REGOLAMEN REGOLAMENTO DIDATTICO DEL CORSO DI STUDIO QUANTUM SCIENCE AND ENGINEERING (CLASSE LM-44)

Scuola: Politecnica e delle Scienze di Base

Dipartimento: Fisica E.Pancini

Regolamento in vigore a partire dall'a.a. 2022-2023

ACRONIMI

CCD	Commissione di Coordinamento Didattico
CdS	Corso/i di Studio
CPDS	Commissione Paritetica Docenti-Studenti
SUA-CdS	Scheda Unica Annuale del Corso di Studio
RDA	Regolamento Didattico di Ateneo

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AVVERTENZA: Nella compilazione di tutti i campi del Regolamento è indispensabile tenere presente che gli articoli che fanno riferimento a campi della SUA devono essere riportati esattamente nella formulazione già presente in SUA. Qualora si desideri modificare parte del testo, è necessario considerare che tale azione comporta un cambio di Regolamento o, se il campo da modificare è RAD, di Ordinamento.

Art. 1
Oggetto

Il presente Regolamento disciplina gli aspetti organizzativi del Corso di Laurea Magistrale in Quantum Science and Engineering (Scienza e Ingegneria Quantistiche), appartenente alla Classe di lauree LM-44. Il Corso di Laurea Magistrale in Quantum Science and Engineering afferisce al Dipartimento di Fisica E.Pancini.

Il CdS è retto dalla Commissione di Coordinamento Didattico (CCD), ai sensi dell'Art. 4 del RDA

Il Regolamento è emanato in conformità alla normativa vigente in materia, allo Statuto dell'Università di Napoli Federico II e al Regolamento Didattico di Ateneo.

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Art. 2
Obiettivi formativi del corso

La laurea magistrale in Quantum Science and Engineering (QSE) ha come obiettivo la formazione di specialisti di tecnologie quantistiche, per potenziali applicazioni nell'ambito della computazione ad alte prestazioni, della simulazione di sistemi complessi, della comunicazione sicura e della sensoristica, nonché negli altri settori in cui tali applicazioni troveranno impiego in futuro.

Gli obiettivi formativi specifici del corso in QSE sono i seguenti:

1) solida conoscenza del formalismo della meccanica quantistica, inclusi gli aspetti matematici, e delle sue applicazioni alla modellistica dei sistemi fisici;

2) buona conoscenza, teorica e sperimentale, dei principali sistemi fisici con cui vengono sviluppate le tecnologie quantistiche e degli apparati tecnologici basati su tali sistemi;

3) competenze teoriche e operative di informatica quantistica, dei principali algoritmi quantistici e della programmazione per computer quantistici;

4) competenze adeguate di tecnologie e metodi dell'ingegneria dell'informazione, in particolare nell'ambito delle tecnologie elettromagnetiche e circuitali, della comunicazione e delle reti, dell'elettronica digitale per sistemi che utilizzano dispositivi quantistici o che vengono potenziate dall'adozione di elementi funzionali quantistici;

5) familiarità con il metodo scientifico e abilità operative di laboratorio, con elevato livello di autonomia, anche con capacità di lavorare in modo cooperativo in gruppo, nel rispetto di protocolli e norme di sicurezza;

6) capacità di comunicare agevolmente in lingua inglese, in forma scritta e orale, con riferimento anche ai lessici disciplinari.

Il percorso formativo prevede un primo anno prevalentemente basato su insegnamenti comuni a tutti gli studenti. Sono previsti in particolare insegnamenti e moduli sui fondamenti della meccanica quantistica (obiettivo 1), sui sistemi fisici con cui vengono implementate le principali tecnologie quantistiche (obiettivi 1 e 2), sull'informatica quantistica e la programmazione mediante algoritmi quantistici di tali sistemi (obiettivo 3), nonché sulle tecnologie dell'ingegneria dell'informazione e della comunicazione tipicamente utilizzate in tali sistemi (obiettivo 4). Il corso prevede attività formative di laboratorio, con accesso a strumentazione avanzata, che contribuiscono al raggiungimento dell'obiettivo 5. Tutte le attività sono tenute in lingua inglese (obiettivo 6). Il secondo anno del percorso lascia ampio spazio per insegnamenti a scelta e di tipo affine e integrativo, finalizzati ad approfondire ulteriormente aspetti più specifici secondo gli interessi degli studenti, seguendo i principi della formazione centrata sullo studente. Queste attività contribuiscono a tutti gli obiettivi elencati in misura variabile a seconda delle scelte degli studenti. Il percorso si conclude con un eventuale tirocinio e la prova finale, che collegano tra loro tutte le conoscenze e competenze acquisite.

Art. 3
Profilo professionale e sbocchi occupazionali

Esperto in tecnologie quantistiche per la ricerca avanzata e per l'industria

Funzione in un contesto di lavoro:
Il corso di laurea magistrale prepara alla figura professionale di esperto in tecnologie quantistiche. Tra le funzioni lavorative che il laureato in Quantum Science and Engineering potrà svolgere rientrano:
- lo sviluppo di applicazioni, sistemi e servizi basati su tecnologie quantistiche, in particolare nel campo dell'informatica e della computazione quantistica, della comunicazione, della simulazione e della sensoristica;
- la realizzazione e manutenzione di apparati per computazione quantistica, per la comunicazione quantistica e per la sensoristica quantistica;
- la programmazione di software quantistici;
- la ricerca e lo sviluppo tecnologico nel campo delle scienze e tecnologie quantistiche;
- la divulgazione nel campo della scienza e delle tecnologie quantistiche.

Competenze associate alla funzione:
Saranno necessarie competenze avanzate sul formalismo teorico della meccanica quantistica, inclusi gli aspetti matematici, e sulle sue applicazioni alla modellistica dei sistemi fisici; una buona conoscenza, teorica e sperimentale, dei principali sistemi fisici con cui vengono sviluppate le tecnologie quantistiche; competenze teoriche e operative di informatica di base, dei principali algoritmi quantistici e della programmazione per computer quantistici; competenze adeguate di tecnologie e metodi dell'ingegneria dell'informazione, in particolare nell'ambito delle tecnologie elettromagnetiche e circuitali, della comunicazione e delle reti, dell'elettronica digitale, utili ad inserirsi in sistemi che utilizzano dispositivi quantistici o che vengono potenziate dall'adozione di elementi funzionali quantistici; competenze metodologiche e capacità di utilizzo di strumentazioni avanzate nell'ambito dell'ingegneria dell'informazione e della fisica; buona padronanza della lingua inglese e della terminologia tecnica del settore.

Sbocchi occupazionali:
Si prevedono sbocchi occupazionali principalmente nell'ambito delle imprese ad alta tecnologia per lo sviluppo di sistemi e servizi innovativi in cui trovano applicazione le tecnologie quantistiche emergenti, quali ad esempio la telecomunicazione protetta mediante crittografia quantistica, la computazione quantistica, la simulazione di sistemi complessi, la sensoristica di precisione. Ulteriori sbocchi occupazionali potranno essere trovati nell'ambito della ricerca di base e applicata o nella comunicazione scientifica.

Art.4
Conoscenze richieste per l'accesso[1]

Per essere ammessi al corso di Laurea Magistrale in Quantum Science and Engineering occorre essere in possesso di un titolo di Laurea I livello o titolo equivalente, con un curriculum di studi che soddisfi i requisiti curriculari elencati di seguito:
- 24 CFU in SSD di matematica (MAT/01-MAT/08);
- 12 CFU in SSD di fisica (FIS/01-FIS/08);
- 6 CFU di INF/01 o ING-INF/05;

[1] Artt. 7, 10, 11 Regolamento Didattico di Ateneo.

- Ulteriori 12 CFU in uno o più dei seguenti SSD in aggiunta ai punti precedenti: FIS/01-FIS/08 - Fisica; MAT/07 - Fisica matematica; CHIM/01- Chimica Analitica, CHIM/02 - Chimica fisica, CHIM/03 -Chimica Generale e inorganica; ING-IND/06 - Fluidodinamica; ING-IND/10 - Fisica tecnica industriale; ING-IND/11 (Fisica Tecnica Ambientale); ING-IND/12 - Misure meccaniche e termiche; ING-IND/13 - Meccanica applicata alle macchine; ING-IND/18 - Fisica dei reattori nucleari; ING-IND/19 (Impianti Nucleari); ING-IND/20 - Misure e strumentazione nucleari; ING-IND/22 - Scienza e tecnologia dei materiali; ING-IND/31 - Elettrotecnica; ING-INF/01 - Elettronica; ING-INF/02 - Campi elettromagnetici; ING-INF/06 - Bioingegneria elettronica e informatica; ING-INF/07 - Misure elettriche e elettroniche.

I 24 CFU in SSD MAT/01-MAT/08 garantiscono conoscenze di matematica al livello tipicamente fornito nei corsi di laurea di ingegneria dell'informazione o di fisica: analisi matematica, algebra lineare, geometria, elementi di analisi funzionale e/o di equazioni differenziali.
I 12 CFU in SSD FIS/01-FIS/08 garantiscono conoscenze di fisica classica ad un livello tipicamente fornito nei corsi di laurea di ingegneria dell'informazione: meccanica, termodinamica, elettromagnetismo.
I 6 CFU di INF/01 o ING-INF/05 garantiscono conoscenze su elementi base di informatica o discipline affini, al livello tipicamente fornito nei corsi di laurea di ingegneria dell'informazione o di fisica.

Bisogna inoltre possedere una conoscenza della lingua inglese ad un livello CEFR minimo di B2.

È altresì richiesto il possesso di un'adeguata preparazione iniziale in relazione agli argomenti di cui sopra, come verrà verificato in fase di ammissione

Art.5
Modalità per l'accesso

L'ammissione sarà basata primariamente sull'analisi della carriera universitaria dei candidati, ossia della media complessiva, la media nei SSD elencati nella sezione precedente e dei voti riportati ai singoli esami; ove ritenuto necessario un colloquio orale con i candidati potrà essere utilizzato per completare la valutazione ai fini dell'ammissione. L'ammissione è finalizzata a verificare il possesso di un'adeguata preparazione iniziale sugli argomenti elencati nella sezione precedente.

Art.6
Attività didattiche e crediti formativi universitari:

Ogni attività formativa prescritta dall'ordinamento del CdS viene misurata in crediti formativi universitari (CFU). Ogni CFU corrisponde convenzionalmente a 25 ore di lavoro per studente e comprende le ore di didattica assistita e le ore riservate allo studio personale o ad altre attività formative di tipo individuale.
Per il corso di studio oggetto del presente Regolamento, le ore di didattica assistita per ogni CFU, stabilite in relazione al tipo di attività formativa, sono le seguenti[2]:
- Lezione frontale: 8 ore per CFU;
- Attività pratiche di laboratorio: 8 ore per CFU.

[2] Il numero di ore tiene conto delle indicazioni presenti nell'art.6 c. 2 del RdA "… delle 25 ore complessive, per ogni CFU, sono riservate alla lezione frontale dalle 5 alle 10 ore, o in alternativa sono riservate alle attività seminariali dalle 6 alle 10 ore o dalle 8 alle 12 ore alle attività di laboratorio, salvo nel caso in cui siano previste attività formative ad elevato contenuto sperimentale o pratico, e fatte salve differenti disposizioni di legge."

I CFU corrispondenti a ciascuna attività formativa sono acquisiti dallo studente con il soddisfacimento delle modalità di verifica (esame, idoneità o frequenza) indicate nella scheda relativa all'insegnamento.

Art.7
Articolazione delle modalità di insegnamento

L'attività didattica viene svolta in modalità in presenza, in aula e in laboratorio (corso di studio convenzionale). La CCD delibera eventualmente quali insegnamenti prevedono anche attività didattiche offerte on-line. Alcuni insegnamenti possono svolgersi anche in forma seminariale e/o prevedere esercitazioni in aula/laboratori linguistici ed informatici. Informazioni dettagliate sulle modalità di svolgimento di ciascun insegnamento sono presenti sulle schede degli insegnamenti.

