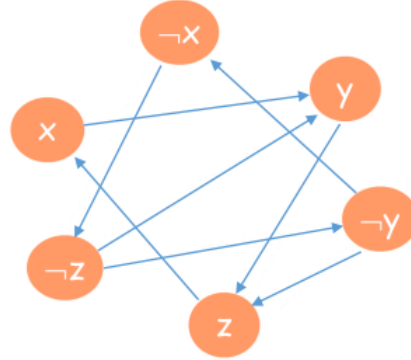
$\impliedby$  : Givet at  $F'$  er tilfredsstillt så er  $F$  selvfølgelig også uanset sandhedsværdien af  $y$ .

## 2.8 2SAT $\in P$

2SAT algoritme:

Konstruer implikationsgraf ud fra en given 2SAT formel: Lav  $2n$  noder, en node for hver variabel og dens negering. Tilføj derefter 2 kanter,  $(\neg a, b)$  og  $(\neg b, a)$  for hver clause  $(a \vee b)$ . Find stærke sammenhængskomponenter i grafen (cykler) i lineær tid. Tjek vha bfs/dfs for hver variabel om der er en cykel hvor både  $x$  og  $\neg x$  indgår. Hvis sådan en variabel eksisterer, så er 2sat formen unsatisfiable. I alt kan dette gøres i polynomiel tid.

$$\Psi = (\neg x \vee y) \wedge (\neg y \vee z) \wedge (x \vee \neg z) \wedge (z \vee y)$$



## 2.9 3SAT ≤ MAX2SAT

Givet en 3SAT formel konstruerer vi en MAX2SAT formel som følger:

For hver clause  $C_i = (\alpha \vee \beta \vee \gamma)$ , tilføj følgende 10 clauses:

$$\begin{aligned} &(\alpha)(\beta)(\gamma)(c_i) \\ &(\neg\alpha \vee \neg\beta)(\neg\beta \vee \neg\gamma)(\neg\alpha \vee \neg\gamma) \\ &(\alpha \vee \neg c_i)(\beta \vee \neg c_i)(\gamma \vee \neg c_i) \end{aligned}$$

Så hvis 3SAT formlen har  $m$  clauses, så har  $r(x)$   $10m$  clauses. The MAX2SAT goal  $K$  is equal to  $7m$ .

Enhver tilfredsstillende assignment for  $C_i$  vil tilfredsstille præcis 7 af de tilsvarende 2sat clauses i  $r(x)$ . Hvis alle literals i 3SAT clausen evaluerer til true, så er hele den første og sidste række tilfredsstillet hvis vi sætter  $c_i$  til true. Hvis 2 ud af 3 literals i 3SAT formlen er true, så er 2 clauses tilfredsstillet i hver række, og vi får den 7. uanset sandhedsværdien af  $c_i$ . Hvis kun en literal er tilfredsstillet er hele 2. række og 1 clause fra første og sidste række tilfredsstillet. Ved at sætte  $c_i$  til false opnås 7 clauses.

Hvis alle literals evaluerer til false kan max 6 clauses i vores konstruktion tilfredsstilles, hvilket er som ønsket.

### 3 NP-complete graph problems.

#### 3.1 Beslutningsproblemer og stand-in sprog

#### 3.2 P, NP, NPC

#### 3.3 Reduktioner

#### 3.4 3SAT $\leq$ HAMILTONIAN PATH

**Theorem 9.7:** HAMILTONIAN PATH is NP-Complete

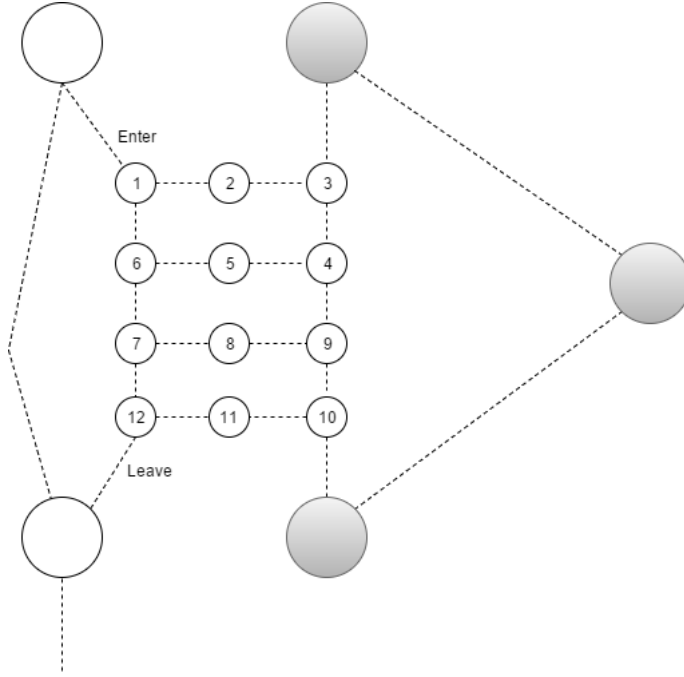
We prove this by reducing from 3SAT, which we know is NP-complete.

We construct a graph  $G$  such that  $G$  has a Hamiltonian path if and only if the input 3sat formula has a satisfying assignment.

For each variable we add a choice gadget and join them. For each clause we add a triangle where each edge corresponds to a literal in the clause. For each edge in the triangle, we add a consistency gadget from the edge, to the edge in the corresponding choice gadget. All nodes in all triangles belong to a clique together with the edge following the last choice gadget, and some other node which is the only one adjacent to the last edge in our path (see figure 6.)

