Kvantni celični avtomati in kvantno procesiranje

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Predgovor

S povečevanjem gostote integriranih vezij postajajo tranzistorji vse manjše nanoelektronske naprave. Želeno delovanje tranzistorjev velikosti le nekaj nanometrov pa pričnejo ovirati kvantni pojavi in sile med elektroni. Zato so se pojavile zamisli o novih platformah, ki jih ti pojavi ne le ne bi ovirali, pač pa bi jih platforme izkoristile za procesiranje. Poleg tega lahko nove nanoelektronske naprave prinesejo še več prednosti pred današnjimi računalniki, npr. večjo gostoto, manjšo porabo energije, hitrejše delovanje itd.

Ena od takih predlaganih platform so kvantni celični avtomati (Quantum Cellular Automata - QCA). Namesto tranzistorjev vsebujejo celice z elektroni, katerih razporeditev znotraj celice določa logično stanje. Procesiranje se izvede z ustrezno razporeditvijo QCA celic, pri čemer se izkoriščata Coulombova sila in kvantno tuneliranje. Do sedaj so bile fizično implementirane le manjše QCA strukture z majhnim številom celic, ker je praktično težko izdelati QCA celice nanometrske velikosti. Možno pa je načrtovati in optimizirati večja QCA vezja s pomočjo računalniškega simulatorja.

V zadnjem času je zaradi praktične implementacije veliko pozornosti posvečene kvantnemu procesiranju z osnovnimi gradniki kvantnimi biti. Superpozicija in kvantna prepletenost omogočata novo paradigmo procesiranja, ki obljublja eksponentno pohitritev nekaterih algoritmov glede na klasične računalnike. Izgradnjo skalabilnega kvantnega računalnika trenutno otežuje zahteven nadzor neizoliranega sistema kvantnih bitov. Vendar predstavljene implementacije, množica razvitih kvantnih algoritmov in protokolov, dostopni računalniški simulatorji in možnost uporabe manjših fizičnih kvantnih računalnikov preko spleta dopuščajo preučevanje in razvoj področja.

Tako QCA kot kvantnemu procesiranju je skupna reverzibilnost. Fizično reverzibilno procesiranje brez izgube informacij se približa minimalni možni porabi energije. Kvantno procesiranje je inherentno reverzibilno, saj informacije v kvantnem bitu ni mogoče izbrisati. Primerna zasnova QCA vezja omogoča implementacijo fizično reverzibilne procesne platforme.

Navodila za izdelavo seminarske naloge

- Vaše datoteke se nahajajo v direktorijih `Skupina*`, kjer * predstavlja številko vaše skupine - glavna datoteka je `main.tex`.
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V okviru prvega seminarja se boste ukvarjali s procesnimi platformami, ki za delovanje izkoriščajo kvantne pojave. Delo bo potekalo v skupinah s štirimi študenti. Za skupinsko delo uporabljajte repozitorij, kot je npr. dropbox[1] ali git[2]. Cilj seminarja so izdelki in poročila, ki jih lahko ob zaključku združimo v celoto (glej rezultate seminarjev iz prejšnjih let). Poročilo pišite v okolju LaTeX, kjer lahko za lažje skupinsko delo uporabljate okolje, kot je npr. overleaf[3]. Za iskanje virov uporabljajte iskalnike znanstvene literature[4]. Rok za izdelavo prvega seminarja je 27. 11. 2022. Predstavitve nalog bodo v tednu od 28. 11. 2022 v terminu vaj. Na zagovoru seminarja bo imela vsaka skupina 10 minutno predstavitev svojega izdelka, nato bo sledila krajša diskusija.

Za predlogo uporabite strukturo znanstvenega članka, ki obsega poglavja Uvod, Metode, Rezultati, Zaključek in Literatura. Slike naj bodo v formatu PDF ali EPS, z ustreznimi viri (literaturo) polnite vašo BIB datoteko. Poročilo redno izpopolnjujte. Ker gre za skupinsko delo, mora biti na koncu poročila tudi poglavje z naslovom Doprinosi avtorjev, kjer v enem stavku zapišite, kakšen je bil doprinos posameznega člana skupine.