Art. 8
Prove di verifica delle attività formative[3]

1. Il CdS, nell'ambito dei limiti normativi previsti[4], stabilisce il numero degli esami e le altre modalità di valutazione del profitto che determinano l'acquisizione dei crediti formativi universitari. Gli esami sono individuali e possono consistere in prove scritte e/o orali e/o pratiche e/o grafiche, in tesine, in colloqui.
2. Le modalità di svolgimento delle verifiche saranno rese note agli studenti prima dell'inizio delle lezioni nelle schede insegnamento pubblicate sul sito web del Dipartimento.
3. Lo svolgimento degli esami è subordinato alla relativa prenotazione che avviene in via telematica. Qualora lo studente non abbia potuto procedere alla prenotazione per ragioni che il Presidente della Commissione considera giustificate, lo studente può essere egualmente ammesso allo svolgimento della prova d'esame, in coda agli altri studenti prenotati.
4. La valutazione degli esami è espressa in trentesimi ovvero con un giudizio di idoneità. Gli esami che prevedono una valutazione in trentesimi sono superati con la votazione minima di diciotto trentesimi; la votazione di trenta trentesimi può essere accompagnata dalla lode per voto unanime della Commissione.
5. Le prove orali di esame sono pubbliche, nel rispetto della normativa vigente in materia di sicurezza. Qualora siano previste prove scritte, il candidato ha il diritto di prendere visione dei propri elaborati dopo la correzione.
6. Le Commissioni d'esame sono disciplinate dal Regolamento Didattico di Ateneo (art. 20).

Art. 9
Struttura del corso e piano degli studi:

1. La durata legale del Corso di Laurea è di due anni. È altresì possibile l'iscrizione sulla base di un contratto secondo le regole fissate dall'Ateneo (art. 21 Regolamento didattico di Ateneo).
   Lo studente dovrà acquisire 120 CFU, riconducibili alle seguenti Tipologie di Attività Formative (TAF):
   B) caratterizzanti,
   C) affini o integrative,
   D) a scelta dello studente,
   E) per la prova finale
   F) ulteriori attività formative.

[3] Art. 20 del Regolamento Didattico di Ateneo
[4] Ai sensi del DD.MM. del 16 marzo 2007 (art. 4) in ciascun corso di studi gli esami o prove di profitto previsti non possono essere più di 20 (lauree), 12 (lauree magistrali), 30 (lauree a ciclo unico quinquennali) o 36 (lauree a ciclo unico sessennali).

2. La laurea si consegue dopo avere acquisito 120 CFU con il superamento degli esami, in numero non superiore a 20, e lo svolgimento delle altre attività formative.
   Fatta salva diversa disposizione dell'ordinamento giuridico degli studi universitari, ai fini del conteggio si considerano gli esami sostenuti nell'ambito delle attività caratterizzanti e affini o integrative nonché nell'ambito dell'attività autonomamente scelta dallo studente. Restano escluse dal conteggio le prove che costituiscono un accertamento di idoneità relativamente alle attività di cui all'art. 10 comma 5 lettere c), d) ed e) del D.M. 270/2004[5]. Gli insegnamenti integrati composti di moduli prevedono un'unica prova di verifica.
3. Per acquisire i CFU relativi alle attività a scelta autonoma, lo studente ha libertà di scelta tra tutti gli insegnamenti attivati nell'Università, purché coerenti con il progetto formativo. Tale coerenza viene valutata dalla Commissione di Coordinamento Didattico del CdS. Anche per l'acquisizione dei CFU relativi alle attività a scelta autonoma è richiesto il "superamento dell'esame o di altra forma di verifica del profitto" (art. 5 comma 4 DM 270/04).
4. Il piano di studi sintetizza la struttura del corso elencando gli insegnamenti previsti suddivisi per anno di corso ed eventualmente per curriculum. Alla fine della tabella del piano di studi sono elencate le propedeuticità previste dal Corso di Studi. Il piano degli studi offerto agli studenti, con l'indicazione dei settori scientifico-disciplinari e dell'ambito di afferenza, dei crediti, della tipologia di attività didattica è riportato nell'Allegato 1 al presente regolamento.

Art. 10
Obblighi di frequenza[6]

1. In generale, la frequenza alle lezioni frontali è fortemente consigliata ma non obbligatoria
   In caso di singoli insegnamenti con frequenza obbligatoria, tale opzione sarà appositamente indicata nella singola scheda insegnamento disponibile nell'Allegato 2.
2. Qualora il docente preveda una modulazione del programma diversa tra studenti frequentanti e non, questa sarà appositamente indicata nella singola scheda insegnamento pubblicata sulla pagina web del corso.
3. La frequenza alle attività seminariali che attribuiscono crediti formativi è obbligatoria. Le relative modalità per l'attribuzione di CFU è compito della CCD.

Art. 11
Propedeuticità

1. Le eventuali propedeuticità e conoscenze pregresse ritenute necessarie sono indicate nella scheda insegnamento.
2. L'elenco delle propedeuticità in ingresso (necessarie per sostenere un determinato esame) è riportato alla fine dell'Allegato 1.

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[5] Art. 10, comma 5 del D.M. 270/2004: «Oltre alle attività formative qualificanti, come previsto ai commi 1, 2 e 3, i corsi di studio dovranno prevedere: a) attività formative autonomamente scelte dallo studente purché coerenti con il progetto formativo; b) attività formative in uno o più ambiti disciplinari affini o integrativi a quelli di base e caratterizzanti, anche con riguardo alle culture di contesto e alla formazione interdisciplinare; c) attività formative relative alla preparazione della prova finale per il conseguimento del titolo di studio e, con riferimento alla laurea, alla verifica della conoscenza di almeno una lingua straniera oltre l'italiano; d) attività formative, non previste dalle lettere precedenti, volte ad acquisire ulteriori conoscenze linguistiche, nonché abilità informatiche e telematiche, relazionali, o comunque utili per l'inserimento nel mondo del lavoro, nonché attività formative volte ad agevolare le scelte professionali, mediante la conoscenza diretta del settore lavorativo cui il titolo di studio può dare accesso, tra cui, in particolare, i tirocini formativi e di orientamento di cui al decreto 25 marzo 1998, n. 142, del Ministero del lavoro; e) nell'ipotesi di cui all'articolo 3, comma 5, attività formative relative agli stages e ai tirocini formativi presso imprese, amministrazioni pubbliche, enti pubblici o privati ivi compresi quelli del terzo settore, ordini e collegi professionali, sulla base di apposite convenzioni».

[6] Art. 20, c.8 del Regolamento Didattico di Ateneo

Art. 12
Calendario didattico del CdS

Il calendario didattico del CdS viene reso disponibile sul sito web del dipartimento prima dell'inizio delle lezioni.

Art. 13
Criteri di riconoscimento dei crediti acquisiti in altri Corsi di Studio della stessa classe[7]

Per gli studenti provenienti da corsi di studi della stessa classe le strutture didattiche competenti assicurano il riconoscimento del maggior numero possibile di crediti formatifivi universitari acquisiti dallo studente presso il corso di studio di provenienza, secondo i criteri di cui al successivo articolo 14. Il mancato riconoscimento di crediti formativi universitari deve essere adeguatamente motivato. Resta fermo che la quota di crediti formativi univeristari relativi al medesimo settore scientifico-disciplinare direttamente riconosciuti allo studente, non può essere inferiore al 50% di quelli già conseguiti.

Art. 14
Criteri di riconoscimento dei crediti acquisiti in Corsi di Studio di diversa classe, presso Università telematiche e in Corsi di Studio internazionali[8]

Per gli studenti provenienti da corsi di studi di diversa classe i crediti formativi universitari acquisiti sono riconosciuti dalla struttura didattica competente sulla base dei seguenti criteri:

- Analisi del programma svolto
- Valutazione della congruità dei settori scientifico disciplinari e dei contenuti delle attività formative in cui lo studente ha maturato i crediti con gli obiettivi formativi specifici del corso di studio e delle singole attività formative da riconoscere, perseguendo comunque la finalità di mobilità degli studenti.

Il riconoscimento è effettuato fino a concorrenza dei crediti formativi universitari previsti dall'ordinamento didattico del corso di studio. Il mancato riconoscimento di crediti formativi universitari deve essere adeguatamente motivato.

Art. 15
Caratteristiche e modalità di svolgimento della prova finale

[7] Art. 16 del Regolamento Didattico di Ateneo.
[8] Art. 16 del Regolamento Didattico di Ateneo.

1) La Laurea Magistrale in Quantum Science and Engineering si consegue al termine del Corso di Laurea a seguito di prova finale e comporta l'acquisizione di 120 CFU.
2) L'Allegato C al presente Regolamento disciplina:
a) le modalità della prova finale, comprensiva in ogni caso di un'esposizione dinanzi a una apposita commissione;
b) le modalità della valutazione conclusiva, che deve tenere conto dell'intera carriera dello studente all'interno del Corso di Laurea, dei tempi e delle modalità di acquisizione dei crediti formativi universitari, della prova finale.
3) Per accedere alla prova finale lo studente deve avere acquisito il quantitativo di crediti universitari previsto dall'Allegato B1 al presente Regolamento, meno quelli previsti per la prova stessa.

Art. 16
Linee guida per le attività di stage

1. Gli studenti iscritti al CdS possono decidere di effettuare uno stage formativo presso Enti o Aziende convenzionati con l'Ateneo. Lo stage e non è obbligatorio, ma può concorrere all'attribuzione di crediti formativi per le Altre attività formative a scelta dello studente inserite nel piano di studi, così come previsto dall'art. 10, comma 5, lettera d, del D.M. 270/2004.
2. Le modalità di svolgimento e le caratteristiche dello stage sono disciplinate dalla CCD.
3. L'Università degli Studi di Napoli Federico II, per il tramite di .... [indicare la struttura o il/gli ufficio/i], assicura un costante contatto con il mondo del lavoro, per offrire a studenti e laureati dell'Ateneo concrete opportunità di *stage* e favorirne l'inserimento professionale.

Art. 17
Decadenza dalla qualità di studente[9]

Incorre nella decadenza lo studente che non abbia superato esami per cinque anni accademici consecutivi a partire dall'ultimo esame superato, a meno che il suo contratto non stabilisca condizioni diverse. In ogni caso, la decadenza va comunicata allo studente a mezzo posta elettronica certificata o altro idoneo mezzo che ne attesti la ricezione.

Art. 18
Procedure di attribuzione dei compiti didattici, comprese le attività didattiche integrative, di orientamento e di tutorato

1. I docenti e ricercatori sono rigorosamente tenuti a garantire il carico didattico assegnato secondo quanto disposto dal Regolamento didattico di Ateneo e nel Regolamento sui compiti didattici e di servizio agli studenti dei professori e ricercatori e sulle modalità per l'autocertificazione e la verifica dell'effettivo svolgimento[10].
2. Tra i compiti didattici dei docenti e ricercatori rientra anche l'obbligo di garantire almeno due ore di ricevimento ogni 15 giorni (o per appuntamento in ogni caso concesso non oltre i 15 giorni) e comunque garantire la reperibilità via posta elettronica.
3. Il servizio di tutorato ha il compito di orientare e assistere gli studenti lungo tutto il corso degli studi e di rimuovere gli ostacoli che impediscono di trarre adeguato giovamento dalla frequenza dei corsi, anche attraverso iniziative rapportate alle necessità e alle attitudini dei singoli.
4. L'Università assicura servizi e attività di orientamento, di tutorato e assistenza per l'accoglienza e il sostegno degli studenti. Tali attività sono organizzate dall'Ateneo (Scuola Politecnica e delle scienze di Base, centro SINAPSI).

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[9] Art. 21 del Regolamento Didattico di Ateneo, come modificato con D.R. n. 1782/2021.
[10] D.R. n. 2482//2020.

Art. 19
Valutazione della qualità delle attività svolte

1. Al fine di garantire agli studenti del Corso di studi la qualità della didattica nonché di individuare le esigenze degli studenti e di tutte le parti interessate, l'Università degli Studi di Napoli Federico II si avvale del sistema di Assicurazione Qualità (AQ)[11], sviluppato in conformità al documento "Autovalutazione, Valutazione e Accreditamento del Sistema Universitario Italiano" dell'ANVUR, utilizzando:
   - indagini sul grado di inserimento dei laureati nel mondo del lavoro e sulle esigenze post–lauream;
   - dati sulla *customer satisfaction* estratti dalla somministrazione agli studenti di questionari di valutazione per ciascun insegnamento presente nel piano di studi con domande relative alle modalità di svolgimento del corso, al materiale didattico, ai supporti didattici, all'organizzazione, alle strutture.

