

High level programming language for quantum computing

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Obiettivo del lavoro

Reasoning su quantum computer

Base di conoscenza classica + query

Embedding su quantum computer

Esecuzione e recupero risultati

Perché il quantum computing

Grazie a

- Superposition
- Entanglement

$$\mathcal{H}(t) |\psi(t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle$$

$$\langle A_0 \otimes B_0 \rangle + \langle A_0 \otimes B_1 \rangle + \langle A_1 \otimes B_0 \rangle - \langle A_1 \otimes B_1 \rangle = 2\sqrt{2}$$

Violiamo

Strong Church-Turing Thesis

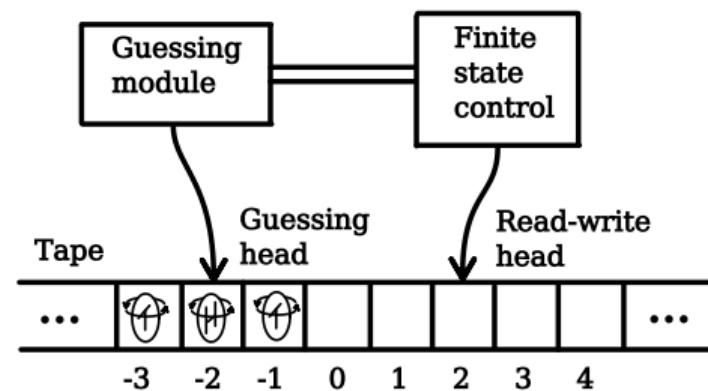


Figure: Probabilistic Turing Machine

Due paradigmi di programmazione

Quantum Gate

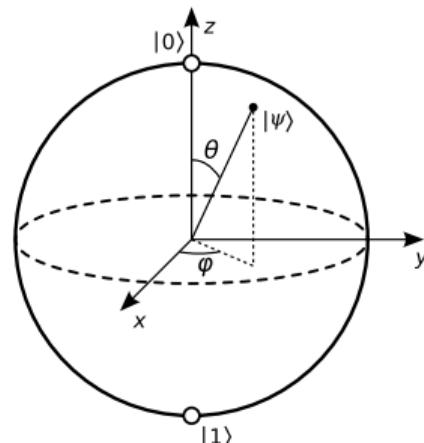


Figure: A single *qubit* gate can be seen as a rotation on the Bloch Sphere

Quantum Annealing

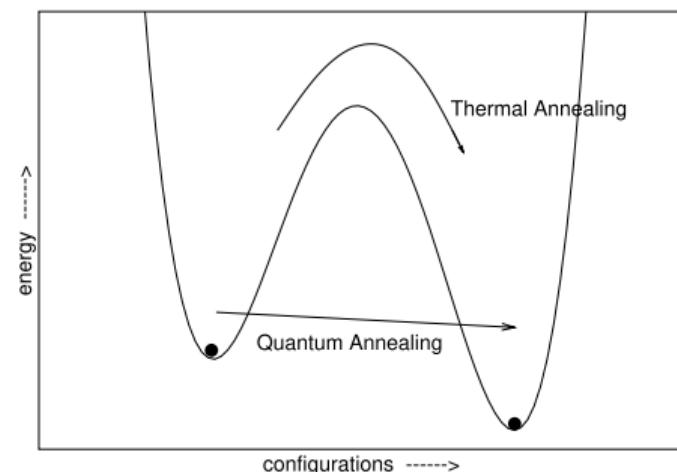


Figure: Tunneling effect (K. Chakrabarti, A. Das)

Quantum Gate

- Formalismo molto studiato
- Gate Reversibili
- Set di porte universali
- Algoritmi di Shor, ecc.