The important thing is that all triangle have at least one edge visited (or actually the 4 nodes on the edges) by the time we get to the clique member after the last choice gadget. If this is not the case then we cannot visit all nodes in a triangle without visiting one of the clique members twice. Recall that edges in the triangles represent literals in the clause - the edges we visit via the choice gadgets are the one for which the corresponding literal make the clause true, and so if no edge is visited, then the clause is false. This is consistent with the fact that we cannot make a hamiltonian cycle.

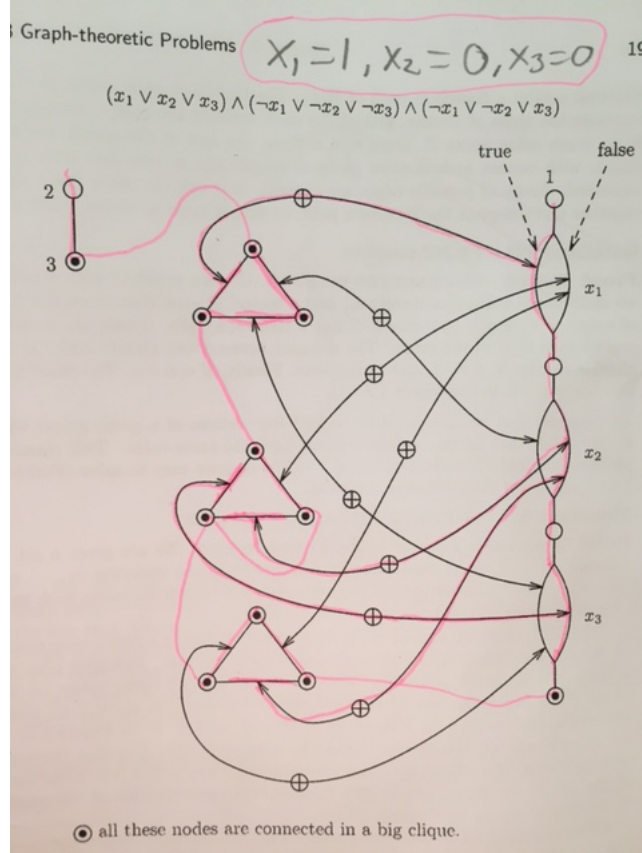
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**Figure 5:** Zooming in on the consistency gadget between the choice gadget and the triangle.

**Example:**

Given a 3SAT formula  $f = (x_1 \vee x_2 \vee x_3) \wedge (\neg x_1 \vee \neg x_2 \vee x_3) \wedge (\neg x_1 \vee \neg x_2 \vee x_3)$  We can construct a graph similar to the one in figure 6. For the satisfying assignment  $x_1 = 1, x_2 = 0, x_3 = 0$ , we can obtain a hamiltonian path by starting at 1, and following the pink line to 2.



**Figure 6:** Graph  $r(f)$  corresponding to the formula  $f$

**Polynomial time reduction:**

For each variable we make one choice gadget, and for each clause we make one triangle and 3 consistency gadgets.

$\implies$  :

Given a satisfying assignment to the input formula  $f$  we can show that  $r(f)$  has a hamiltonian path: Simply follow the path through the choice gadgets which corresponds to the truth value of the variables. When reaching the clique node after the last choice gadget, we just jump around in the clique and traverse the missing edges in each triangle and finally jump to node 3 and then finally 2.

$\Leftarrow$  :

Given that the graph has a hamiltonian path, we show that the input formula is satisfiable: Since there is only two nodes with degree one we can assume the path starts at node 1. Since we know the structure of the graph and the given hamiltonian path, a truth assignment  $T$  is defined by the way the path traverses the choice gadgets and the consistency gadgets along the way.  $T$  satisfies the input formula since it makes sure one edge is visited in each triangle.

### 3.5 HAMILTONIAN PATH $\leq$ TSP

(with triangle inequality)

Given a graph  $G = (V, E)$  with  $n$  nodes, we make a distance matrix  $d_{ij}$  and a budget  $B$  such that there is a TSP tour of at most  $B$  iff  $G$  has a hamiltonian path.

We enter the distances into the matrix as described below, and set the budget  $B = n + 1$

$$d_{ij} : \begin{cases} d_{ij} = 1 & \text{if } (i,j) \in E \\ d_{ij} = 2 & \text{else} \end{cases}$$

Polynomial time reduction since we just fill a  $n \times n$  matrix, for each entry looking in  $E$  if there is a matching edge.

$\implies$  :

Given a hamiltonian path in  $G$  we must show that  $r(G)$  has a TSP cycle of length at most  $n + 1$ . Just follow the hamiltonian path which has length  $n - 1$ , now follow an edge back to start, if it is in  $G$  then the total length is  $n$ , else it becomes  $n + 1$ .

$\impliedby$  :

If we have TSP tour of length at most  $n + 1$  it must use at least  $n - 1$  edges of  $G$ , and this will be our hamiltonian path.

### 3.6 3SAT $\leq$ INDEPENDENT SET

**Theorem 9.4:** INDEPENDENT SET is NP-Complete

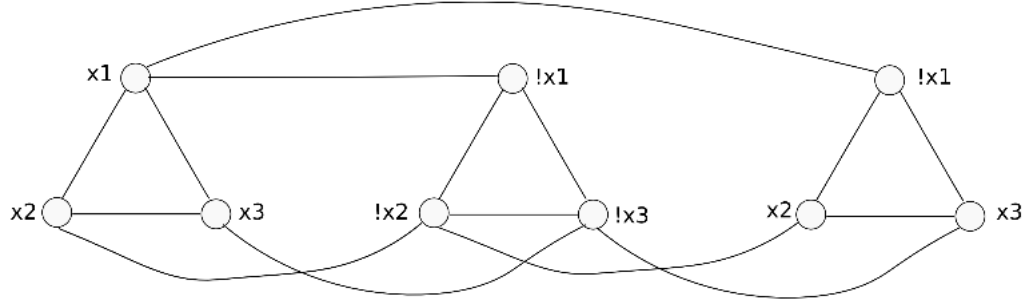
We prove this by reducing from 3SAT, which we know is NP-Complete.