   I requisiti derivanti dall'analisi dei dati sulla *customer satisfaction*, discussi e analizzati dalla Commissione di Coordinamento Didattico e dalla Commissione Paritetica Docenti Studenti (CPDS), sono inseriti fra i dati di ingresso nel processo di progettazione del servizio e/o fra gli obiettivi della qualità.
2. L'organizzazione dell'AQ sviluppata dall'Ateneo realizza un processo di miglioramento continuo degli obiettivi e degli strumenti adeguati per raggiungerli, facendo in modo che in tutte le strutture siano attivati processi di pianificazione, monitoraggio e autovalutazione che consentano la pronta rilevazione dei problemi, il loro adeguato approfondimento e l'impostazione di possibili soluzioni.

Art. 20
Norme finali

1. Il Consiglio di Dipartimento, su proposta della Commissione di Coordinamento Didattico, sottopone all'esame del Senato Accademico eventuali proposte di modifica e/o integrazione del presente Regolamento.

Art. 21
Pubblicità ed entrata in vigore

1. Il presente Regolamento entra in vigore il giorno successivo alla pubblicazione all'Albo ufficiale dell'Università; è inoltre pubblicato sul sito d'Ateneo. Le stesse forme e modalità di pubblicità sono utilizzate per le successive modifiche e integrazioni.
2. Sono parte integrante del presente Regolamento l'Allegato 1 e l'Allegato 2.

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[11] Il sistema di Assicurazione Qualità, basato su un approccio per processi e adeguatamente documentato, è progettato in maniera tale da identificare le esigenze degli studenti e di tutte le parti interessate, per poi tradurle in requisiti che l'offerta formativa deve rispettare.

ALLEGATO 1 – PIANO DI STUDI STANDARD

Insegnamento o attività formativa		CFU	SSD	Ambito Disciplinare	Tipologia (*)	Propedeuticità
I Anno – I semestre						
Foundations of Quantum Mechanics (FQM)	Mod I: Principles	6	FIS/02	Discipline matematiche, fisiche e informatiche	B	
	Mod II: Physical systems	6	FIS/03	Discipline matematiche, fisiche e informatiche	B	
Microwave Circuits and Technologies (MCT)		6	ING-INF/02	Discipline ingegneristiche	B	
Digital Electronics for Quantum Applications (DEQA)		6	ING-INF/01	Discipline ingegneristiche	B	
Principles of Quantum Communication (PQC)		6	ING-INF/03	Attività affini e integrative	C	
I Anno – II semestre						
Quantum Computation (QC)	Mod I: Theory	6	INF/01	Discipline matematiche, fisiche e informatiche	B	FQM
	Mod II: Architectures and High Performance	6	ING-INF/05	Discipline ingegneristiche	B	QC mod I
Applied Quantum Systems (AQS)		9	FIS/03	Discipline matematiche, fisiche e informatiche	B	FQM, MCT, DEQA
Quantum circuit electrodynamics and Quantum devices (QCEQD)		9	ING-IND/31	Discipline ingegneristiche	B	FQM, MCT, DEQA
II Anno – I semestre						
Corsi integrativi a scelta dello studente da elenco A oppure come indicato in Nota 1		18		Attività affini e integrative	C	
Attività formative a scelta libera dello studente (Nota 2)		12		A scelta dello studente	D	
II Anno – II semestre						
Attività formative a scelta libera dello studente (Nota 2)		6		A scelta dello studente	D	
Ulteriori attività formative (nota 3)		3		Ulteriori attività formative	F	
Prova finale		21		Prova finale	E	

Nota 1: Oltre ai corsi dell'elenco A, lo studente potrà anche inserire in questo spazio qualsiasi insegnamento offerto per le seguenti lauree magistrali: Fisica, Informatica, Ingegneria Elettronica, Ingegneria delle Telecomunicazioni, Ingegneria Informatica.

Nota 2: Lo studente può scegliere qualsiasi insegnamento offerto dall'Ateneo. Può altresì inserire attività di tirocinio formativo, purché preventivamente approvate.

Nota 3: Lo studente può utilizzare questi CFU per acquisire ulteriori conoscenze linguistiche, ovvero abilità informatiche e telematiche, per tirocini formativi e di orientamento, per acquisire altre conoscenze utili per l'inserimento nel mondo del lavoro. È possibile in particolare acquisire questi CFU per attività formative propedeutiche alla prova finale.

Elenco A: corsi affini e integrativi a scelta dello studente			
Insegnamento	**CFU**	**SSD**	**Propedeuticità**
Physics of quantum information	6	FIS/03	FQM
Quantum optics	6	FIS/03	FQM
Quantum simulators	6	FIS/03	FQM
Quantum materials and solid-state qubits	6	FIS/03	FQM
Advanced computer programming	6	ING-INF/05	
Quantum software	6	INF/01	QC
Quantum metrology and sensors	6	ING-INF/07	FQM
Advanced Quantum Communication Networks	6	ING-INF/03	PQC
Quantum detectors for fundamental science	6	FIS/01	FQM
Superconducting Quantum Technologies	6	FIS/03	AQS
Quantum chemistry	6	CHIM/02	FQM
Quantum Measurement Theory	6	FIS/02	FQM
Quantum Algorithms	6	FIS/02	FQM
Nanoscale Processing and Characterization for Advanced Devices	6	FIS/01	
Nonlinear systems	6	ING-INF/04	
Quantum detectors for applied science	6	FIS/07	
Mathematics of quantum mechanics	6	MAT/07	FQM
Mathematical methods for quantum information	6	MAT/05	FQM

Oltre al percorso standard descritto sopra per studenti provenienti da lauree triennali, percorsi abbreviati accelerati per studenti che sono già laureati magistrali in fisica o in ingegneria sono previsti al fine di consentire il conseguimento della laurea magistrale in Quantum Science and Engineering in un anno (60 CFU).

La Commissione di Coordinamento Didattico (CCD) definirà i percorsi abbreviati in dipendenza della specifica laurea magistrale e della carriera pregressa dello studente.

Allegato 2 – Schede sintetiche insegnamenti

COURSE DETAILS

"ADVANCED COMPUTER PROGRAMMING"

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-23

GENERAL INFORMATION – TEACHER REFERENCES

TEACHERS:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE: NO
MODULE: -, SSD ING-INF/05
CHANNEL: SINGLE
YEAR OF THE DEGREE PROGRAMME (I, II, III): II
SEMESTER (I, II): II
CFU: 6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

n.a.

PREREQUISITES (IF APPLICABLE)

n.a.

LEARNING GOALS

The course aims at providing knowledge and competences in the area of advanced concurrent and distributed programming, by introducing application programming tools based on Java and Python languages and providing the foundations of the middleware concept as well as various industrial solutions, including the distributed object model, the component-based model, the message-oriented model, and the service-oriented model, demonstrated with applications relying on real-world technologies.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

Students shall know the issues related to advanced concurrent and distributed programming as well as the most common programming tools and models.

Applying knowledge and understanding

Students shall be capable of developing concurrent and distributed programs by using the Java and Python languages.

COURSE CONTENT/SYLLABUS

Review of the Java language. Concurrent Java programming. Java threads, states of a thread, thread pool. Synchronization in Java. Java Monitor and the java.util.concurrent package in Java 1.5. Network programming in Java. The java.net package. TCP sockets in Java: Socket and ServerSocket classes. UDP sockets in Java: DatagramSocket and DatagramPacket classes. Multithread servers. Abstracting a remote object. Proxy-Skeleton.
Middleware models. Definition and properties of the middleware level. Enterprise Application Integration (EAI). Remote procedure call (RPC), message exchange (MOM), transational processing (TP), tuple space (TS), remote data access (RDA), distributed object model (DOM), component-based model (CM), web services, microservices.
Distributed object and component-based models. Java Remote Method Invocation (Java RMI). RMI registry. Codebase and serialization. Java RMI architecture. Distributed Callback. Review of CORBA and JavaEE. Message exchange model. Java Message Service (JMS), clients and providers. Point-to-point communication and publish-subscribe model. JMS programming model. JMS messages and advanced aspects. Service-oriented model. Review of SOAP and RPC services. RESTful Web Services, resources and Uniform Resource Identifier (URI). RESTful services and HTTP methods. RESTful Web Services implementation in Java.
Introduction to the Python language. Files and sockets in Python. Examples of multi-language integration.

READINGS/BIBLIOGRAPHY

- B. Eckel "Thinking in Java"
- C. Savy, S. Russo, D. Cotroneo, A. Sergio "Introduzione a CORBA".
- Web resources

TEACHING METHODS

Front lessons (about 80% of the total time) and exercises (about 20%), taking place in a blended modality.

EXAMINATION/EVALUATION CRITERIA

a) Exam type:

Exam type	
written and oral	
only written	
only oral	
project discussion	X
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	
	Numerical exercises	

(*) multiple options are possible

Oral exams are aimed at verifying the student's understanding of the general conceptual issues addressed by the course.

b) Evaluation pattern:

Only an oral exam is foreseen along with the discussion of a student project.

COURSE DETAILS
"ADVANCED QUANTUM COMMUNICATION NETWORKS"
SSD INF-INF/03

DEGREE PROGRAMME: **MASTER'S DEGREE COURSE IN QUANTUM SCIENCE AND ENGINEERING**

ACADEMIC YEAR **2022-2023**

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE (IF APPLICABLE):	**NONE**
MODULE (IF APPLICABLE):	**NONE**
CHANNEL (IF APPLICABLE):	**NONE**
YEAR OF THE DEGREE PROGRAMME (I, II, III):	**II**
SEMESTER (I, II):	**I**
CFU:	**6**

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

Principles of Quantum Communications

PREREQUISITES (IF APPLICABLE)

Basic knowledge of quantum information theory. Knowledge of quantum communication theory.

LEARNING GOALS

The aim of the course is to provide the students with the knowledge related to the analysis and design of communication protocols for quantum networks. First, the fundamentals of classical communication networks will be introduced. Then, the advanced notions related to the design of quantum networks, including the issues arising with the distribution of entanglement among remote nodes, are presented. Furthermore, the Quantum Internet protocol stack will be carefully presented and analyzed. To this aim, its unconventional requirements and peculiarities with respect to the classical TCP/IP protocol stack will be properly discussed. Some use cases, such as distributed quantum computing and quantum placement of quantum links, will be presented and analyzed.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

The course aims at providing the students with the principles and the methodological tools needed to design communication protocols for the Quantum Internet protocol stack. Furthermore, the course allows the students to understand the similarities and the differences between classical communication networks (e.g., the classical Internet) and quantum communication networks, and to grasp the implications and the opportunities enabled by such differences.

Applying knowledge and understanding

The students need to show the ability to apply the acquired knowledge and methodological tools to the analysis and the design of quantum communications protocols for small-scale (e.g., quantum processors) and large-scale (e.g., Quantum Internet) communication networks.

COURSE CONTENT/SYLLABUS

Part I: Core Concepts
Fundamentals of classical communication networks. Multi-party entanglement. Quantum networks: physical and logical network entities. Quantum Internet protocol stack: entanglement generation, entanglement distribution, entanglement distillation, entanglement swapping, quantum repeaters and advanced Quantum Error Correction (QEC), quantum routing, quantum connectivity.

Part 2: Applications
Quantum networking for distributed quantum computing: data vs communication qubits, local vs remote operations, remote quantum gates: teledata & telegate. Beyond quantum Shannon theory: superposition of causal orders and quantum placement of quantum links.

READINGS/BIBLIOGRAPHY

Please list here textbooks or other readings.

Slides presented during the lectures, available on webdocenti.

Textbooks and further readings:

- *Van Meter, "Quantum Networking", Wiley, 2014*
- *W. Kozlowski, S. Wehner, R. Van Meter, B. Rijsman, A.S. Cacciapuoti, M. Caleffi, S. Nagayama, "Architectural Principles for a Quantum Internet, Internet draft, Internet Engineering Task Force (IETF).*

TEACHING METHODS

Describe how teaching activities are deployed: lectures, classes, exercises, laboratory, stages, seminars, others.
If applicable also list tools for teaching delivery (recorded lectures, multimedia, software, on line material, etc.)

The course is organized by integrating traditional lectures with interactive laboratory sessions. Furthermore, seminars will be organized during the course by inviting experts in the relevant fields and innovative teaching methods such as flipped classroom and feedback teaching strategies will be adopted.