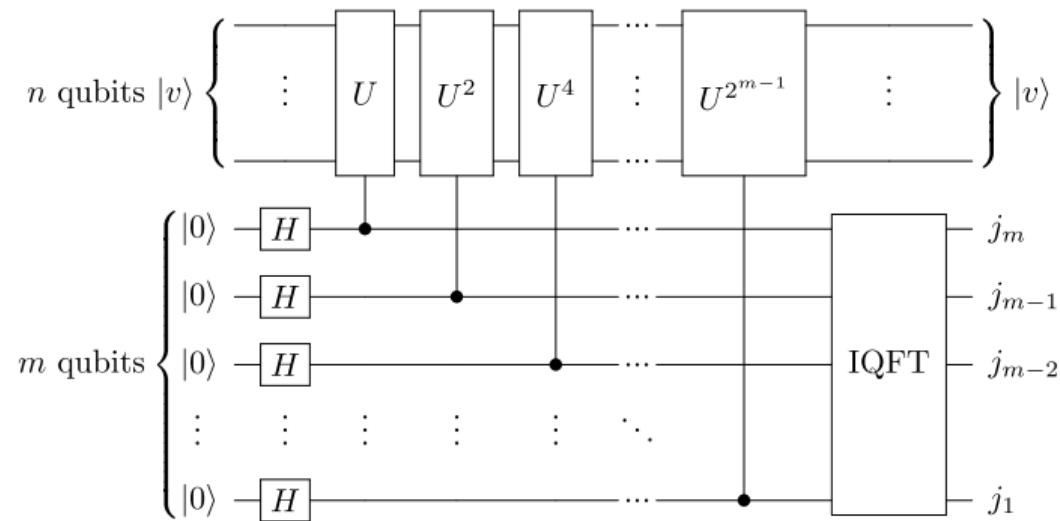
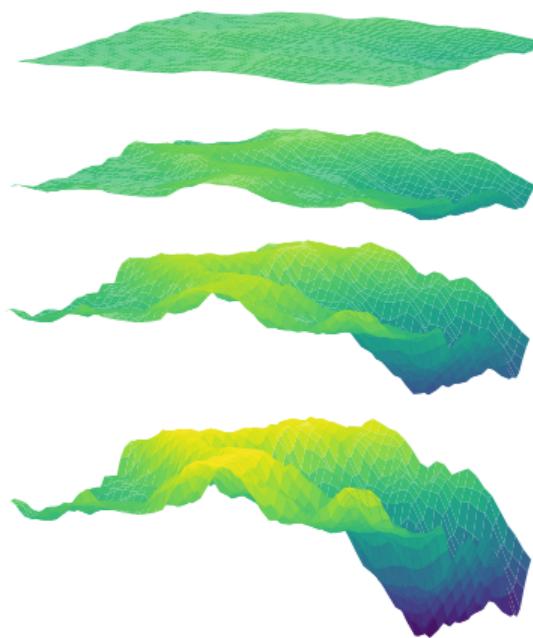


Figure: Step for Shor algorithm (Thomas G. Wong)

Quantum Annealer



- Problemi in forma QUBO
- Ispirato a Simulated Annealing
- Effetto tunneling
- Adiabatic Quantum Computing (AQC)
- $\mathcal{H}(t) = s(t)\mathcal{H}_i + (1 - s(t))\mathcal{H}_f$

Figure: Complete sovrapposizione → ground state \mathcal{H}_f

QA-Prolog

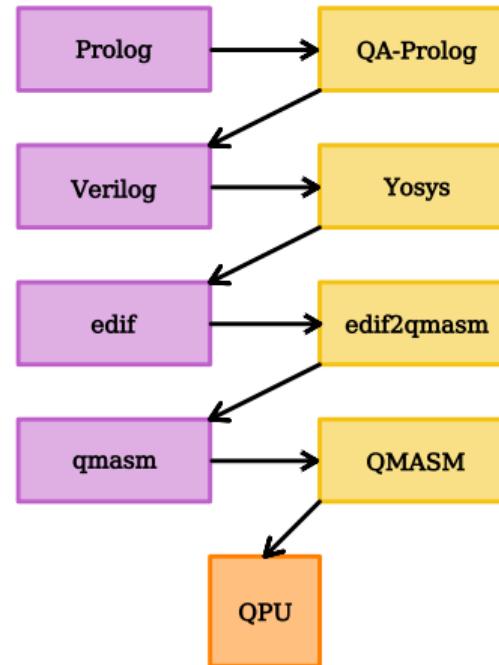
Il progetto

- Sviluppato da Scott Pakin
- Proof of concept
- Trasformazioni successive
- Prolog + Query $\rightarrow \mathcal{H}_f$
- Interagisce direttamente con il solver
- Raccoglie e organizza i risultati