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Kvantni celični avtomati

Ena izmed tem za prvi seminar je področje kvantnih celičnih avtomatov (angl. QCA) [1, 2, 3, 4], ki so možna alternativna tehnologija procesiranja v prihodnosti. Cilj seminarja je lahko na primer zasnova in realizacija reverzibilne QCA strukture v okolju QCADesigner. Reverzibilno procesiranje je opisano v [5, 6, 7]. Primera osnovnih univerzalnih reverzibilnih logičnih operatorjev sta Toffolijeva in Fredkinova vrata. V seminarju izdelajte kompleksnejšo reverzibilno strukturo, na primer polni seštevalnik, LFSR (pomikalni register z linearno povratno vezavo) itd. Potreben pogoj za fizično reverzibilnost je logična reverzibilnost. Zato najprej zasnujte logično reverzibilno QCA strukturo. Logična reverzibilnost pomeni, da lahko iz logičnih vrednosti izhodov enolično določimo logične vrednosti vhodov, torej med vhodi in izhodi obstaja bijektivna preslikava. Nato poskusite z orodjem QCADesigner zasnovati še fizično reverzibilno strukturo QCA. Slednja mora biti najprej logično reverzibilna. Poleg tega mora izpolnjevati tudi dodatni pogoj: če spremenimo izhodne celice v vhodne in obratno ter določimo vhodne logične vrednosti (na prej izhodnih celicah), moramo na izhodih (prej vhodne celice) dobiti ustrezne vrednosti, določene z bijekcijo. Z reverzibilno strukturo lahko torej izračunamo vrednost bijektivne funkcije (npr. pretvorbo v dvojiški komplement, izračun zgoščevalnih (hash) funkcij itd.) in z zamenjavo vhodov in izhodov tudi njeno inverzno vrednost.

V poglavju Metode opišite, ali ste uporabili ad hoc metodo ali ste formalizirali metodo snovanja QCA strukture. Navedite tudi, ali prosto določite urino cono vsaki posamezni QCA celici ali je vaša struktura zasnovana z uporabo strukturiranih pravokotnih urinih con.

QCA strukturo izdelajte s pomočjo orodja QCADesigner, s katerim tudi simulirajte in testirajte njeno delovanje. Poročilo izdelajte v okolju LaTeX in dopolnjujte repozitorij s pripadajočimi datotekami (QCAD datoteke, slike itd.).

Kvantni računalniki

Danes v računalništvu prevladujoča tehnologija CMOS se z miniaturizacijo tranzistorjev bliža vrhuncu učinkovitosti, ko je zaradi fizikalnih omejitev ne bo več možno izboljševati. Za nadaljnji napredek strojne računalniške opreme bo nujno prevzeti katero od alternativnih procesnih platform. Ena od teh je kvantno računalništvo, ki za procesiranje izkorišča kvantne pojave in operira z delci na nanometrskem nivoju. Poleg tega teoretične raziskave in tudi praktične implementacije prikazujejo večjo zmogljivost kvantnega računalništva od današnje tehnologije.

Kvantno računalništvo se s hitrim razvojem kaže kot perspektivna alternativa za dopolnitev in nadomestitev tehnologije CMOS. Številna velika podjetja so razvila in izdelala svoje kvantne računalnike ter prikazala njihovo delovanje. Med najbolj znanimi so izvedbe:

- IBM,
- Google,
- Intel,
- Rigetti,
- D-Wave Systems
- ter mnoga druga podjetja in univerze po celem svetu.

Raziskovalci so predstavili kvantne algoritme (npr. Shorov in Groverjev), ki imajo manjšo časovno kompleksnost kot najboljši klasični algoritmi. To bi lahko privedlo do eksponentno hitrejšega reševanja določenih problemov, vendar zaenkrat praktične implementacije teh algoritmov še niso skalabilne. V zadnjem času pa so fizično izdelali kvantne računalnike, ki nekatere probleme rešijo hitreje od najzmogljivejših klasičnih računalnikov, s čimer so prikazali t.i. ”quantum supremacy”. Med najbolj odmevnimi izvedbami sta Googlov procesor Sycamore [8] in računalnik Zuchongzhi, razvit na univerzi USTC [9].

Cilj seminarske naloge s področja kvantnega računalništva je spoznavanje osnovnih konceptov te procesne platforme. V nadaljevanju je naštetih nekaj predlogov tem (odebeljeno besedilo). Za seminarsko nalogo si izberite eno izmed njih, lahko pa predlagate tudi kakšno drugo temo s tega področja.