EXAMINATION/EVALUATION CRITERIA

a) Exam type:

Exam type	
written and oral	
only written	
only oral	
project discussion	X
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
" APPLIED QUANTUM SYSTEMS "
SSD – FIS/03 “PHYSICS OF MATTER”

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

YEAR OF THE DEGREE PROGRAMME (I, II, III): I
SEMESTER (I, II): II
CFU:9

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

Foundations of quantum mechanics

PREREQUISITES (IF APPLICABLE)

None

LEARNING GOALS

This course aims at illustrating "quantum mechanics at work", not only as a key to interpret nature but also as a drive to build new "machines" It will be shown how to implement quantum machines on the basis of quantum effects.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

Ability to understand quantum platforms and the underlying physical concepts;

Applying knowledge and understanding

Ability of engineering quantum principles into devices; how to use quantum principles to design quantum machines and devices including macroscopic quantum devices; ability to realize a quantum measurement.

COURSE CONTENT/SYLLABUS

This course will cover a breadth of archetypal systems for quantum technologies: nuclear magnetic resonance, masers and atomic clocks (beam and solid-state), laser amplifiers and self-sustained oscillators, dynamic nuclear polarizations, pulse sequence techniques, Ramsey spectroscopy, meso-scale low-dimensional devices, quantum Hall effect, quantum confinement and optical pumping, conductance quantization, magneto oscillation, macroscale quantum effect devices and circuits such as Cooper-pair boxes and superconducting quantum circuits—as well as Berry phase physics as they appear in quantum and/or low-dimensional contexts. The course will also deal with materials challenges which provide opportunities for quantum computing hardware.

READINGS/BIBLIOGRAPHY

- Steven M. Girvin , Kun Yang, Modern Condensed Matter Physics , Cambridge Univ. Press.
- P.M. Chaikin and T.C. Lubensky, Principles of Condensed Matter Physics Cambridge University Press
- T.T. Heikkilä, The Physics of Nanoelectronics: Transport and Fluctuation Phenomena at Low Temperatures, Oxford
- Selected manuscripts

TEACHING METHODS

Live lectures on theory for 80% of frontal time, Lab activities for 20% of frontal time.

EXAMINATION/EVALUATION CRITERIA

b) Exam type:

Exam type	
written and oral	
only written	

only oral	x
project discussion	
other	A project on a speficic quantum platform

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
"DETECTORS AND DETECTION METHODS FOR APPLIED SCIENCE"
SSD – FIS/07

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE (IF APPLICABLE): NONE
MODULE (IF APPLICABLE): NONE
CHANNEL (IF APPLICABLE): NONE
YEAR OF THE DEGREE PROGRAMME (I, II): II
SEMESTER (I, II): II
CFU: 6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

Foundations of Quantum Mechanics

PREREQUISITES (IF APPLICABLE)

Foundations of Quantum Mechanics

LEARNING GOALS

To provide scientific and technical knowledge and basic expertise of radiation and bio-target detectors in

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

The course provides students with specific knowledge of quantum radiation detectors and sensors/biosensors and widespread detection techniques for physical experimental and industrial usage.

Applying knowledge and understanding

The course delivers ability to understand the functioning and utilization of modern photon detectors and sensing scheme in applied science fields, including biology and medicine, mostly focusing on their use in the most widespread detection techniques.

COURSE CONTENT/SYLLABUS

Part I: Fundamentals of quantum radiation detectors: PMT (PhotoMultiplier Tubes), PSPMT (Position sensitive PMT), Flat panel PMT. Photodiodes. CCD (Charge Coupled Devices). CMOS (Complementary Metal Oxide Semiconductor devices). APD (Avalanche photodiode detectors). HPD (Hybrid photon detectors). SiPM Silicon photomultipliers. Infrared detectors.

Part II: Spectrofluorometers. Plasmonic biosensors. Colorimetric biosensors. SPR (Surface Plasmon Resonance)-based biosensors. PEF (Plasmon Enhanced Fluorescence)-based biosensors. Nanomaterials and their use for detection and sensing. Main techniques for 2D-material and nanoparticle production and characterization: Liquid Phase Exfoliation. Optical and Microscopy characterizations (UV-VIS, Raman, SEM, TEM, AFM). Biofunctionalization of nanomaterials. Sensing of biomolecules and biotargets.

Part III: Scintillator based and semiconductor X-ray and gamma-ray detectors. Application of photon counting detectors in nuclear medicine and computed tomography.

READINGS/BIBLIOGRAPHY

- Stefan A. Mayer, Plasmonics: Fundamentals and Applications. Springer, 2007
- Joseph R. Lakowicz, Principles of Fluorescence Spectroscopy. Springer (III Edition), 2006.
- Photomultiplier tubes: Basics and Applications. 3rd Edition. Hamamatsu Photonics K.K., 2007.
- Lecture notes

TEACHING METHODS

Front lectures with course parts held by different teachers and laboratory sessions for applied physics demonstrations.

EXAMINATION/EVALUATION CRITERIA

c) Exam type:

Exam type	
written and oral	
only written	
only oral	X
project discussion	
other	

In case of a written exam, questions refer to: (*)	Multiple choice answers	
	Open answers	
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
"DIGITAL ELECTRONICS FOR QUANTUM APPLICATIONS”
SSD ELECTRONICS ING INF 01 *

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE (IF APPLICABLE): NONE
MODULE (IF APPLICABLE): NONE
CHANNEL (IF APPLICABLE): NONE
YEAR OF THE DEGREE PROGRAMME (I, II): I
SEMESTER (I, II): I
CFU: 6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

Fundamentals of quantum physics, solid state physics and electronics...

PREREQUISITES (IF APPLICABLE)

LEARNING GOALS

Knowledge and understanding

Ability to understand the use of digital circuits to interface with quantum circuits architectures, and for sensing and applications.

Applying knowledge and understanding

Ability of designing digital circuits for control and digital read-out of quantum platforms.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

The student is expected to learn the basic knowledge of the use of digital circuits to interface quantum systems for quantum computing, sensing and communications

COURSE CONTENT/SYLLABUS

Fundamentals on superconducting digital electronics fundamentals, single flux quantum logics, quantum flux parametron logics, circuit examples: from gates to processors, memories, interfacing to CMOS/optics; Circuit Implementation, design/simulation, fabrication, cryogenic testing; Digital control for qubits and couplers, SFQ pulse control, flux bias control, flux tuning; Digital qubit readout, types of readout, Josephson Photon Multiplier (JPM), Digitizing, Phase detection; Digital processing, multiplexing, quantum error correction decoders, post-processing

READINGS/BIBLIOGRAPHY

Note from the course, the most recent publications and handbooks of the main systems

TEACHING METHODS

Most od the course will be based on front end, In addition we schedule a set of visit at the CONS Labs (Center of nanophotonics and nanotechnology for the health and for industrial applications) in order to understand the basic principle of the main technologies used for to production of quantum devices

EXAMINATION/EVALUATION CRITERIA

d) Exam type:

Exam type	
written and oral	
only written	

only oral	X
project discussion	
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	
	Numerical exercises	

COURSE DETAILS
"FOUNDATIONS OF QUANTUM MECHANICS: MODULE 1 - PRINCIPLES "

* *In case of an integrated course, the SSD (scientific disciplinary sector) should be written above only if all modules of the course belong to the same SSD, otherwise the SSD is to be written alongside the MODULE (see below).*

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE: FOUNDATIONS OF QUANTUM MECHANICS
MODULE: MODULE 1 – PRINCIPLES
SSD: FIS/02 – THEORETICAL PHYSICS
YEAR OF THE DEGREE PROGRAMME (I, II, III): I
SEMESTER (I, II): I
CFU:6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

………

PREREQUISITES (IF APPLICABLE)

Students should have bases of Mathematical Analysis (calculus), Classical Physics and Linear Algebra**.**

………

LEARNING GOALS

The course is aimed at conveying working knowledge of the principles of quantum mechanics towards the understanding of quantum information processing and quantum computation. Quantum mechanics will be taught using mostly linear algebra.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Learning outcomes are statements of what students, endowed with adequate initial background, are expected to know, understand and/or be able to demonstrate or have acquired on successful completion of their studies (knowledge and abilties).

Descriptors such as "Knowledge and understanding" and "Applying knowledge and understanding" refer to disciplinary knowledge and should be used to designate peculiar capabilities conferred by the specific degree. The content of these sections should be relevant to what is mentioned in the course structure "ordinamento".

Knowledge and understanding

Students are expected to understand the fundamental postulates of quantum mechanics as a probabilistic theory, its differences with classical probabilistic theories, the special role of measurement in quantum mechanics, and the mathematical structure based on linear operators.

Applying knowledge and understanding

Students will need to be able to solve the Schroedinger equation in some simple settings, being able to extract probabilistic prediction from general quantum states, and compute correlations in a composite quantum systems. Students will have to be able to show how interference and entanglement can provide a distinct different way of manipulating information.

COURSE CONTENT/SYLLABUS

One semester course targeted at students who have passed classes of Analysis, Classical Physics and Linear Algebra, that introduces them to the basic ideas and formalism of Quantum Mechanics. This course will cover the fundamentals of quantum physics in its phenomenological, theoretical and experimental basis. The course is aimed at conveying working knowledge of the principles of quantum mechanics towards the understanding of quantum information processing and quantum computation. Quantum mechanics will be taught using mostly linear algebra.

Topics covered include:

1. Physical systems and experiments. Classical and quantum questions.
2. Probability theory.
3. Stern and Gerlach experiment.
4. The double slit experiment.
5. The need for linear algebra.
6. Vector spaces. Bra and Kets, Inner products.
7. Quantum states.
8. Quantum measurements.
9. Principles of quantum mechanics I.
10. Linear operators.
11. Principles of quantum mechanics II: The Born Rule.
12. Uncertainty principles.

13. Density matrices and mixed systems.
14. Evolution.
15. Quantum gates.
16. Quantum channels.
17. More on interference and quantumness.
18. Composite systems.
19. EPR and Bell inequalities.
20. Entanglement.

READINGS/BIBLIOGRAPHY

Lectures are based on the book by L. Susskind Quantum Mechanics: the theoretical minimum plus selected chapters from Nielsen and Chuang, Quantum Computation and Quantum Information. Moreover, instructor's Lecture Notes will contain more details on the mathematical, methodological, and epistemological aspects of quantum physics.

TEACHING METHODS

Teacher will use a) lectures for approx. 2/3 of total hours; b) Exercises for approx. 1/3 pf total hours.

EXAMINATION/EVALUATION CRITERIA

e) Exam type:

Exam type	
written and oral	x
only written	
only oral	
project discussion	
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	x
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
"FOUNDATIONS OF QUANTUM MECHANICS:
MODULE 2 – PHYSICAL SYSTEMS "

* *In case of an integrated course, the SSD (scientific disciplinary sector) should be written above only if all modules of the course belong to the same SSD, otherwise the SSD is to be written alongside the MODULE (see below).*

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE: FOUNDATIONS OF QUANTUM MECHANICS
MODULE: MODULE 2 – PHYSICAL SYSTEMS
SSD: FIS/03 – PHYSICS OF MATTER
YEAR OF THE DEGREE PROGRAMME (I, II): I
SEMESTER (I, II): I
CFU:6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

None

PREREQUISITES (IF APPLICABLE)

Content of 1^{st} module. Elementary notions of atomic and molecular structure.

LEARNING GOALS

Students are expected to learn how quantum mechanics can be applied to describing physical systems such as atoms, molecules, solids, photons, etc., and their coherent interactions. The focus is on the possible use of such physical systems in the field of quantum information and computation.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

Ability to explain and use the quantum mechanics key theoretical tools and methods, providing examples, and discussing the behavior of physical systems such as atoms, molecules, solids, photons, etc., and their coherent interactions. Ability to explain and illustrate the possible use of such physical systems in the field of quantum information and computation.

Applying knowledge and understanding

Capability of solving problems in quantum mechanics involving one or several particles moving in an external potential. Ability to compute expressions predicting the rate of certain transitions arising from interaction between physical systems and electromagnetic radiation. Capability of predicting unitary coherent evolution of a two-level quantum system under the effect of simple external fields and implications for quantum computation. Ability to predict measurement probabilities in various situations.

COURSE CONTENT/SYLLABUS

Simple single-electron systems: rectangular quantum well in 1D, 2D and 3D, harmonic oscillator, hydrogen atom. Multi-electron systems, basic notions on multi-electronic atoms. Basic notions on the quantum description of the chemical bond and on the theory of electronic bands. Radiation-matter interaction, perturbative semiclassical description, quantization of the electromagnetic field and fully quantum description. Two-level quantum systems (qubits realizations), Bloch / Poincaré sphere, quantum dynamics and coherent control, examples of implementation of quantum gates, decoherence phenomena. No-cloning theorem. Quantum tomography. Entanglement and its measure. Examples of quantum protocols: quantum cryptography, quantum teleportation.