Figure: Scott Pakin - Los Alamos National Laboratory

Pipeline



Trasformazioni

- ① Prolog → Verilog (HDL)
- ② Verilog → Circuito digitale
- ③ Circuito digitale → \mathcal{H}_f simbolica
- ④ \mathcal{H}_f simbolica → \mathcal{H}_f fisica

QASM

\mathcal{H}_f simbolica $\rightarrow \mathcal{H}_f$ fisica

Cos'è

- Quantum macro assembler
- Sviluppato in Python
- Basso livello di astrazione
- Si interfaccia con Ocean

Cosa permette di fare

- Riferimento simbolico a *qubit*
- *Qubit* “pinnati” a TRUE o FALSE
- Incapsulare pattern in macro
- Creazione di librerie di macro
- Pulizia dell'output:
 - solo *qubit* “interessanti”
 - no slack variables

QASM

Esempio: Macro

```
# Y = A OR B
!begin_macro OR
$A 0.5
$B 0.5
$Y -1
$A $B 0.5
$A $Y -1
$B $Y -1
!end_macro OR
```

Figure: or gate

```
# Y = NOT A
!begin_macro NOT
$A $Y 1.0
!end_macro NOT
```

Figure: not gate

```
# Y = A AND B
!begin_macro AND
$A -0.5
$B -0.5
$Y 1
$A $B 0.5
$A $Y -1
$B $Y -1
!end_macro AND
```

Figure: and gate

possiamo racchiudere queste macro nel file gates.qasm

QASM

Esempio: $y = x_1 \wedge \neg(x_2 \vee x_3)$

```
!include <gates>

!use_macro OR x2_or_x3
x2_or_x3.$A = x2
x2_or_x3.$B = x3
x2_or_x3.$Y = $x4

!use_macro NOT not_x4
not_x4.$A = $x4
not_x4.$Y = $x5

!use_macro AND x1_and_x5
x1_and_x5.$A = x1
x1_and_x5.$B = $x5
x1_and_x5.$Y = y
```

“Pinniamo” il valore di y per ottenere l’assegnamento delle x_i che verificano la formula logica:

```
qasm --run --pin="y := true" circsat.qasm
```

Solution #1 (energy = -20.0000, tally = 647):

Variable	Value
x1	True
x2	False
x3	False
y	True

Figure: CircSat problem

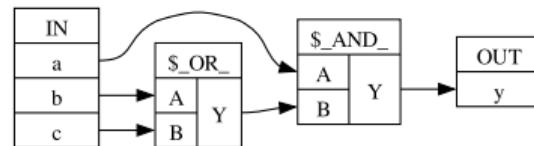
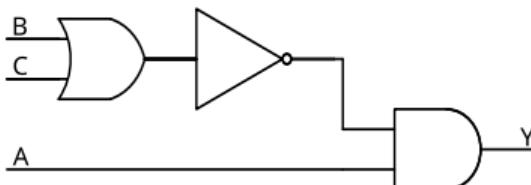
Figure: CircSat solution

Yosys - edif2qasm

Verilog → Circuito digitale → \mathcal{H} simbolica

Yosys

- Framework per la sintesi del Verilog
- Output: RTL Netlist in formato EDIF



edif2qasm

- Converte dal formato EDIF a QMASM
- Attinge a una libreria di gate

```

!begin_macro sat
  !use_macro AND $id00006
  !use_macro NOT $id00004
  !use_macro OR $id00005
  $id00004.A = $id00005.Y
  $id00005.A = b
  $id00005.B = c
  $id00006.A = a
  $id00006.B = $id00004.Y
  $id00006.Y = y
!end_macro sat
  
```

Yosys - edif2qasm

Esempio: moltiplicazione tra interi

```
module mult (multiplicand, multiplier, product);
    input [1:0] multiplicand;
    input [1:0] multiplier;
    output [2:0] product;

    assign product = multiplicand * multiplier;
endmodule
```

Figure: Factorization problem

Traduzione in EDIF

```
yosys myfile.v synth.ys -b edif -o myfile.edif
```

Traduzione in QMASM

```
edif2qasm -o="myfile.qasm" myfile.edif
```

Esecuzione

```
qasm --run --pin="mult.product[2:0] := 110"
      --solver="sim_anneal" mult.qasm
```

Solution #1 (energy = -57.5000, tally = 68):

Variable	Value
mult.multiplicand[0]	False
mult.multiplicand[1]	True
mult.multiplier[0]	True
mult.multiplier[1]	True
mult.product[0]	False
mult.product[1]	True
mult.product[2]	True