Ker kvantni računalniki še niso v splošni uporabi, se za analizo delovanja uporabljajo razni simulatorji, s katerimi lahko načrtujemo, implementiramo in simuliramo delovanje kvantnih algoritmov. V številnih programskih jezikih je bilo razvitih mnogo simulatorjev z različnimi funkcijami in lastnostmi. Obsežen seznam se nahaja na spletni strani Quantiki. Ena izmed tem seminarske naloge je **načrtovanje in implementacija kvantnih algoritmov v več različnih simulatorjih**. Pri tem predstavite prednosti in slabosti izbranih simulatorjev in njihove koristne funkcije.

Za fizično implementacijo kvantnih računalnikov so raziskovalci ponudili številne tehnologije in v izbranih dejansko realizirali procesorje. Med tehnologijami so superprevodna vezja, ujeti ioni, kvantne pike, jedrska magnetna resonanca, uporaba fotonov, elektronov in številni drugi predlogi. V seminarski nalogi lahko **predstavite predlagane tehnologije, njihove prednosti in slabosti ter primere fizične implementacije**.

Razvitih je bilo mnogo kvantnih algoritmov, ki predstavljajo reševanje problemov učinkoviteje kot s klasičnimi računalniki. V seminarju lahko **izvedete podrobno analizo kompleksnega kvantnega algoritma**. Pri tem algoritem načrtujete in implementirate v simulatorju, analizirate njegovo kompleksnost, simulirate delovanje z različnimi vhodnimi podatki in predlagate možne optimizacije katerega od parametrov algoritma.

Sčasoma želimo splošno uporabljati univerzalne kvantne računalnike, s katerimi lahko izvedemo poljubno aplikacijo, kot sedaj to omogočajo klasična vezja. Trenutno pa realizacije kvantnih računalnikov prikazujejo svojo učinkovitost pri reševanju specifičnih nesplošnih problemov. **Navedite nekatere od teh problemskih področij (npr. boson sampling), jih podrobno opišite in predstavite obstoječe ter potencialne rešitve**.

Za izdelavo skalabilnih kvantnih računalnikov je zelo pomembno popravljanje napak pri kvantnem procesiranju, ki se zaradi lastnosti kvantnih delcev precej razlikuje od popravljanja napak pri klasičnem procesiranju. **Podrobno preučite algoritme za popravljanje napak pri kvantnem procesiranju, jih implementirajte, prikažite njihovo delovanje z uporabo simulatorja in analizirajte njihove lastnosti**.

Kazalo

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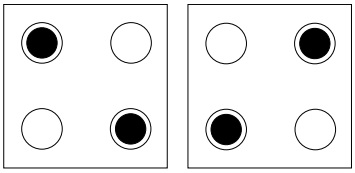

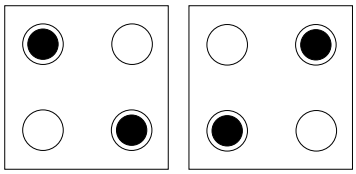

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Tabela 1.1: Please write your table caption here

Classes	Subclass	Length	Action Mechanism
Translation	mRNA[a]	22 (19–25)	Translation repression, mRNA cleavage
Translation	mRNA cleavage	21	mRNA cleavage
Translation	mRNA	21–22	mRNA cleavage
Translation	mRNA	24–26	Histone and DNA Modification

[a] Table foot note (with superscript)

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Theorem 1.1. *Theorem text goes here.*

Definition 1.1. Definition text goes here.

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Appendix

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$$a \times b = c \tag{1.3}$$

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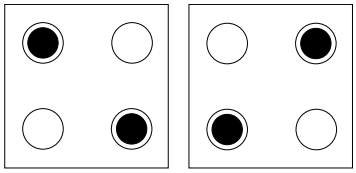
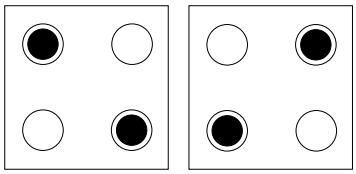
  – Livelihood and survival mobility are oftentimes coutcomes of uneven socioeconomic development.