READINGS/BIBLIOGRAPHY

TEACHING METHODS

Live lectures on theory for 70% of frontal time, exercises for 30% of frontal time.

EXAMINATION/EVALUATION CRITERIA

f) **Exam type:**

Exam type	
written and oral	x

only written	
only oral	
project discussion	
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	X
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
"MATHEMATICAL METHODS FOR QUANTUM INFORMATION"
SSD – MAT/05 "MATHEMATICAL ANALYSIS"

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE (IF APPLICABLE): NONE
MODULE (IF APPLICABLE): NONE
CHANNEL (IF APPLICABLE): NONE
YEAR OF THE DEGREE PROGRAMME (I, II): II
SEMESTER (I, II): II
CFU: 6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

Foundations of quantum mechanics

PREREQUISITES (IF APPLICABLE) None

LEARNING GOALS

Students are expected to learn the key concepts and main methods of the mathematics being used and applied to the field of quantum information.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

Ability to explain and use the mathematical principles and concept used in the field of quantum information and illustrate the main analytical and possibly numerical methods.

Applying knowledge and understanding

Capability of solving mathematical problems posed by quantum information topics, both analytically and, when applicable, numerically.

COURSE CONTENT/SYLLABUS

Mathematical formulation of quantum systems. Information-entropy quantities and parameter estimation in classical systems. Quantum hypothesis testing and discrimination of quantum states. Classical-quantum channel coding. State evolution and trace-preserving completely positive maps. Quantum information geometry and quantum estimation. Quantum measurement and state reduction. Entanglement and locality restrictions. Quantum communication protocols. Source coding in quantum systems.

READINGS/BIBLIOGRAPHY

TEACHING METHODS

Live lectures on theory for 75% of frontal time, exercises for 25% of frontal time.

EXAMINATION/EVALUATION CRITERIA

g) Exam type:

Exam type	
written and oral	x
only written	
only oral	
project discussion	
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	x
	Numerical exercises	

COURSE DETAILS
"MATHEMATICS OF QUANTUM MECHANICS"
SSD – MAT/07 "MATHEMATICAL PHYSICS"

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE (IF APPLICABLE): NONE
MODULE (IF APPLICABLE): NONE
CHANNEL (IF APPLICABLE): NONE
YEAR OF THE DEGREE PROGRAMME (I, II): II
SEMESTER (I, II): II
CFU: 6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

Foundations of quantum mechanics

PREREQUISITES (IF APPLICABLE) None

LEARNING GOALS

Students are expected to learn the mathematical structure of quantum mechanics, as well as the key concepts and methods of the mathematics being used in the theory of quantum mechanics.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

Ability to explain and use the mathematical principles and concepts used in quantum mechanics and illustrate the main analytical and possibly numerical methods.

Applying knowledge and understanding

Capability of solving mathematical problems posed by quantum mechanics, both analytically and, when applicable, numerically.

COURSE CONTENT/SYLLABUS

Reminders of basic notions on complex numbers and linear algebra. Mathematical axioms of quantum mechanics, information-theoretical aspects. Entanglement and decoherence. Automorphisms; Quantum dynamics. Theorems of Wigner, Kadison, Segal. Continuity and generators. Operators on Hilbert spaces. A selection between various possible advanced topics of mathematics of quantum mechanics.

READINGS/BIBLIOGRAPHY

TEACHING METHODS

Live lectures on theory for 75% of frontal time, exercises for 25% of frontal time

EXAMINATION/EVALUATION CRITERIA

h) Exam type:

Exam type	
written and oral	x
only written	
only oral	
project discussion	
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	x
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
MICROWAVE CIRCUITS AND TECHNOLOGIES
SSD ING-INF/02

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022 - 2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE (IF APPLICABLE):	------
MODULE (IF APPLICABLE):	------
CHANNEL (IF APPLICABLE):	------
YEAR OF THE DEGREE PROGRAMME (I, II, III):	I, II
SEMESTER (I, II):	I
CFU:	6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

……

PREREQUISITES (IF APPLICABLE)

Basic knowledge of applied electromagnetics.

LEARNING GOALS

The course aims to present to the students the methodological and operational tools necessary to concretely apply, in the quantum technologies framework, the operating principles of microwaves and radio-frequency components and circuits, the theoretical-numerical analysis methods, and the synthesis and design techniques. In addition, the theoretical lectures will be integrated with laboratory experiences and design sessions during which the student will apply, with the aid of the most recent numerical tools, his skills to the design and the characterization of specific components and circuits adopted in quantum systems.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

The student must know the principles of microwave and radio-frequency engineering and must know the operating principles of the most relevant microwave and RF devices and circuits to understand their role in the framework of Quantum Computing.

Applying knowledge and understanding

The student must show the ability to use, in the quantum systems framework, the methodological tools he has learned during the course, with reference to the methods for the theoretical-numerical analysis, and to the techniques to synthesize and design microwave and radio-frequency components and circuits.

COURSE CONTENT/SYLLABUS

Elements of guided propagation and main guiding structures.
Matching circuits, from the simplest to the most advanced configurations.
Microwave circuit analysis. Reciprocal and non-reciprocal components and their representation by means of the Scattering, Impedance and Admittance matrix. Outline of the modal analysis for the discontinuities modelling.
The coupling among lines and the main analysis methods: equivalent circuit description, matrix description of coupled lines.
Analysis and synthesis techniques of microwave and radio-frequency components: loads, attenuators, junctions and interconnections, power dividers, hybrid junctions. Directional couplers and reflectometric bridges. Filters.
Non-reciprocal components: isolators, circulators. Solutions for the miniaturization of non-reciprocal devices and their integration in quantum systems.
Control elements: switches, fixed and variable phase shifters.
Resonant structures: theoretical analysis of resonators. Series and parallel resonant circuits. Quality factor. Transmission line resonators, planar and cavity resonators. Dielectric resonators. Coupling of resonators.
Design methodologies of microwave and radiofrequency filters. Impedance step filters. Coupled-line filters. Coupled resonators filters.
Use of microwave signals to control and measure the qubit state, with reference to the main physical implementations: main schemes and their hardware implementation. Interfacing a microwave source. Microwave techniques in the implementation of quantum-gates.
Microwave and radiofrequency circuits: analysis and design techniques, use of modern tools to design highly complex circuits and to estimate the performance of a circuit as a whole. Optimization techniques.
During the course, electromagnetic software will be exploited. Students will thus be able, in laboratory sessions, to put into practice the analysis and synthesis methodologies to develop devices and circuits of interest in quantum systems.
Seminars will also be organized, by industrial partners aimed at demonstrating, by means of practical implementations of quantum systems, the use of microwave and radiofrequency circuits.
The course concludes with an overview of the main challenges and open-problems related to the use of microwave and radiofrequency circuits necessary to reach the full potential of quantum-computing systems.

READINGS/BIBLIOGRAPHY

R. Sorrentino e G. Bianchi, "Microwave and RF Engineering", Wiley, 2010.
G. Bianchi, R. Sorrentino, "Electronic filter simulation and design", The Mac-Graw Hill Companies, 2007.
R, J. Cameron; C. M. Kudsia, "Microwave Filters for Communication Systems: Fundamentals, Design, and Applications", Wiley, 2018.
Scientific publications related to the use of microwave and radiofrequency circuits in quantum systems will be provided to the students.

TEACHING METHODS

Teacher will use:
a) lectures, for about 70% of the hours;
b) Practical exercises - laboratories, through the use of numerical software, for about 20% of the hours;
c) Tutorials by industrial partners, for about 10% of the hours.

EXAMINATION/EVALUATION CRITERIA

i) Exam type:

Exam type	
written and oral	
only written	
only oral	x
project discussion	
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	1 oral exam, with open answer
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
"NANOSCALE PROCESSING AND CHARACTERIZATION FOR ADVANCED DEVICES"
SSD – FIS/03 "PHYSICS OF MATTER"

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

YEAR OF THE DEGREE PROGRAMME (I, II): II
SEMESTER (I, II): I
CFU:6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

PREREQUISITES (IF APPLICABLE)

None

LEARNING GOALS

Students are expected to learn the key concepts and methods used for fabricating and measuring, at cryogenic temperature and by low noise measurements, devices at nanoscale.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

Ability to explain the techniques used for developing devices at nanoscale and to characterize quantum devices at low temperatures by using low noise techniques.

Applying knowledge and understanding

Capability to design and apply the techniques useful for building up nanodevices for quantum technologies and implementing codes that allow to control their quantum properties.

COURSE CONTENT/SYLLABUS

Experimental methods used in clean room environments, classical and quantum transport theory of junctions and devices, low temperature cryostats, DC and RF low noise measurement, realization of superconducting nanowires, properties and applications in quantum computation.

READINGS/BIBLIOGRAPHY

- Nanofabrication: Nanolithography techniques and their applications, by Jose Maria de Teresa, IOP Publishing Ltd (December 11, 2020)
- Nanofabrication Techniques and Principles, Stepanova Maria and Dew, Steven (Eds.) Springer 2012
- Fundamentals of Semiconductors, P.Y. Yu and M. Cardona, Springer
- Quantum Phenomena, S. Datta, Addison Wesley
- Electronic Transport in mesoscopic systems, S.Datta, (Cambridge Studies in semiconductor physics and microelectronic engineering)
- Fundamentals and Frontiers of the Josephson Effect, Editors: Tafuri, Francesco (Ed.)
- T. Van Duzer, T. Van, and C. W. Turner. *Principles of Superconductive Devices and Circuits*. 2nd ed. Upper Saddle River, NJ: Prentice Hall, 1999. ISBN: 0132627426.
- P. Krantz, M. Kjaergaard, F. Yan, T. P. Orlando, S. Gustavsson, and W. D. Oliver, *A quantum engineer's guide to superconducting qubits* Appl. Phys. Rev. 6, 021318 (2019)

TEACHING METHODS

Live lectures on theory for 70% of frontal time and measurements in lab for 30% of rest time.

EXAMINATION/EVALUATION CRITERIA

a) Exam type:

Exam type	
written and oral	
only written	
only oral	X
project discussion	X
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
"NONLINEAR SYSTEMS"
SSD ING/INF-04 *

** In case of an integrated course, the SSD (scientific disciplinary sector) should be written above only if all modules of the course belong to the same SSD, otherwise the SSD is to be written alongside the MODULE (see below).*

DEGREE PROGRAMME: QUANTUM SCIENCE & ENGINEERING

ACADEMIC YEAR ....-....

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE (IF APPLICABLE):
MODULE (IF APPLICABLE):
CHANNEL (IF APPLICABLE):
YEAR OF THE DEGREE PROGRAMME (I, II): II
SEMESTER (I, II): II
CFU: 6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

None

PREREQUISITES (IF APPLICABLE)

Fundaments of linear dynamical systems; Algebra

LEARNING GOALS

The aim of the course is to introduce students to the foundations of the mathematical theory of nonlinear systems of ODEs and to illustrate the theory via some representative examples from applications.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Learning outcomes are statements of what students, endowed with adequate initial background, are expected to know, understand and/or be able to demonstrate or have acquired on successful completion of their studies (knowledge and abilties).
Descriptors such as "Knowledge and understanding" and "Applying knowledge and understanding" refer to disciplinary knowledge and should be used to designate peculiar capabilities conferred by the specific degree. The content of these sections should be relevant to what is mentioned in the course structure "ordinamento".

Knowledge and understanding

The course provides students with knowledge and basic methodological tools needed to analyze nonlinear dynamical systems described by ordinary differential equations (ODEs). Such tools may allow the students to understand the relationship between differential equations and their solutions and fundamental properties (i.e., existence, uniqueness, dependence on initial conditions and on parameters, Lyapunov stability, structural stability).

Applying knowledge and understanding

The student needs to show ability to analyze the dynamics of any physical dynamical system described by ODEs, by means of both qualitative and numerical methods presented during the lectures. Specifically, find solutions to the dynamical system, analyze their local stability by means of analytical methods based on Lyapunov's theory, sketch a qualitative description of the global dynamics of the system, analyze the dependence on the parameters of the solutions, classify bifurcations. Moreover, the student needs to show ability to use numerical tools (e.g., MATLAB) to quantitively analyze the dynamics of the system.