Figure: Factorization Solution

QA-Prolog

- Traduzione da Prolog a Verilog
- Wrapper per tutta la Pipeline
- Risultati in formato Human Readable
- Decide dimensione delle variabili

```
sat(A, B, C, Y) :-  
    or(B, C, X),  
    not(X, Z),  
    and(A, Z, Y).
```

Figure: Prolog Code

```
module sat (a, b, c, y);  
    input a, b, c;  
    output y;  
  
    assign y = a & ~(b | c);  
endmodule
```

Figure: Verilog Code

QA-Prolog

Esempio

Base di conoscenza

Il nemico del mio nemico è mio amico

```
hates(alice, bob).  
hates(bob, charlie).  
  
enemies(P, Q) :- hates(P, Q).  
enemies(P, Q) :- hates(Q, P).
```

```
friends(A, B) :-  
    enemies(A, X),  
    enemies(X, B),  
    A \= B.
```

Esecuzione

```
QA-Prolog --qasm-args="--postproc=opt"  
--query='friends(P1, P2).' friends.pl
```

```
P1 = alice  
P2 = charlie
```

```
P1 = charlie  
P2 = alice
```

Figure: Query Solution

Figure: Enemy of my Enemy

Update al progetto

Integrazione con Ocean

- Aggiornamento librerie obsolete
- Rimozione metodi deprecati
- Sostituzione funzioni “spostate”
- Correzione parametri funzioni

Altro

- Sostituzione funzioni rinominate
- Parametri command line

```
#from dwave.cloud import Client, hybrid, qpu, sw
from dwave.cloud import Client
import hybrid

#from greedy import SteepestDescentSolver
from dwave.samplers import SteepestDescentSolver

#from tabu import TabuSampler
from dwave.samplers import TabuSampler

#from scipy.stats import median_absolute_deviation
from scipy.stats import median_absDeviation
```

Figure: Update librerie

```
#elif solver == "neal":
elif solver == "sim_anneal":
```

Figure: Correzione parametri command line

Update al progetto

Incompatibilità tra output edif2qasm e input QMASM

```
// Define hates(atom, atom).
module \hates/2 (A, B, Valid);
...
endmodule
```

Figure: Verilog

```
# hates/2
!begin_macro id00011
...
!end_macro id00011

# enemies/2
!begin_macro id00010
  !use_macro OR $id00031
  !use_macro hates/2
...
```

Figure: qmasm

```
with open(file, 'r') as input:
    first = input.readline()
    second = input.readline()
    while(second_row != ""):
        if first.startswith("#") and second.startswith("!begin_macro"):
            self.name[first[2:-1]] = second[len("!begin_macro "):-1]
        first_row = second_row
        second_row = input.readline()

with open(file, 'r') as input:
    doc = input.read()
    lines = doc.splitlines()
    for line in lines:
        for word in line.split():
            if word in self.name.keys():
                line = line.replace(word, self.name[word])
    self.new_lines.append(line)
```

Figure: Preprocessing

QAOA

Quantum approximate optimization algorithm

- ① Definire matrici: \mathcal{H}_c e \mathcal{H}_m
- ② Definire oracoli parametrici: $\mathcal{U}_c(\gamma) = e^{-i\gamma\mathcal{H}_c}$ e $\mathcal{U}_m(\beta) = e^{-i\beta\mathcal{H}_m}$
- ③ Applicazione ripetuta di $\mathcal{U}_c(\gamma)$ e $\mathcal{U}_m(\beta)$
- ④ Ottimizzazione (classica) dei parametri γ_i e β_i

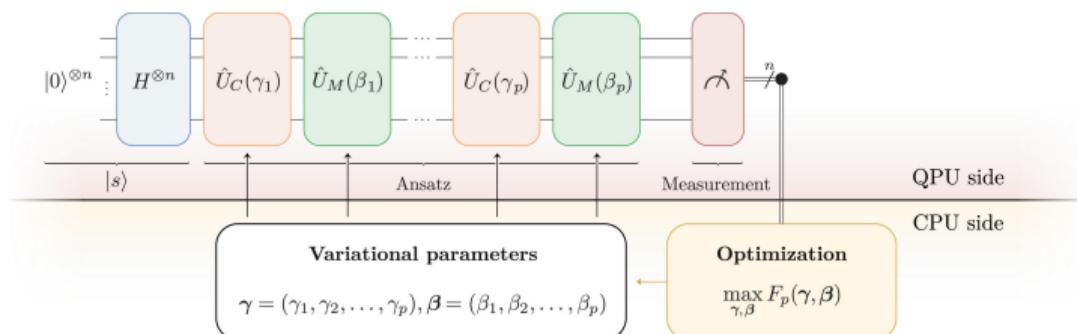


Figure: QAOA sketch (BLEKOS, Kostas, et al.)