For this reduction we need a gadget, the triangle. The logic behind this is that, if a graph contains a triangle, then at most one of the nodes can be in the independent set. We restrict the class of graphs we consider, to graphs whose nodes can be partitioned in  $m$  disjoint triangles. This ensures that an independent set can contain at most  $m$  nodes.

For each of the  $m$  clauses in our input CNF formula, we create a triangle where the nodes are labeled with the literals of the clause. Next, we add an edge between two nodes in different triangles if and only if the nodes correspond to opposite literals. Adding these edges between opposite literals, ensures that we cannot pick both (as it would not be an independent set). The reduction is completed by setting the independent set goal  $K = m$ .

**Example:**

Given a 3CNF formula:  $f = (x_1 \vee x_2 \vee x_3) \wedge (\neg x_1 \vee \neg x_2 \vee \neg x_3) \wedge (\neg x_1 \vee x_2 \vee x_3)$   
 We construct the graph shown in figure 1.



**Figure 1:** Graph  $r(f)$  corresponding to the formula  $f$

### Analysis

For each clause, we just create a triangle. Then we scan every pair of edges and add an edge if the labels are opposite - so the reduction is clearly polynomial.

$\Rightarrow$  :

Given a satisfying assignment for the CNF formula  $f$  from above, we must show that the graph,  $r(f)$ , has an independent set of size  $K=m$ . The assignment:  $x_1 = 0, x_2 = 1, x_3 = 0$  satisfies the formula, and for our independent set of size  $K$ , we pick a node in each triangle which make the corresponding clause true. For the truth assignment we chose above, this means  $x_2$  from triangle 1,  $\neg x_1$  in triangle 2,  $\neg x_1$  in triangle 3. (Note that this is not the only valid set since some clauses are satisfied by more than one literals).

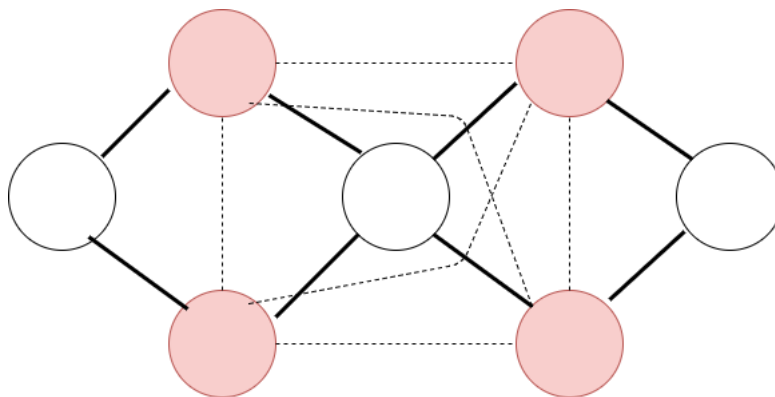
$\Leftarrow$  :

Given an independent set of size  $K$  of  $r(f)$ , we need to show that there is a satisfying assignment for  $f$ . Since it is of size  $K$ , it must have one vertex from each triangle, and it cannot contain a variable and its negation. Now, for each vertex in the independent set, we look at the label and assign a truth value to the corresponding variable, so the literal of the label become true. If a variable is not restricted to a truth value by any vertex label, we just assign it some value, since all clauses are already satisfied by the assignments to the other variables.

*Read more in papadimitriou page 188-190.*

### 3.7 INDEPENDENT SET $\leq$ CLIQUE

The independent set problem asks for a maximum set of vertices of size  $K$ . So does the CLIQUE problem. While the independent set problem asks for a set  $S$  of vertices where there is no edge between any pair  $u, v \in S$ , the clique problem asks for the "opposite": a set  $S$  where any pair  $u, v \in S$  DOES have an edge between them. So the reduction is trivial - we obtain a clique of size  $K$  when taking the complementary graph of an independent set of size  $K$ .



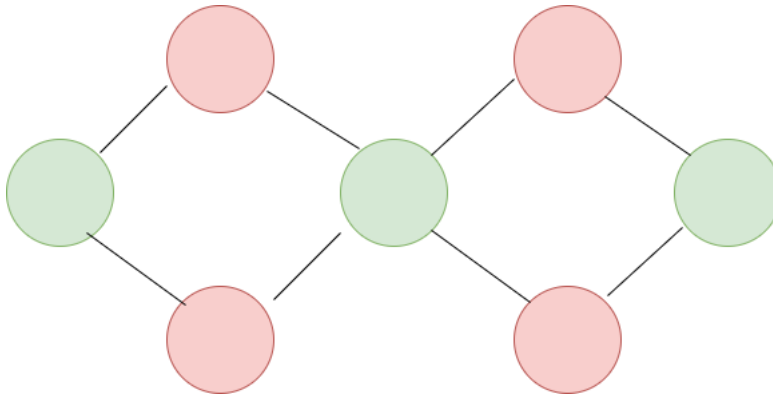
**Figure 2:** The red nodes are the maximum independent set  $I$  - the dotted lines completes the complementary graph of  $I$ . A clique of same size.