COURSE CONTENT/SYLLABUS

Introduction: linear vs nonlinear systems; planar nonlinear systems: equilibria, limit cycles, phase portraits, existence of periodic orbits and bifurcations; Fundamental properties: well-posedness, continuous dependence on initial conditions; Lyapunov stability and applications; Nonlinear Dynamics and Bifurcation theory: local bifurcations of maps, local bifurcations of flows, introduction to global bifurcations and deterministic chaos; Perspectives on advanced topics in nonlinear systems: piecewise smooth systems, nonsmooth stability analysis.

READINGS/BIBLIOGRAPHY

Steven H Strogatz, Nonlinear dynamics and chaos, Westview Press, (2001).
Yu. A. Kuznetsov, Elements of applied bifurcation theory, New York: Springer-Verlag (1998).
Hassan Khalil, Nonlinear systems, (3rd edition) Prentice-Hall (1996).
Jorge Cortés, "Discontinuous dynamical systems", IEEE Control Systems Magazine, vol. 28, no. 3, (2007).

TEACHING METHODS

Teacher will use: a) lectures for approx. 80% of total hours, b) laboratories to further elaborate on applied knowledge by means of MATLAB for approx. 8 hours, c) seminars.

EXAMINATION/EVALUATION CRITERIA

j) Exam type:

Exam type	
written and oral	
only written	
only oral	X
project discussion	X
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	
	Numerical exercises	

(*) multiple options are possible

In substitution of the oral exam, students attending the lectures may take two written intermediate exams, with equal weights, consisting in open questions and numerical exercises. Intermediate exams will take place at the middle and at the end of the course.

COURSE DETAILS
"PHYSICS OF QUANTUM INFORMATION"
SSD – FIS/03 “PHYSICS OF MATTER”

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

YEAR OF THE DEGREE PROGRAMME (I, II, III): II
SEMESTER (I, II): I
CFU:6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")
Foundations of quantum mechanics

PREREQUISITES (IF APPLICABLE)
None

LEARNING GOALS
Students are expected to learn the key concepts and main methods of the physics of quantum information.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding
Ability to explain and use the key concepts of quantum information, including communication and computation, and illustrate the main physical implementation methods.

Applying knowledge and understanding
Capability of calculating the evolution of the quantum state for a given quantum information circuit. Ability to sketch the schematic layout of a physical system implementing the most important tasks of quantum information and communication.

COURSE CONTENT/SYLLABUS
Basic principles of quantum information, including entanglement, Bell inequalities, no-cloning theorem, measurement theory in QM, coherence and de- coherence; the concepts of fidelity and state reconstruction (with experimental aspects); qubit and Continuous Variable QI (with examples of physical implementations); simple quantum protocols (quantum cryptography and teleportation); intrinsic and technological limits of QI.
Important modifications in the central results of classical information theory, including: quantum parallelism, compression of quantum information, bounds on classical information encoded in quantum systems, bounds on quantum information sent over a noisy quantum channel, efficient quantum algorithms and quantum complexity.
More specifically: Classical model of computation: The Turing Machine, Universal and Probabilistic TMs, Complexity classes, Universal Gate sets, Reversible vs Non-reversible gates, The Landauer Principle and the second principle of thermodynamics; Quantum Gates: One-qubit gates, Generalized Euler decomposition, Universal sets and Approximate universal sets for one qubit, Two-qubit gates: C-NOT, C-U from C-NOT, Quantum Supremacy; Quantum Parallelism; Quantum Algorithms, Deutch-Jozsa Algorithm, Quantum Fourier Transform, Period Finding Algorithm, Shor Algorithm, Grover Algorithm; Quantum Error Correction; Hints on Quantum Cryptography, Private key vs. public key algorithms, Quantum Key distribution protocols, Ekert protocol.

READINGS/BIBLIOGRAPHY

TEACHING METHODS
Live lectures on theory for 70% of frontal time, exercises for 30% of frontal time.

EXAMINATION/EVALUATION CRITERIA

k) Exam type:

Exam type

written and oral	x
only written	
only oral	
project discussion	
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	x
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
"PRINCIPLES OF QUANTUM COMMUNICATIONS"
SSD INF-INF/03

DEGREE PROGRAMME: **MASTER'S DEGREE COURSE IN QUANTUM SCIENCE AND ENGINEERING**

ACADEMIC YEAR **2022-2023**

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE (IF APPLICABLE):	**NONE**
MODULE (IF APPLICABLE):	**NONE**
CHANNEL (IF APPLICABLE):	**NONE**
YEAR OF THE DEGREE PROGRAMME (I, II, III):	**I**
SEMESTER (I, II):	**I**
CFU:	**6**

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

None

PREREQUISITES (IF APPLICABLE)

Basic knowledge of linear algebra

LEARNING GOALS

Expected learning outcomes refer to the overall learning aims of the subject in relationship with the degree structure.

The aim of the course is to provide the students with the principles of quantum information theory and their application to quantum communications. First, the fundamentals of classical communications will be introduced. Then, the notion of quantum bit (qubit), together with the principles and the unconventional peculiarities of quantum information processing, are presented. Stemming from these preliminaries, the course will provide the students with the advanced notions related to quantum communications, namely, to the issues of transmitting classical/quantum information through quantum channels. To this aim, the quantum noise and its peculiarities with respect to classical noise will be properly introduced. Subsequently, secure communications will be discussed by analyzing Quantum Key Distribution (QKD) techniques (including BB84 and Ekert-91) and their practical realization. Furthermore, genuine entangled-based quantum communication techniques (including superdense coding and quantum teleportation) will be properly introduced and analyzed, by also discussing the strategies (e.g., quantum error correction) for counteracting the noise effects. Finally, the challenges arising with the design of quantum communications will be discussed in the light of an integration within the lowest layers of the Quantum Internet protocol stack, by also briefly introducing its unconventional requirements and differences with respect to the standard-de-facto TCP/IP protocol stack. The students will have the opportunity to perform simple experiments on a real quantum computer via the IBM Q-Experience platform

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

The course aims at providing the students with the principles and the methodological tools needed to learn and understand the issues arising with the transmission and the processing of quantum information. Furthermore, the course allows the students to understand the similarities and the differences between classical and quantum communications, and to grasp the implications and the opportunities enabled by such differences.

Applying knowledge and understanding

The students need to show the ability to apply the acquired knowledge and methodological tools to the analysis and the design of quantum communication techniques, both in ideal conditions as well as in presence of quantum noise. The students need also to be able to assess the potential applications of the different quantum communication strategies to both short-range and long-range communication scenarios.

COURSE CONTENT/SYLLABUS

Part I: Foundations
Fundamentals of classical communication theory. Quantum information: qubit vs bit, Hilbert space, ket-bra notation, Bloch sphere, multiple-qubit systems. Quantum information processing: quantum states transformations, quantum gates, no-cloning theorem, quantum measurement. Quantum entanglement: entanglement, bell states, EPR communication paradox. Pure and mixed states, density matrix formalism, reduced density matrix.

Part 2: Communications
Quantum noise and quantum channel models. Introduction to Quantum Error Correction (QEC). Secure Communications: quantum cryptography principles, BB84, Ekert-91, practical implementations. Superdense coding. Quantum teleportation.

Noisy quantum teleportation. Quantum Internet protocol stack: introductory notes.

READINGS/BIBLIOGRAPHY

Slides presented during the lectures, available on webdocenti.

Textbooks and further readings:

- *Nielsen and Chuang, "Quantum computation and information", Cambridge University Press, 10th Edition, 2020*
- *Rieffel and Polak, "Quantum Computing: a Gentle Introduction", MIT Press, 2011*
- *W. Kozlowski, S. Wehner, R. Van Meter, B. Rijsman, A.S. Cacciapuoti, M. Caleffi, S. Nagayama, "Architectural Principles for a Quantum Internet, Internet draft, Internet Engineering Task Force (IETF).*

TEACHING METHODS

The course is organized by integrating traditional lectures with interactive laboratory sessions based on the IBM Q-Experience platform. Furthermore, seminars will be organized during the course by inviting experts in the relevant fields and innovative teaching methods, such as flipped classroom and feedback teaching strategies, will be adopted.

EXAMINATION/EVALUATION CRITERIA

l) Exam type:

Exam type	
written and oral	
only written	
only oral	
project discussion	X
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS

"QUANTUM ALGORITHMS

SSD -FIS/02 *

** In case of an integrated course, the SSD (scientific disciplinary sector) should be written above only if all modules of the course belong to the same SSD, otherwise the SSD is to be written alongside the MODULE (see below).*

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:

PHONE:

EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE (IF APPLICABLE): NONE
MODULE (IF APPLICABLE): NONE
CHANNEL (IF APPLICABLE): NONE
YEAR OF THE DEGREE PROGRAMME (I, II): II
SEMESTER (I, II): II

CFU:6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

Calculus, Linear Algebra, Fundamentals of Quantum Mechanics

PREREQUISITES (IF APPLICABLE)

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LEARNING GOALS

Expected learning outcomes refer to the overall learning aims of the subject in relationship with the degree structure.

This course will cover fundamental concepts of Quantum Computation and Quantum Algorithms. The course will contain a broad overview of the main concepts and tools in quantum computation. The necessary notions in math, physics and information theory will be developed during the course. We will focus on the most fundamental elements necessary to perform quantum computation and show a survey of the existing quantum algorithms, the features they offer, and the challenges they face. The course will also cover how to use quantum technology for quantum simulation and quantum communication channels. Quantum error correction and other ways to prevent decoherence will be presented in depth.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

This course is an introduction to the main concepts and methods of Quantum Computing and Quantum Information Processing, from the basic algorithms in quantum computation and quantum communication to advanced algorithms, methods and tools. This course:

- Introduces the basic concepts of quantum bits, quantum circuits, gates and algorithms.
- Teaches the main quantum computing algorithms, including Shor's algorithm.
- Teaches the main problems and techniques in Quantum Cryptography.
- Teaches the main problems and techniques in Quantum Error Correction.

Knowledge and understanding

The student will develop a solid grasp of core concepts and applications of quantum mechanics, quantum foundations and quantum computation and communication. The student will learn how quantum algorithms are applied quantum foundations. Students will also become effective in communicating in written and oral work the main concepts and goals of quantum information processing.

Applying knowledge and understanding

The students are expected to learn problem solving skills in the area of quantum computation and communication. They will be able to understand advanced quantum algorithms and invent basic quantum algorithms for specific tasks. Students will be able to understand and implement quantum correction codes in practical applications.

COURSE CONTENT/SYLLABUS

- Quantum Bits
- No Cloning
- Quantum Teleportation
- Interference and the Deutsch Josza algorithm
- Turing Machines and circuits
- Computational complexity
- Overview of Quantum Algorithms
- Quantum gates and operations
- Universal quantum gates
- Simulation of Quantum systems
- Shor's Algorithm and Quantum Search Algorithms
- Quantum Communication Channels
- Quantum Algorithms for Linear Algebra
- Quantum Cryptography
- Adiabatic Quantum Computation
- A zoology of quantum algorithms
- Errors and decoherence
- Quantum error correcting codes

READINGS/BIBLIOGRAPHY

Nielsen and Chuang, Quantum Computation and Quantum Information

TEACHING METHODS

Teacher will use a) lectures for approx. 2/3 of total hours; b) Exercises for approx. 1/3 pf total hours.

EXAMINATION/EVALUATION CRITERIA

Exam type:

Exam type	
written and oral	
only written	
only oral	**X**
project discussion	
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
"QUANTUM CHEMISTRY"
SSD – CHIM/02

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

YEAR OF THE DEGREE PROGRAMME (I, II, III): II
SEMESTER (I, II): I
CFU:6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

Foundations of quantum mechanics

PREREQUISITES (IF APPLICABLE)

None

LEARNING GOALS

This course is an introduction to quantum chemistry: the application of quantum theory to atoms, molecules, and materials. You'll learn about wavefunctions, probability, special notations, and approximations that make quantum mechanics easier to apply. You'll also learn how to use Python to program quantum-mechanical models of atoms and molecules.

Knowledge and understanding

At the end of the course the student should have acquired a basic knowledge of the physical theories, the approximations and some computational strategies that are involved in the quantum-mechanical description of atomic and molecular systems.