QUBO → ISING → Operatori di Pauli

```
qubo = qubovert.utils.matrix_to_qubo(qubo_mat)
ising = qubovert.utils.qubo_to_quso(qubo)
qubo_dict = dict(qubo)
ising_dict = dict(ising)
ising_dict.pop(())
ising_mat = qubovert.utils.qubo_to_matrix(ising_dict)
```

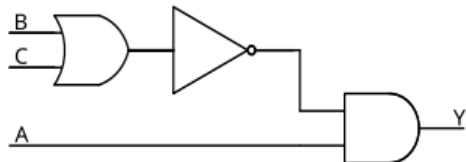
Figure: QUBO → ISING (libreria qubovert)

```
def build_paulis(matrix):
    pauli_list = []
    for i in range(len(matrix)):
        pauli_list.append(("Z", [i], matrix[i][i]))
        for j in range(i+1, len(matrix)):
            pauli_list.append(("ZZ", [i, j], matrix[i][j]))
    return pauli_list

sat_paulis = build_paulis(ising_mat)
cost_hamiltonian = SparsePauliOp.from_sparse_list(sat_paulis, n_qubits)
```

Figure: ISING → Operatori di Pauli

Esempio



```

!begin_macro sat
  !use_macro AND $id00006
  !use_macro NOT $id00004
  !use_macro OR $id00005
  $id00004.A = $id00005.Y
  $id00005.A = b
  $id00005.B = c
  $id00006.A = a
  $id00006.B = $id00004.Y
  $id00006.Y = y
!end_macro sat
  
```

$$\left(\begin{array}{cccccccccccc} 0.5 & 0.5 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -2 \\ 0 & 0.5 & -1 & 0 & -2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -0.5 & 0.5 & -1 & -2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.5 & -1 & 0 & -2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array} \right)$$