*Read more in papadimitriou page 190.*



### 3.8 INDEPENDENT SET $\leq$ VERTEX COVER

While independent set is a maximization problem, vertex cover is a minimization problem. For a graph  $G = (V, E)$  and a max independent set  $I \subseteq V$ , the minimum vertex cover set is just  $V - I$ .



**Figure 3:** The red node forms the maximum independent set. The green form the minimal vertex cover.

*Read more in papadimitriou page 190.*

## 4 NP-complete problems involving sets and numbers.

### 4.1 Beslutningsproblemer og stand-in sprog

### 4.2 P, NP, NPC

### 4.3 Reduktioner

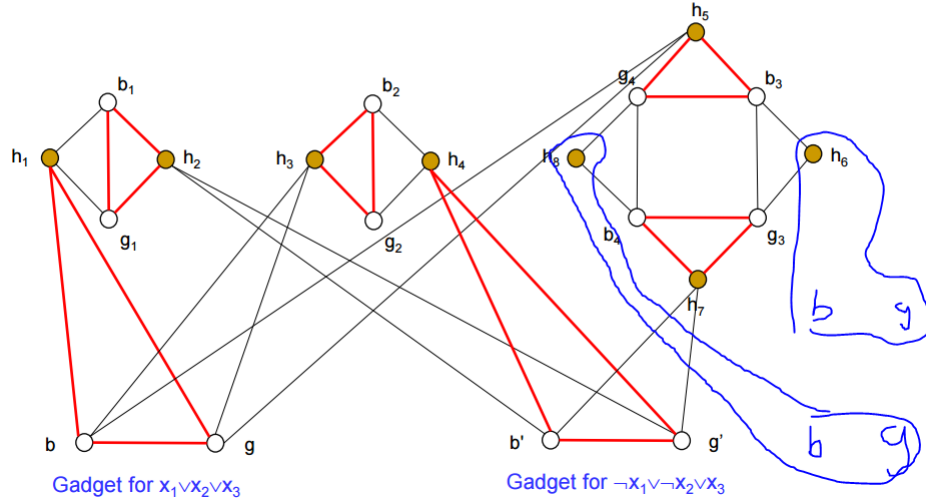
### 4.4 $3SAT \leqslant$ TRIPARTITE MATCHING

For this reduction we use a combined choice- and consistency gadget. We create one for each variable  $x_i$ . Each one of such gadget will have  $k$  boys,  $k$  girls and  $2k$  homes. Where  $k$  is equal to the highest occurrence of  $x_i$  or  $\neg x_i$ . The uneven numbered homes represent occurrences of  $x$ , and the other of  $\neg x$ . The boys and girls of these gadgets are only paired with the homes of the same gadget. If a matching exists then  $b_i$  is matched with either  $g_i$  and  $h_{2i}$ , or to  $g_{i-1}$  and  $h_{2i-1}$ . The first matching is taken to mean that  $x = 1$  and the second that  $x = 0$ .

For each clause we add another pair of boy and girl. These will be paired with the corresponding literals in the gadgets. The idea is that if one of these three homes was left unoccupied when the variables were assigned truth values, this means that it corresponds to a true literal, and therefore the clause is satisfied. **If all three literals in  $c$  are false, then the corresponding b/g pair cannot be matched with a home.**

There are always  $L$  extra homes in this construction, and to make sure they can be matched, we introduce  $L$  more boy/girl pairs. These pairs all paired with every home in the construction. So these  $L$  boy/girl pairs are "easy to please" and are just used to pair the leftover homes.

Example:  $(x_1 \vee x_2 \vee x_3) \wedge (\neg x_1 \vee \neg x_2 \vee x_3)$ : the matching and the satisfiable assignment  $T(x_1)=\text{true}$ ,  $T(x_2)=\text{false}$ ,  $T(x_3)=\text{false}$



**Polynomial:** For each variable we make a gadget with at most  $m$  boys/girls and  $2m$  homes. For each clause we make a  $b/g$  pair. And for each extra home another  $b/g$  pair. So it is polynomial.

$\Rightarrow$  :

Given a satisfying assignment for input formula, we must show that our construction has a valid matching.

See example above. Given the truth assignment  $x_1 = 1, x_2 = 0, x_3 = 0$ , first, in the gadgets, pick the triples with the homes corresponding to the opposite of the assignment. After this, match the clause  $b/g$  pair with a leftover home from the gadgets. And in the end, match remaining homes with the "easy to match"  $b/g$  pairs.

$\Leftarrow$  :

Given  $r(x)$  has a matching, show that the input formula  $x$  is satisfiable.

Look at the homes paired with the clause  $b/g$  pairs. These give us a satisfying assignment.

## 4.5 Corollary: EXACT COVER BY 3-SETS, SET COVERING AND SET PACKING ARE NP COMPLETE

TRIPARTITE MATCHING is a special case of EXACT COVER BY 3-SETS. And EXACT COVER BY 3-SETS is a special case of both SET COVER and SET PACKING.

(<https://people.eecs.berkeley.edu/~vazirani/algorithms/chap8.pdf>)

### 4.5.1 TRIPARTITE MATCHING $\leq$ EXACT COVER BY 3-SETS

Given a TRIPARTITE MATCHING instance: let the EXCB3-S subsets be the same as in the TRIPARTITE MATCHING instance. The EXCB3-S universe is obtained by the union of B G and H.

Think of EXCB3-S as kind of the same problem but where you can match 3 Boys, or 2 girls and 1 home etc.