Applying knowledge and understanding

At the end of the course the student should be in a position to judge the appropriateness of a quantum-chemical model for the description of molecular / chemical systems, also by reference to specialized monographs and review papers.

COURSE CONTENT/SYLLABUS

Intro to Quantum Mechanics: a quick review of classical mechanics and wave mechanics, plus the postulates that form the basis of quantum theory. The time-independent Schrödinger equation in one, two, and three dimensions. The hydrogen atom. Approximation methods and computational approaches for quantum chemistry: perturbation theory, nonlinear and linear variational method. Many-electron atoms: antisymmetry principle and Slater determinants; classification of atomic states; spin-orbit interaction. Molecules and the chemical bond: the Born-Oppenheimer approximation, the hydrogen molecule; homonuclear and heteronuclear diatomic molecules. Polyatomic molecules and molecular orbital theory. Use of group theory for the symmetry classification of molecular orbitals. Nuclear motion. Molecular spectroscopy: rotational, vibrational and electronic. Chemical reactions. The interaction of atoms and molecules with light.

READINGS/BIBLIOGRAPHY

TEACHING METHODS

Live lectures on theory for 70% of frontal time, exercises for 30% of frontal time.

EXAMINATION/EVALUATION CRITERIA

m) Exam type:

Exam type	
written and oral	
only written	
only oral	X
project discussion	
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
"QUANTUM CIRCUIT ELECTRODYNAMICS AND QUANTUM DEVICES"
SSD ING/31

DEGREE PROGRAMME: ***Quantum Science and Engineering***
ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

YEAR OF THE DEGREE PROGRAMME: I
SEMESTER: II
CFU: 9

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

- FOUNDATIONS OF QUANTUM MECHANICS
- MICROWAVE CIRCUITS AND TECHNOLOGIES

LEARNING GOALS

Qubits are the basic units of systems for quantum information (quantum computer, quantum internet, ...). They are two - state quantum mechanical devices, the quantum version of the classical two - state devices. Classical two - state devices would have to be in one state or the other, instead qubits can be in a coherent superposition of both states, a fundamental property of quantum mechanics. Examples of qubits include: the spin of the electron in which the two states can be taken as spin up and spin down; or the polarization of a single photon in which the two states can be taken to be the vertical polarization and the horizontal polarization. The most promising technology for the fabrication of qubits uses at present superconducting electrical circuits based on Josephson junctions (IBM, D-Wave Systems, Rigetti, Google, Quantum Circuits – Yale,…).
If decoherence due to uncontrolled degrees of freedom is sufficiently reduced electrical circuits can behave quantum mechanically. In a superconducting material, all super electrons can be in the same quantum coherent state. As a consequence, superconducting devices can be engineered in a way to behave as macroscopic artificial two – level atoms. The research field of quantum state engineering with superconducting electrical circuits was born from fundamental questionings about the possibility of observing macroscopic quantum phenomena. Experiments have widely demonstrated that the quantum state of superconducting electrical circuits based on the Josephson junction can be effectively manipulated, controlled and readed–out.
Compared to real atoms, superconducting electrical circuits are macroscopic in size, leading to large electrical or magnetic dipoles, which facilitates their coupling to other circuits and systems.

In particular, superconducting qubits can be strongly coupled to superconducting resonators, which offer architectures for quantum information processing. In fact, this enables single - qubit control and read–out, multi - qubit entanglement and gates. In addition, it is possible to couple superconducting circuits and resonators to other quantum systems such as spins or mechanical resonators, forming so called Hybrid Quantum Devices.
This course starts from the Lagrangian and Hamiltonian formulations of classical electrical circuits, give the concept of quantum electrical circuit and, then, superconducting qubits are progressively introduced. The links between electrical quantum gates, entanglement and quantum measurement are pointed out. The fundamental circuits for quantum computing are introduced.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

This course, starting from the fundamentals of quantum mechanics, the classical electromagnetism, and the (lumped and distributed) circuit model, introduces the new paradigm of "quantum electrical circuit" at the basis of quantum computers based on Josephson junctions.

Applying knowledge and understanding

This course provides both the basic knowledge for understanding quantum electrical circuits, and the tools for their analysis, design and development.

COURSE CONTENT/SYLLABUS

1) What are Quantum Circuits, Qubits and Quantum logic gates. The Bloch sphere.
2) **Classical Electrical Circuits**: Lumped element circuits, distributed element circuits, Kirchhoff circuit laws, constitutive relations. Dissipative and non-dissipative circuits. Lagrangian and Hamiltonian formulations for non dissipative circuits, conjugate electrical variable pairs, Poisson brackets. Circuits with dissipative elements, the Caldeira – Legget model. Fluctuation – dissipation theorem. Langevin equation.
3) **Non Dissipative Quantum Electrical Circuits**: Basic notions of Quantum Mechanics. State of a non dissipative quantum electrical circuit: measurements, from electrical variables to operators, quantum state vector, commutators of charges and fluxes. Quantization of an electrical circuit. Schrödinger and Heisenberg Pictures. Quantum linear LC circuits. Entanglement. “Black Box” Quantization of Linear Circuits.
4) **Superconducting Qubits**: Josephson junction. Non-linear LC circuits. Charge - qubit circuits. Flux - qubit circuits. Phase - qubit circuits. Cooper - pair box. Transmon. Entangled qubits.
5) **Dissipative Quantum Electrical Circuits**: Quantum dissipation-fluctuation theorem. Quantum fluctuations in the damped LC oscillator. Nyquist model of resistance: semi-infinite transmission line. Heisenberg - Langevin equation. Environment and measurement operators. Noise and the environment. Decoherence, decay and dephasing. Noise induced Decoherence in Qubit Circuits. A glimpse to stocastic master equations.
6) **Qubit - cavity coupling**: Resonant coupling and dispersive coupling. Amplification and feedback. Dispersive Read-out of a Qubit in a Cavity. Quantum Control of Qubits in a Cavity. Multi-qubit Dispersive Readout.
7) **Quantum state engineering and quantum gates**: One qubit gates. Two qubit gates. The Grover search algorithm, error correction (ancilla qubit), steps toward quantum computers.
8) A glimpse to Hybrid Quantum Devices: Spin superconducting circuits. Quantum dots. Hybrid quantum processor.

READINGS/BIBLIOGRAPHY

- A. M. Zagoskin *Quantum Engineering: Theory and Design of Quantum Coherent Structures*, Cambridge University Press, 2011.
- U. Vool, M. Devoret, *Introduction to quantum electromagnetic circuits*, Special Issue on Quantum Technologies, International Journal of Circuit, Theory and Applications, 897-934, 2017.
- G. Wendin, *Quantum information processing with superconducting circuits: a review*, Rep. Prog. Phys. 80 106001, 2017.
X. Gua, A. F. Kockum, A. Miranowicz, Y. Liu, F. Nori, *Microwave photonics with superconducting quantum circuits*, Physics Reports 718–719, 1–102, 2017.
- P. Krantz, M. Kjaergaard, F. Yan, T. P. Orlando, S. Gustavsson, and W. D. Oliver, *A quantum engineer's guide to superconducting qubits*, Appl. Phys. Rev. 6, 021318 (2019); https://doi.org/10.1063/1.5089550
- A. Blais, A. L. Grimsmo, S. M. Girvin, A. Wallraff, *Circuit quantum electrodynamics*, Rev. Mod. Phys. 93, 025005 (2021).
- Lecture Notes**.**

TEACHING METHODS

Lectures for approximate 80% of total hours and 20 % laboratories

EXAMINATION/EVALUATION CRITERIA

n) Exam type:

Exam type	
written and oral	
only written	
only oral	X
project discussion	
other	

o) Evaluation pattern: -

COURSE DETAILS
"QUANTUM COMPUTATION" MODULE-1

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-23

GENERAL INFORMATION – TEACHER REFERENCES

TEACHERS:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE: YES
MODULE: MOD I: THEORY, SSD INF/01
CHANNEL: SINGLE
YEAR OF THE DEGREE PROGRAMME (I, II, III): I
SEMESTER (I, II): II
CFU: 6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE “ORDINAMENTO”)

Foundations of Quantum Mechanics

PREREQUISITES (IF APPLICABLE)

n.a.

LEARNING GOALS

The goal of the first module of this course is introducing quantum computation theory, by describing its foundations both in terms of quantum gates and their use, and in terms of quantum Turing machines, in order to formally compare classical and quantum computations, and understanding how and in which cases quantum computations overcome the limitations of classical computing.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

Students shall know and understand the issues related to quantum computation theory, and should be able to discuss the relationships between classical and quantum computational complexity.

Applying knowledge and understanding

Student shall be capable of operating with the fundamental components of quantum computing, in order to design quantum algorithms. Moreover, students shall be able to analyze quantum algorithms and show any possible benefits with respect to classical computations.

COURSE CONTENT/SYLLABUS

Complex numbers and Hilbert spaces. Quantum systems dynamics. A discussion on quantum architectures in terms of qubits and quantum gates, and their role in designing significant quantum algorithms such as Deutsch, Shor, and Grover’s algorithms. Computational complexity theory (problems as languages, classical and quantum Turing machines, complexity classes). Systematic comparison comparison of classical, probabilistic and quantum computing. Analysis of the problem solving potential of quantum computing in general, and in selected fields like cryptography, AI, and combinatorial optimization.

READINGS/BIBLIOGRAPHY

- N.S. Yanofsky, M. A. Mannucci, Quantum Computing for Computer Scientists, Cambridge University Press
- Christos H. Papadimitriou. Computational Complexity. Addison Wesley. 1995 (o versioni successive).
- Jupyter Python Notebooks
- Scientific articles and slides provided by the lecturers.

TEACHING METHODS

Front lessons (about 80% of the total time) and exercises (about 20%), taking place in a blended modality.

EXAMINATION/EVALUATION CRITERIA

a) Exam type:

Exam type	
written and oral	X
only written	
only oral	
project discussion	
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	X
	Open answers	X
	Numerical exercises	X

(*) multiple options are possible

Written exams are aimed at verifying the student's understanding of quantum computations' behavior, and their relationships with classical computations, as well as the problem solving capabilities of quantum computations. Oral exams are aimed at verifying the student's understanding of the general theory – including relevant formal proofs – and the student's capability of designing quantum algorithms.

b) Evaluation pattern:

Students should successfully pass the written exam before accessing the oral part. The two modules have equal weight in the computation of the final score.

COURSE DETAILS
"QUANTUM COMPUTATION" MODULE-2

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-23

GENERAL INFORMATION – TEACHER REFERENCES

TEACHERS:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE: YES
MODULE: MOD II: ARCHITECTURES, SSD ING-INF/05
CHANNEL: SINGLE
YEAR OF THE DEGREE PROGRAMME (I, II, III): I
SEMESTER (I, II): II
CFU: 6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

Foundations of Quantum Mechanics

PREREQUISITES (IF APPLICABLE)

n.a.

LEARNING GOALS

The goal of the second module of this course is to provide an understanding of quantum computation (QC) as a near future perspective for high performance computing (HPC), by considering the following teaching areas: hardware design and efficiency, programming and software engineering, system design and administration.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

Students shall know the issues related to HPC architectures and should be able to discuss their potential evolution towards Quantum Computing.

Applying knowledge and understanding

Students shall be capable of understanding the performance requirements of applications at the HPC scale and potential benefits brough by QC to certain classes of applications.

COURSE CONTENT/SYLLABUS

The module will provide a comprehensive overview of the architecture of modern HPC facilities and datacenters and will introduce concepts related to computer architecture, networks, software engineering, system design and application frameworks, performance analysis and metrics for HPC, projecting such concepts in the perspective of the emerging QC technologies. The module will then focus on existing experimental QC platforms provided by leading commercial players, namely IBM. Last, the module will present a case-study application of interest for HPC showing promising opportunities when translated to a QC algorithm.

READINGS/BIBLIOGRAPHY

- L.A. Barroso et al, "The Datacenter as a Computer: Designing Warehouse-Scale Machines", Morgan-Claypool, 2018
- V. Silva, "Practical Quantum Computing for Developers", APress, 2018
- Scientific articles and slides provided by the lecturers

TEACHING METHODS

Front lessons (about 80% of the total time) and exercises (about 20%), taking place in a blended modality.

EXAMINATION/EVALUATION CRITERIA

c) Exam type:

Exam type	
written and oral	

only written	
only oral	X
project discussion	
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	
	Numerical exercises	

(*) multiple options are possible

Oral exams are aimed at verifying the student’s understanding of the general conceptual issues addressed by the module.

d) Evaluation pattern:

Only oral exam is foreseen.