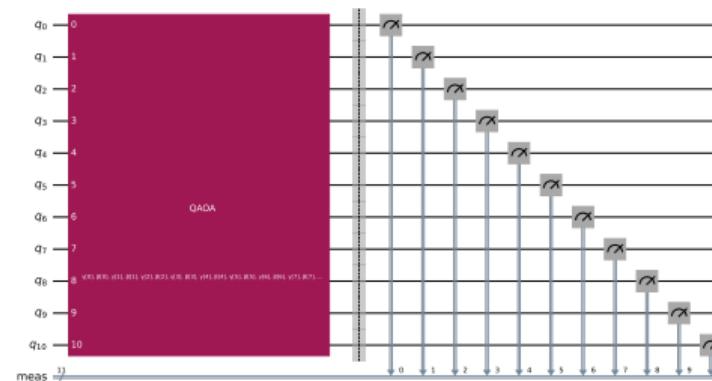


Figure: CircSat

Figure: \mathcal{H}_f and QAOA Quantum Circuit

Esempio

Risultato 1

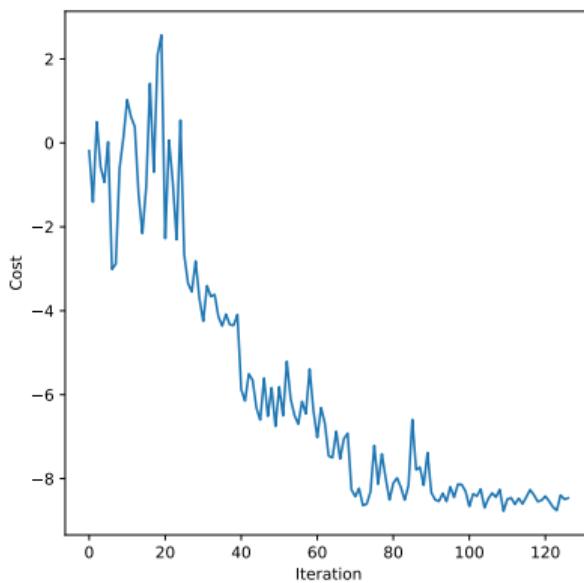


Figure: Parameter optimization

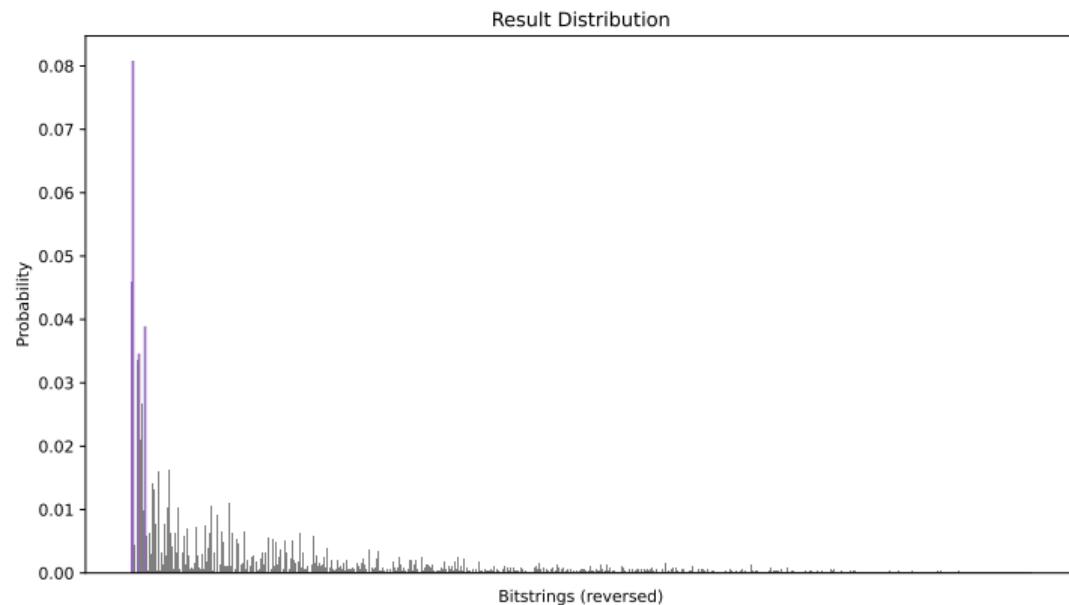


Figure: Sample results

Esempio

Risultato 2

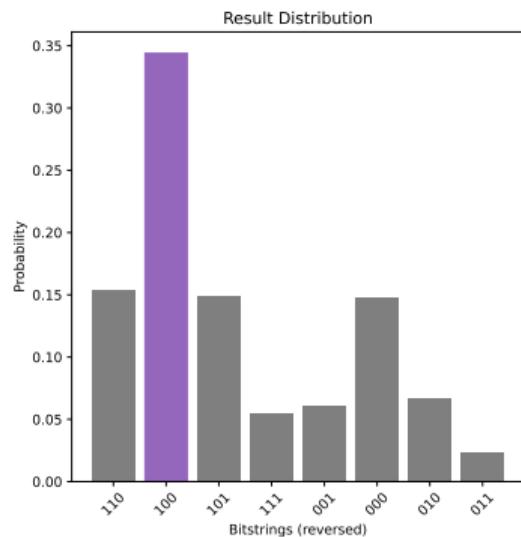


Figure: 3 “interesting” bit

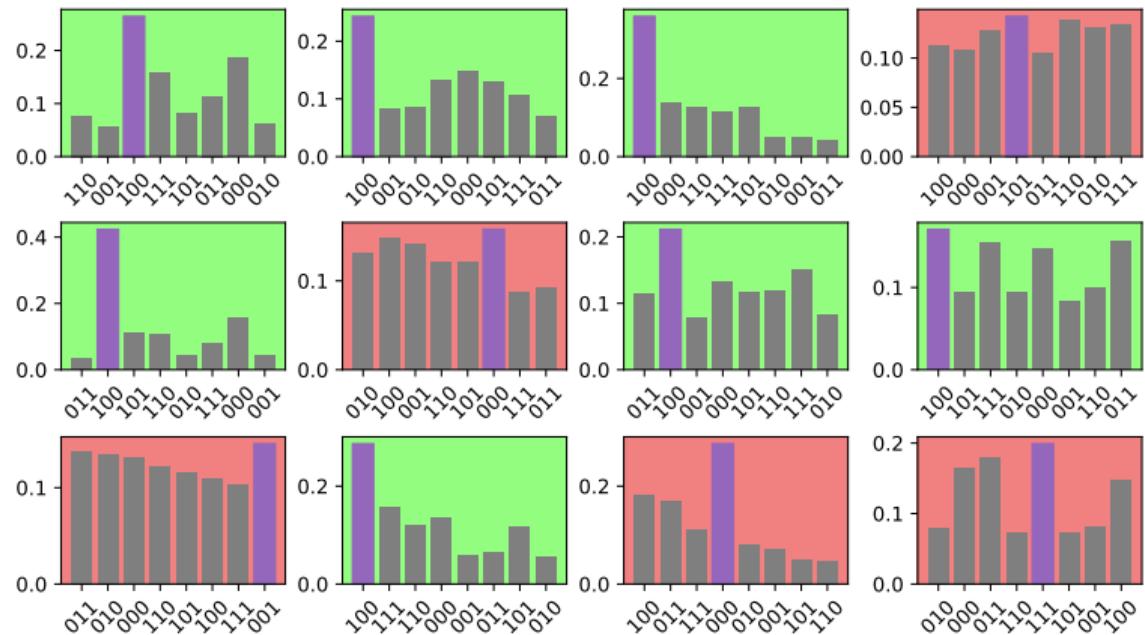