Slika 2.1 If the width of the figure is less than 7.8 cm use the `sidecapion` command to flush the caption on the left side of the page. If the figure is positioned at the top of the page, align the sidecaption with the top of the figure – to achieve this you simply need to use the optional argument `[t]` with the `sidecaption` command

Slika 2.2 If the width of the figure is less than 7.8 cm use the `sidecapion` command to flush the caption on the left side of the page. If the figure is positioned at the top of the page, align the sidecaption with the top of the figure – to achieve this you simply need to use the optional argument `[t]` with the `sidecaption` command



  - Livelihood and survival mobility are oftentimes coutcomes of uneven socioeconomic development.

- Livelihood and survival mobility are oftentimes coutcomes of uneven socioeconomic development.

Run-in Heading Boldface Version Use the LaTeX automatism for all your cross-references and citations as has already been described in Sect. 2.2.

Run-in Heading Italic Version Use the LaTeX automatism for all your cross-references and citations as has already been described in Sect. 2.2.

Tabela 2.1: Please write your table caption here

Classes	Subclass	Length	Action Mechanism
Translation	mRNA[a]	22 (19–25)	Translation repression, mRNA cleavage
Translation	mRNA cleavage	21	mRNA cleavage
Translation	mRNA	21–22	mRNA cleavage
Translation	mRNA	24–26	Histone and DNA Modification

[a] Table foot note (with superscript)

2.3 Section Heading

Instead of simply listing headings of different levels we recommend to let every heading be followed by at least a short passage of text. Further on please use the LaTeX automatism for all your cross-references and citations as has already been described in Sect. 2.2.

Please note that the first line of text that follows a heading is not indented, whereas the first lines of all subsequent paragraphs are.

If you want to list definitions or the like we recommend to use the Springer-enhanced `description` environment – it will automatically render Springer's preferred layout.

Type 1 That addresses central themes pertainng to migration, health, and disease. In Sect. 2.1, Wilson discusses the role of human migration in infectious disease distributions and patterns.

Type 2 That addresses central themes pertainng to migration, health, and disease. In Sect. 2.2.1, Wilson discusses the role of human migration in infectious disease distributions and patterns.

2.3.1 Subsection Heading

In order to avoid simply listing headings of different levels we recommend to let every heading be followed by at least a short passage of text. Use the LaTeX automatism for all your cross-references and citations citations as has already been described in Sect. 2.2.

Please note that the first line of text that follows a heading is not indented, whereas the first lines of all subsequent paragraphs are.

If you want to emphasize complete paragraphs of texts we recommend to use the newly defined Springer class option `graybox` and the newly defined environment `svgraybox`. This will produce a 15 percent screened box 'behind' your text.

If you want to emphasize complete paragraphs of texts we recommend to use the newly defined Springer class option and environment `svgraybox`. This will produce a 15 percent screened box 'behind' your text.

2.3.1.1 Subsubsection Heading

Instead of simply listing headings of different levels we recommend to let every heading be followed by at least a short passage of text. Further on please use the LaTeX automatism for all your cross-references and citations as has already been described in Sect. 2.2.

Please note that the first line of text that follows a heading is not indented, whereas the first lines of all subsequent paragraphs are.

Theorem 2.1. *Theorem text goes here.*

Definition 2.1. Definition text goes here.

Dokaz. Proof text goes here. □

Paragraph Heading

Instead of simply listing headings of different levels we recommend to let every heading be followed by at least a short passage of text. Further on please use the LaTeX automatism for all your cross-references and citations as has already been described in Sect. 2.2.

Note that the first line of text that follows a heading is not indented, whereas the first lines of all subsequent paragraphs are.

Theorem 2.2. *Theorem text goes here.*

Definition 2.2. Definition text goes here.

Dokaz. Proof text goes here. □

Acknowledgements If you want to include acknowledgments of assistance and the like at the end of an individual chapter please use the `acknowledgement` environment – it will automatically render Springer's preferred layout.

Appendix

When placed at the end of a chapter or contribution (as opposed to at the end of the book), the numbering of tables, figures, and equations in the appendix section continues on from that in the main text. Hence please *do not* use the `appendix` command when writing an appendix at the end of your chapter or contribution. If there is only one the appendix is designated "Appendix", or "Appendix 1", or "Appendix 2", etc. if there is more than one.

$$a \times b = c \tag{2.3}$$

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