### 4.5.2 EXACT COVER BY 3-SETS $\leq$ SET COVERING

EXACT COVER BY 3-SETS instances are a subset of all SET COVERING instances, so the is easy. Nothing is changed and the Budget  $B = m$  from the EXCB3-S instance.

### 4.5.3 NODE COVER $\leq$ SET COVERING

SET COVER is a generalization of NODE COVER. In our construction the universe is all edges in the NODE COVER instance. The subsets are obtained as follows: For each node in the graph, all adjacent edges form a subset.

### 4.5.4 EXACT COVER BY 3-SETS $\leq$ SET PACKING

Set the SET PACKING goal  $k$  to be  $m$ . Then there is a 3-SET cover of size  $m$  iff there is a SET PACKING of size  $m$ . (Since the input set is  $3m$ ). Rest is unchanged.

## 4.6 EXACT COVER BY 3-SETS $\leq$ KNAPSACK

Once again we will prove a problem NP hard by showing that a special case is NP hard. The special case of KNAPSACK where  $v_i = w_i$  and goal  $K = W$  is called SUBSET SUM. (see definition in first section).

In our construction we think of the 3-sets as binary vectors in  $\{0,1\}^{3m}$ . And the  $i$ 'th bit will be 1 iff the  $i$ 'th element is contained with this particular 3-set. Therefore in each vector, only 3 ones will appear. The vectors can be thought of as binary integers, and set union now resembles integer addition and the goal is to find vectors which sum up to the all 1's vector.

But binary addition has a carry, which could break the bi-implication. For example  $0011 + 0101 + 0111 = 1111$ , but the sets  $\{3, 4\}, \{2, 4\}, \{2, 3, 4\}$  are not disjoint, and their union is not  $\{1, 2, 3, 4\}$ .

To fix this, we think of the numbers in base  $n+1$  instead of 2. since we have  $n$  vectors, there can never be a carry.

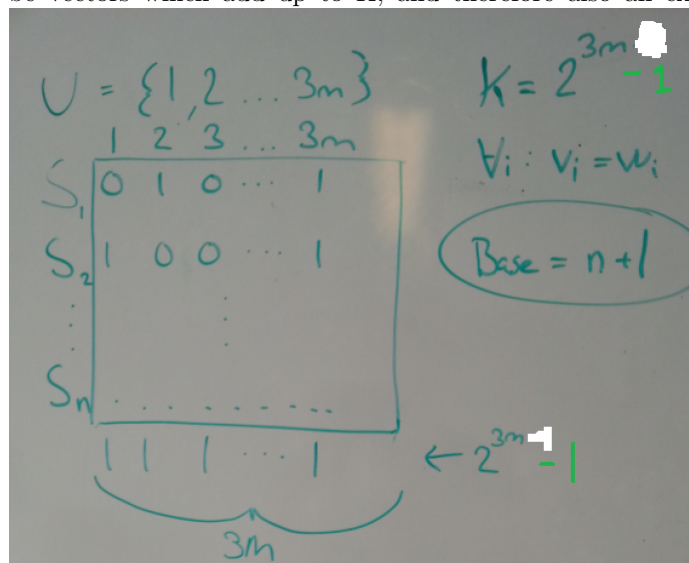
The weight goal of  $2^{3m} - 1$  completes the reduction.

$\Rightarrow$  :

If there is an exact cover by 3-sets, then the bit vectors in our construction corresponding to the exact cover will provide a number equal to the wanted  $K$ .

$\Leftarrow$  :

Since we can include every number once, and there is no carry, then there must be vectors which add up to  $K$ , and therefore also an exact cover by 3-sets.



## 5 Approximation algorithms.

### 5.1 Disposition

1. P, NP, NPC
2. Løsning af NPC problemer
3. Approximations algoritmer
4. Approx schemes
5. Algo design
6. vertex cover
7. TSP

## 5.2 P, NP, NPC

## 5.3 Løsninger af NPC problemer

NPC indeholder mange problemer som vi gerne vil løse på en eller anden måde. Vi har følgende muligheder:

- Små instanser kan ofte løses selvom udførselstiden er eksponentiel
- Der kan være nogle specielle instanser som kan løses i polynomiel tid. Eksemlvis INDENPENDET SET med en træ instans
- Approximations algoritmer og heuristics

## 5.4 Approx. algoritmer

En approximerings algoritme returnerer en valid løsning men som ikke er optimal. Den kører i polynomiel tid.

En algoritme for et givent problem har en approximations ratio  $p(n)$  hvis, for alle inputs af størrelse  $n$ , den returnerede løsning med cost  $C$  er indenfor en faktor  $p(n)$  af den optimale løsning med cost  $C^*$ :

$$\max(\frac{C}{C^*}, \frac{C^*}{C}) \leq p(n)$$

## 5.5 Approx. schemes

## 5.6 Design

## 5.7 Vertex cover

Følgende algoritme er en 2-Approximations algoritme.

```
1  C ← ∅
2  E' ← E[G]
3  while E' ≠ ∅
4      let (u,v) be an arbitrary edge of E'
5      C ← C ∪ {u, v}
6      remove from E' every edge incident on either u or v
7  return C
```

Bevis:

Først og fremmest så returnerer algoritmen en valid node cover: for hver iteration vælges en tilfældig kant, og alle kanter som ligger op af de to noder bliver fjernet. Dette sker indtil der ikke er flere kanter, og dermed er alle kanter dækket.