Figure: Multiple experiment runs

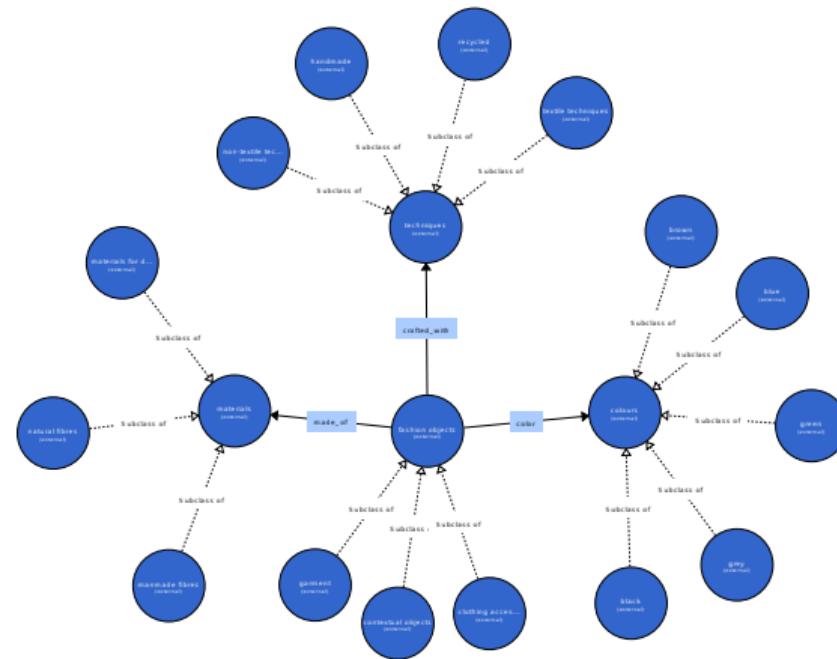
Ontologie

Cos'è un'ontologia

- Insieme di fatti
 - Riguardanti un dominio di interesse
 - Prevengono interpretazioni sbagliate
 - Assicurano la cooperazione tra software

Come si definisce un'ontologia

- Ontology Web Language (OWL)
 - Diversi “flavours”
 - OWL Full
 - OWL DL
 - Classi Individui e Relazioni



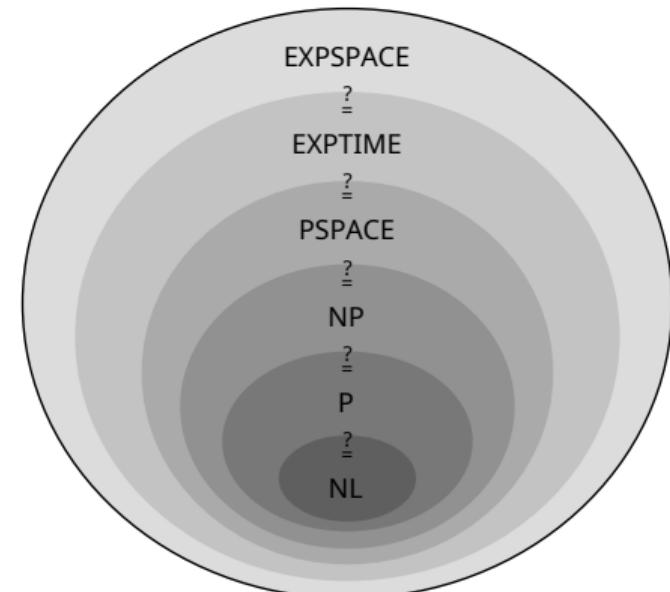
Inferenze in OWL

Complessità

- Variazione sintattica di \mathcal{SROIQ}
- \mathcal{ALC} è una restrizione di \mathcal{SROIQ}
- \mathcal{ALC} è PSpace-hard

Reasoner

- Pellet
- Fact++
- Hermit
- ...



Esempio completo

Quantum Simpson

```
<owl:NamedIndividual rdf:about="http://www.people#marge">
    <rdf:type rdf:resource="http://www.people#People"/>
    <www:marry rdf:resource="http://www.people#homer"/>
    <www:parent_of rdf:resource="http://www.people#bart"/>
</owl:NamedIndividual>
```

Figure: Marge Simpson entry

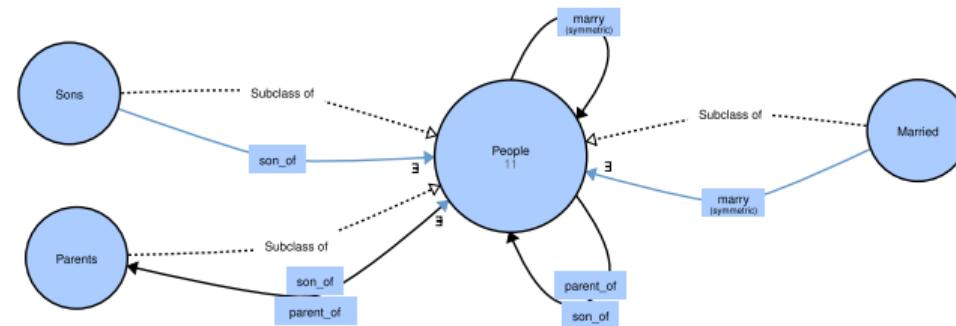


Figure: Ontology Structure

Da OWL-rdf a Prolog

```
person(marge).  
person(bart).  
person(jackie).  
person(selma).  
person(ling).  
  
parent_of(marge, bart).  
parent_of(jackie, marge).  
parent_of(jackie, selma).  
parent_of(selma, ling).  
  
son_of(P, Q) :- parent_of(Q, P).  
  
gran_parent_of(P, Q) :-  
    son_of(Q, X),  
    son_of(X, P).
```

Figure: Prolog Ontology

Interrogazione

```
QA-Prolog --verbose --qasm-args="--solver=sim_anneal  
--postproc=opt" --query='gran_parent_of(P1, P2).' family.pl
```

```
P1 = jackie  
P2 = bart
```

```
P1 = jackie  
P2 = selma
```

Figure: Query Result 1

```
P1 = jackie  
P2 = bart
```

Figure: Query Result 2

Limitazioni del simulatore

```
cousins(P, Q):-  
    gran_parent_of(X, P),  
    gran_parent_of(X, Q),  
    parent_of(Y, P),  
    parent_of(Z, Q),  
    Z \= Y.
```

Figure: Cousins rule

Interrogazione

```
QA-Prolog --verbose --qasm-args="--solver=sim_anneal  
--postproc=opt" --query='cousins(P1, P2).' family.pl
```

QA-Prolog: No solutions were found

Figure: Query Result

Lavoro Futuro

Monte

- Compilatore OWL/RDF → Prolog
- Sperimentare altri linguaggi

Valle

- Aggiungere simulated annealing
- Interfacciare QMASM con quantum gate

- Mantenere aggiornati i componenti
- Testare su hardware quantistico
- Confronto ACQ e QAOA

Grazie per l'attenzione

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