Lad  $A$  være de tilfældigt udvalgte kanter som vælges i linje 4. For alle noder  $i$   $A$  må mindst én af endpoint noderne være i  $C^*$ , dermed har vi en lower bound på den optimale løsning:

$$|C^*| \geq |A|$$

Hver gang vi udvælger en kant i linje 4, så inkluderer vi 2 noder i vores vertex cover. Dermed har vi:

$$|C| = 2|A|$$

Ved at kombinere disse kan vi udlede at denne algoritme er en 2-approximations algoritme:

$$\begin{aligned} |C| &= 2|A| \\ &\leq 2|C^*| \end{aligned}$$

Ovenstående siger os at cost af den producerede løsning maximalt kan være 2 gange cost af optimal løsning.

## 5.8 Metric TSP

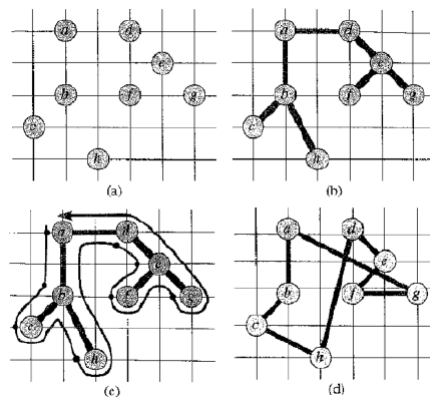
Følgende er en beskrivelse af en 2-approximations algoritme til TSP som overholder trekantsuligheden.

$$(Dvs \text{ cost funktionen } c(A) = \sum_{(u,v) \in A} c(u,v))$$

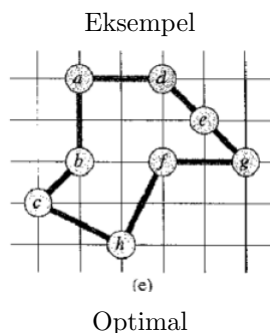
tilfredstiller at for alle noder  $u, v, w \in V : c(u, w) \leq c(u, v) + c(v, w)$  )

- 1 Select a vertex  $r \in V[G]$  to be "root" vertex
- 2 Compute a minimum spanning tree  $T$  for  $G$  from root  $r$
- 3 using MST-PRIM( $G, c, r$ )
- 4 Let  $L$  be the list of vertices visited in a preorder tree walk of  $T$
- 5 return the hamiltonian cycle  $H$  that visits the vertices in the order  $L$

Algoritmen genererer et minimum spanning tree vha prims algoritme ( $O(|V|^2)$ ), og returnerer en hamiltonian path bestående af en noderne besøgt i en depth first preorder traversal af dette træ.







**2-approximation:** Lad  $H^*$  være en optimal tour. Hvis vi fjerner en kant fra en tour, så får vi et spanning tree. Derfor kan vi bruge vægten af et MST  $T$  som lower bound:

$$c(T) \leq c(H^*)$$

Et full preorder walk  $FW$  lister knuderne hver gang de besøges. Det er let at se at hver kant i træet traverseres præcis 2 gange. Dermed har vi:

$$c(FW) = 2c(T)$$

Og ved at kombinere disse to får vi:

$$c(FW) \leq 2c(H^*)$$

Altså at costen af vores full walk er indenfor en faktor af 2 af costen af en optimal tour. Men  $FW$  er ikke en tour da den besøger nogle noder mere end 1 gang. Dog kan vi bruge vores antagelse omkring trekantsuligheden, og slette noder i vores full walk uden at øge costen. Derfor sletter vi alle "anden forekomster" af noder i vores full walk, og den resterende liste udgør en tour. For eksemplet ovenfor reduceres listen:

$$a, b, c, b, h, b, a, d, e, f, e, g, e, d, a \rightarrow a, b, c, h, d, e, f, g$$

Den reducerede liste udgør nu vores approximative tour  $H$  som returneres af algoritmen. Da  $H$  er opnået ved at slette noder fra full walk  $FW$  ved vi at costen af  $H$  er mindre eller lig med costen af  $FW$ :

$$c(H) \leq c(FW)$$

Og ved at kombinere dette og det forrige udtryk kan vi konkludere at:

$$c(H) \leq 2c(H^*)$$

## 5.9 Generel TSP approx?

Hvis vi ikke antager at trekantsuligheden holder, så kan det vises at der ikke kan eksistere en  $\rho$ -approximerings algoritme for  $\rho \geq 1$  med mindre  $P = NP$ .

**Tænk på dette som en modifikation af reduktionen fra HAM CYCLE til TSP(D). Vi laver også her en distance matrix, og ideen er at lave distance matrix så der er et stort gap mellem den bedste løsning og den næstbedste løsning.**

Beviset er et modstridsbevis. Vi antager at der for et tal  $\rho \geq 1$  eksisterer en polytids approximations algoritme A med approx ration  $\rho$ . Uden tab af generalitet kan vi antage at  $\rho$  er et heltal (ved at runde op ellers). Vi viser nu, at vi så kan bruge A til at løse HAM cycle problemet i polynomiell tid, hvilket vil medføre at  $P = NP$ .

Lad  $G = (V, E)$  være en HAM CYCLE instans. Vi ønsker at finde ud af om G indeholder en HAM cycle vha. A.

Vi laver nu instansen om til en TSP instanse på følgende måde:  
Lad  $G' = (V', E')$  være en komplet graf, dvs  $E'$  indeholder alle tænkelige kanter, altså:

$$E' = \{(u, v) : u, v \in V \text{ og } u \neq v\}$$

Tilføj en cost til hver kant i  $E'$  på følgende måde:

$$c(u, v) = \begin{cases} 1 & \text{if } (u, v) \in E \\ \rho|V| + 1 & \text{else} \end{cases}$$

Repræsentationer af  $G'$  og  $c$  kan laves af  $G$  i tid polynomielt i  $|V|$  og  $|E|$ .

Hvis man ser på TSP problemet  $(G', c)$ , så er det klart at hvis den originale graf  $G$  havde en HAM cycle  $H$ , så har cost funktionen  $c$  nu hivet hver kant i  $H$  cost 1, og  $(G', c)$  har dermed en tour med cost  $|V|$ . Hvis ikke  $G$  havde en HAM cycle, så må en tour i  $G'$  bruge en af de "dyre" kanter, som ikke var i det originale  $E$ . Men sådan en tour må have en cost på mindst:

$$(\rho|V| + 1) + (|V| - 1) = \rho|V| + |V| > \rho|V|$$

Fordi de kanter som ikke er i  $E$  er så dyre, så er det et gap på mindst  $|V|$  af cost ved en tour som også er en HAM cycle i  $G$ , og en som ikke er.

Hvis vi nu kører A på  $(G', c)$ , så er A garanteret at returnere en tour med cost max  $\rho$  gange cost af optimal tour. Så hvis  $G$  indeholder en HAM cycle, så returnerer A den. Hvis  $G$  ikke indeholder en HAM cycle, så returner A en tour med cost der er højere end  $|V|$ . A kan derfor bruges til at løse HAM cycle problemer i polynomiell tid.

**Since the cost of the optimal tour differ by a factor of more than  $\rho$  depending on if  $G$  has a Hamiltonian cycle or not, the  $\rho$ -approximation**

will always be able to distinguish between the two cases, hence decide if  $G$  has a Hamiltonian Cycle. This give us the desired contradiction

**Claim 1** *There is no  $\alpha$ -approximation algorithm for Traveling Salesman Problem where  $\alpha$  is a constant.*

**Proof:** Suppose for contradiction that such an  $\alpha$ -approximation algorithm exists. We will use this algorithm to solve the Hamiltonian Cycle Problem in polynomial time, giving a contradiction.

Given an instance of Hamiltonian Cycle with graph  $G$ , construct an instance of TSP with graph  $G'$  that is a complete graph on the same set of vertex. Set the edge costs as follows: if an edge  $e$  is in  $G$  then let  $c_e = 1$ , otherwise set  $c_e = \alpha n$ , where  $n$  is the number of vertices in  $G$ .

Notice that if  $G$  has a Hamiltonian cycle, then the optimal tour in  $G'$  has cost  $n$  by using only the edges in  $G$  that are in the Hamiltonian Cycle.

Otherwise if  $G$  does not have a Hamiltonian cycle, then the optimal tour in  $G'$  must contain some edge not in  $G$  and hence has cost  $> \alpha n$ .

---

<sup>1</sup>Based on previous note by Maurice Cheung

Since the cost of the optimal tour differ by a factor of more than  $\alpha$  depending on if  $G$  has a Hamiltonian cycle or not, the  $\alpha$ -approximation will always be able to distinguish between the two cases, hence decide if  $G$  has a Hamiltonian Cycle. This give us the desired contradiction.  $\square$

This lead us to consider the special case of **Metric TSP**. In the metric TSP, edge costs have to satisfy the triangle inequality, i.e. for any three vertices  $x, y, z$ ,  $c_{xz} \leq c_{xy} + c_{yz}$

We note that the metric TSP is still NP-complete. In the proof of the previous claim, set  $c_e = 2$  if  $e \notin G$ . Then the edge costs satisfy triangle inequality, and using the same argument as in the proof above we will that any algorithm that solves the metric TSP can solve the Hamiltonian cycle problem.

## 6 Problemer og flere reduktioner

### 6.1 INDEPENDENT SET

**Given:** Graph  $G = (V, E)$ , target  $K$ .

**Question:** Does there exist  $I \subseteq V$  such that  $|I| \geq K$  and for all  $u, v \in I$  we have  $(u, v) \notin E$ ?

### 6.2 CLIQUE

**Given:** Graph  $G = (V, E)$ , target  $K$ .

**Question:** Does there exist  $C \subseteq V$  such that  $|C| \geq K$

and for all  $u, v \in C$  we have  $(u, v) \in E$ ?

### 6.3 VERTEX COVER

**Given:** Graph  $G = (V, E)$ , budget  $B$ .

**Question:** Does there exist  $C \subseteq V$  such that  $|C| \leq B$  and for all  $(u, v) \in E$  we have  $(u \in C \vee v \in C)$ ?

### 6.4 MAX CUT

**Given:** Graph  $G = (V, E)$ , target  $K$ .

**Question:** Does there exist a cut  $(S, V \setminus S)$  of size at least  $K$ ?

### 6.5 MAX BISECTION

**Given:** Graph  $G = (V, E)$ , target  $K$ .

**Question:** Does there exist a cut  $(S, V \setminus S)$  of size at least  $K$ , such that  $|S| = |V \setminus S|$ ?

### 6.6 BISECTION WIDTH

**Given:** Graph  $G = (V, E)$ , target  $K$ .

**Question:** Does there exist a cut  $(S, V \setminus S)$  of size at most  $K$ , such that  $|S| = |V \setminus S|$ ?

### 6.7 HAMILTONIAN PATH

**Given:** Graph  $G = (V, E)$ .

**Question:** Does  $G$  have a path that visits every vertex exactly once?

### 6.8 TSP

**Given:** Distance matrix  $D$ , budget  $B$ .

**Question:** Is there a tour of length at most  $B$  that visits every node in the graph defined by  $D$  exactly once?

### 6.9 SET COVERING

**Given:** A set  $U$  (universe). A collection of subsets  $S_1, S_2, \dots, S_n \subseteq U$

**Question:** Does there exist  $B$  subsets whose union is  $U$ ?

## 6.10 EXACT COVER BY 3-SETS

**Given:** A set  $U$  of size  $3m$ . A collection of subsets  $S_1, S_2, \dots, S_n \subseteq U$  of size three.

**Question:** Does there exist  $m$  subsets which cover  $U$  exactly?

## 6.11 TRIPARTITE MATCHING

**Given:** Three sets  $B, G, H$  of size  $n$ . A collection of triples  $T \subseteq B \times G \times H$ .

**Question:** Does there exist  $n$  triples such that every element of  $B, G$  and  $H$  is contained in exactly one of these triples?

## 6.12 SET PACKING

**Given:** A set  $U$ . A collection of subsets  $S_1, S_2, \dots, S_n \subseteq U$ . A goal  $K$ .

**Question:** Does there exist  $k$  pairwise disjoint subsets?

## 6.13 KNAPSACK

**Given:**  $N$  items. Item  $i$  has value  $v_i$  and weight  $w_i$ , both positive integers. A max weight  $W$ . And a goal  $K$ .

**Question:** is there a subset of the  $N$  items such that the total weight is at most  $W$  and that the total value is at least  $K$ ?

## 6.14 SUBSET SUM (SPECIAL CASE OF KNAPSACK)

In this version of knapsack an items value is equal to its weight, and the goal  $K$  is equal to the max weight  $W$ . So, we are given a set of  $N$  integers and an integer  $K$  and ask if there is a subset of the given integers that adds up to  $K$ .

## 6.15 BIN PACKING

**Given:**  $N$  positive integers and two more integers  $C$ (capacity) and  $B$ (number of bins).

**Question:** can these numbers be partitioned into  $B$  subsets, each of which has a total sum of at most  $C$ ?

## 6.16 NAESAT $\leq$ MAX CUT

**Theorem 9.5:** MAX CUT is NP-Complete

We prove this by reducing from NAESAT, which we know is NP-complete.

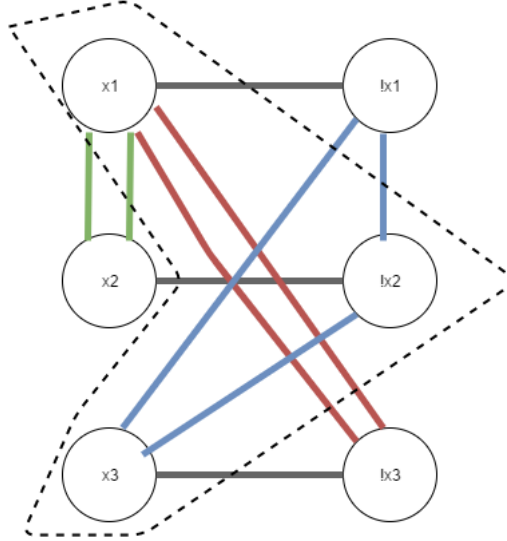
We construct a graph  $G = (V, E)$ , and a goal  $K$  such that there is a way to separate the nodes of  $G$  into two sets  $S$  and  $V-S$  with  $K$  or more edges going from one set to the other, if and only if there is a truth assignment for our NAESAT formula  $f$  which satisfies  $f$ . We allow more than one edge between two

vertices, and each such edge contributes one to the cut.

Our input formula has  $m$  clauses and  $n$  variables, and we construct a graph with  $2n$  nodes - one for each variable and its negation. For each clause, we add edges to our graph to form triangles. If two literals of a clause are the same, for example  $(x \vee y \vee y)$ , (which is equivalent to  $(x \vee y)$ ), we just add two edges between the nodes representing the two distinct literals. The point of the triangles and the two edges between same literals, is that for both constructs, the cut is always two. Now we add an edge between variables and their negation, and set our target  $K = n + 2m$ . **The  $n$  is for cutting the horizontal edges, and  $2m$  is because we need to cut each triangle (each clause) - if we don't, then it is possible for all literals in a single clause to be true (and then it's not *naesat*)).** This completes the reduction.

**Example:**

Given a *NAESAT* formula:  $f = (x_1 \vee x_2) \wedge (x_1 \vee \neg x_3) \wedge (\neg x_1 \vee \neg x_2 \vee x_3)$   
We can construct the graph shown in figure 4. The green edges come from the first clause, red the second clause, and blue the third clause.



**Figure 4:** Graph  $r(f)$  corresponding to the formula  $f$

**Analysis:**

For each variable we add two nodes and one edge between them. For each clause we add at most 3 edges. So the reduction is polynomial.

$\implies$  :

Given a satisfying *naesat* assignment for  $f$ , we must show that  $r(f)$  has a cut of size at least  $K$ .  $x_1 = 1, x_2 = 0, x_3 = 1$  is a satisfying assignment for  $f$ . We have 3 variables and 3 clauses, so the target  $K$  is  $2 * 3 + 3 = 9$ . The cut of

9 is obtained by cutting the vertices within the dotted line in the example above.

$\Leftarrow$  :

Given a cut of size at least  $K$  of  $r(f)$ , we must show that there is a satisfying naesat assignment for  $x$ . Here we just take the truth values of the nodes in our cut set.

*Read more in papadimitriou page 191-192.*

## **6.17 NAESAT $\leq$ 3-COLORING**

TODO