COURSE DETAILS
"QUANTUM DETECTORS FOR FUNDAMENTAL SCIENCE "
SSD – FIS/03 "PHYSICS OF MATTER"

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

YEAR OF THE DEGREE PROGRAMME (I, II, III): II
SEMESTER (I, II): I
CFU:6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

Foundations of quantum mechanics

PREREQUISITES (IF APPLICABLE)

None

LEARNING GOALS

Students are expected to learn the fundamentals about the state-of-the-art of quantum detectors with a critical understanding of emerging applications in fundamental science applications.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

Ability to explain and use the principles of quantum theory of electromagnetic radiation within the main experimental methods presented within the course.

Applying knowledge and understanding

Capability of sketch and explain the schematic layout of investigated quantum detectors and the configurations of the experiments where they are proposed or used.

COURSE CONTENT/SYLLABUS

Theory of quantum noise. Fundamentals of Single-Photon Detectors (i.e. AVP, SMP, SNSPDs, PCC). Superconducting qubit-based detectors. Quantum sensing devices including magnetometers and interferometers, Applications of quantum detectors to fundamental science experiments.

READINGS/BIBLIOGRAPHY

TEACHING METHODS

Live lectures on theory for 80% of course time, laboratory demos for remaining 20% .

EXAMINATION/EVALUATION CRITERIA

p) Exam type:

Exam type	
written and oral	
only written	
only oral	X
project discussion	X
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS

" QUANTUM MATERIALS AND SOLID-STATE QUBITS"

* *Nel caso di un insegnamento integrato il Settore Scientifico Disciplinare (SSD) va indicato solo se tutti i moduli dell'insegnamento sono ricompresi nello stesso SSD, altrimenti il Settore Scientifico Disciplinare verrà indicato in corrispondenza del MODULO (v. sotto).*

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

DOCENTE:
TELEFONO:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE: QUANTUM MATERIALS AND SOLID-STATE QUBITS
MODULE:
SSD: FIS/03 – PHYSICS OF MATTER
YEAR OF THE DEGREE PROGRAMME (I, II): II
SEMESTER (I, II): I
CFU:6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

Foundations of Quantum Mechanics, Quantum Information, Solid State Physics

PREREQUISITES (IF APPLICABLE)

none

LEARNING GOALS

The aim of the course is to introduce students to understanding the basic elements related to the implementation of the hardware of a quantum computer. After having examined the necessary criteria for the construction of quantum bits and theirs interconnections, the course will focus on the most promising implementations in solid state systems. The program of the course focuses on superconductor and semiconductor implementations. In both cases, it will be discussed the ideal operating scheme together with the most important challenges related to the control and reduction of noise and imperfections. The state of the art in the construction of a quantum computer will be presented.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

Ability to explain and use the basi requirement to design the building blocks of a quantum information architecture. Ability to explain and illustrate the phenoimena studied in the context of quantum information and computation.

Applying knowledge and understanding

Capability of solving problems in quantum information processing involving few qubits. Ability to compute expressions predicting the coherent dynamics of few level systems and evaluate the effect of external environments. Ability to solve simple problems in the area of coherent nano-electronics.

COURSE CONTENT/SYLLABUS

Physical implementations of quantum computers: requirements and properties

- Introduction to the physics of nanostructures
    . transport properties,
    . Coulomb blockade,
    . coherent transport and interference effects
    . Landauer-Buttiker theory
    . nanostructures with superconductors
- Quantum dots and wires
    . spin and charge qubits
    . quantum gates
    . decoherence and dissipation effects
    . experimental review on the state of the art
- Superconducting nanocircuits
    . macroscopic quantum effects

. Charge and Flux qubit
    . circuit-QED
    . noise and imperfections

- Perspectives: topological computation

READINGS/BIBLIOGRAPHY

TEACHING METHODS

Live lectures on theory for 70% of frontal time, exercises for 30% of frontal time.

EXAMINATION/EVALUATION CRITERIA

q) Exam type:

Exam type	
written and oral	
only written	
only oral	X
project discussion	
other	

In case of a written exam, questions refer to: (*)	Multiple choice answers	
	Open answers	
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
"QUANTUM MEASUREMENT THEORY"
SSD FIS/02 *

** In case of an integrated course, the SSD (scientific disciplinary sector) should be written above only if all modules of the course belong to the same SSD, otherwise the SSD is to be written alongside the MODULE (see below).*

DEGREE PROGRAMME:

ACADEMIC YEAR ....-....

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:

PHONE:

EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE (IF APPLICABLE): NONE

MODULE (IF APPLICABLE): NONE

CHANNEL (IF APPLICABLE): NONE

YEAR OF THE DEGREE PROGRAMME (I, II): II

SEMESTER (I, II): II

CFU:6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

………

PREREQUISITES (IF APPLICABLE)

A basic knowledge of algebra, analysis, operator theory and quantum mechanics is assumed. More advanced technical tools will be introduced during the course, before their application.

LEARNING GOALS

The main aim of the course is to provide the student with some concepts and tools of quantum measurement theory that are fundamental for a deeper understanding of quantum mechanics and quantum information, and of the sharp differences – but also of the analogies – between classical and quantum theory. The course is also aimed at introducing the student to the theory of open quantum system and quantum decoherence. During the course some advanced technical tools will be introduced that are of central importance for quantum information science and its applications to quantum technologies. The effective understanding and mastering of the theoretical topics of the course is supported by the discussion of several selected examples.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

After the course, students should be able to:

- Understand some fundamental aspects of quantum measurement theory and of its applications to quantum information science (e.g., the concepts of quantum channel and of quantum instrument).
- Derive and analyze the main consequences of a theoretical model, provide a suitable physical interpretation and envision its potential applications.
- Formalize, express and communicate the contents of their study and research in a clear, technically sound and effective scientific language (e.g., in preparing a research project, a seminar or a scientific article).

Knowledge and understanding

The course will provide the student with the knowledge and tools necessary to face the difficult task of understanding quantum phenomena and predicting the behavior of a quantum system.

Applying knowledge and understanding

After the course, the student is expected to be able to actively explore and manipulate the vast realm of quantum information science, quantum experiments and quantum technologies.

COURSE CONTENT/SYLLABUS

Quantum states: The space of states of a physical system: quantum vs classical. Quantum effects; duality between states and effects. Dispersion-free states and Gleason's theorem. Symmetry transformations: pure state and mixed state automorphisms; the theorems of Wigner, Uhlhorn and Kadison. Majorization of states and Schur-concavity; quantum entropies. Composite systems; partial trace; state purification; entangled states.

Quantum observables: Definitions, fundamental properties and examples. POVMs (positive operator-valued measures); generalizing Gleason's theorem. 'Sharp' and 'unsharp' observables. Discrete observables; real observables; mixtures of observables; coexistence of effects. Symmetry transformations of quantum observables: Jordan-Segal automorphisms. Informational completeness of quantum observables; quantum state estimation. Relations between observables: state distinction and state determination; coarse-graining. Photon-counting observables. Joint measurability.

Algebraic formulation of the state-observable duality: The algebraic formulation of quantum mechanics. Normal states of a quantum system. Superselection rules.

Some remarkable cases: Position and momentum; number and phase; time and energy.

Quantum operations and quantum channels: Quantum operations, quantum stochastic maps and complete positivity. Quantum channels (completely positive stochastic maps). A physical model for a quantum channel. Stinespring's dilation theorem. Decomposition of a quantum channel. Mixtures of channels. Conjugate channels. The Choi-Jamiolkowski isomorphism. Strictly contractive, random-unitary and phase-damping channels. Qubit channels.

Measurement models and quantum instruments: The three levels in the description of a quantum measurement: measurement models, instruments and observables. Disturbance of a quantum system associated with a measurement; no information without disturbance. BB84 quantum key distribution. Lüders' instruments and Lüders' theorem. The mean king's problem. Repeatable measurements; Wigner-Araki-Yanase theorem. Programmable quantum processors.

Covariance of measurements: group-covariant POVMs and quantum instruments.

Open quantum systems: Open systems and quantum decoherence. Quantum dynamical semigroups. The Markovian regime (the Gorini-Kossakowski-Lindblad-Sudarshan master equation) and beyond. Evolution of quantum entropies.

READINGS/BIBLIOGRAPHY

T. Heinosaari, M. Ziman, *The Mathematical Language of Quantum Theory*, Cambridge University Press

A.S. Holevo, *Statistical Structure of Quantum Theory*, Springer

I. Bengtsson, K. Zyczkowski, *Geometry of Quantum States*, Second Ed., Cambridge University Press

P. Busch, P. Lahti, J.P. Pellonpää, K. Ylinen, *Quantum Mesurement*, Springer

H.-P. Breuer, F. Petruccione, *The Theory of Open Quantum Systems*, Oxford University Press

Teacher's Notes of the Course

TEACHING METHODS

Lectures. During classes, students will be encouraged to interact with the teacher and give their feedback.

EXAMINATION/EVALUATION CRITERIA

Exam type:

Exam type	
written and oral	
only written	
only oral	X
project discussion	
other	

In case of a written exam, questions refer to: (*)		
	Multiple choice answers	
	Open answers	
	Numerical exercises	

(*) multiple options are possible

Evaluation pattern:
[this field needs to be filled in only when there are different weights among written and oral exams, or among modules if this refers to an integrated course]

COURSE DETAILS
"QUANTUM METROLOGY AND SENSORS"
SSD ING-INF/07

* *In case of an integrated course, the SSD (scientific disciplinary sector) should be written above only if all modules of the course belong to the same SSD, otherwise the SSD is to be written alongside the MODULE (see below).*

DEGREE PROGRAMME: **QUANTUM SCIENCE AND ENGINEERING**

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE (IF APPLICABLE):
MODULE (IF APPLICABLE):
CHANNEL (IF APPLICABLE):
YEAR OF THE DEGREE PROGRAMME (I, II, III): **II**
SEMESTER (I, II): **ANY**
CFU: **6**

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE “ORDINAMENTO”)

Foundations of Quantum Mechanics

PREREQUISITES (IF APPLICABLE)

Foundations of Measurements

LEARNING GOALS

Expected learning outcomes refer to the overall learning aims of the subject in relationship with the degree structure.

Training of metrologists with thorough physical and technical knowledge to provide research, design, production, as well as technological, organizational, and managerial activities in metrology applied to quantum technologies.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

The course provides students with specific knowledge and methodological tools needed to analyze main issues in metrology applied to quantum technologies. Such tools may allow the student to grasp the causal connections among the properties of physical quantum phenomena and the main characteristics that an adequate measurement method addressed to them must exhibit, and to understand the implications of measurement choices on the final measurement outcomes.

Applying knowledge and understanding

The course delivers ability and tools needed to apply knowledge in practice, favoring the capability to use methodological tools to define, design and implement a proper metrological approach to face typical measurement issues in engineering applications involving quantum technologies.

COURSE CONTENT/SYLLABUS

Fundamentals of classical measurement theory: units and standards; SI system; measurement model; metrological traceability; measurement error versus uncertainty; the GUM standard and the law of propagation of measurement uncertainty.

Going beyond classical metrology by exploiting the peculiar properties of quantum states. Implications of quantum mechanics in the field of metrology: the new SI system, fundamental physical constants, quantum standards and quantum metrology techniques, covering both theoretical and experimental aspects. Applications: ultra-low noise measurements; uncertainty evaluation by means of Monte Carlo simulation; specific measurement techniques used in several domains and implying quantum devices.

Exploring the basic capabilities of complex quantum systems to better understand what future quantum technologies will allow us to measure, compute, and simulate.

READINGS/BIBLIOGRAPHY

- W.Nawrocki, *Introduction to Quantum Metrology – Quantum Standards and Instrumentation,* Springer, ISBN 978-3-319-15668-2, DOI 10.1007/978-3-319-15669-9.
- JCGM 100:2008*, Evaluation of measurement data — Guide to the expression of uncertainty in measurement,* JCGM 2008
- Lecture notes

TEACHING METHODS

The teacher will use: a) lectures for approx. 65% of total hours; b) laboratories to further elaborate on applied knowledge for approx. 30% of total hours; d) seminars on specific themes for approx. 5% of total hours.

EXAMINATION/EVALUATION CRITERIA

r) Exam type:

Exam type	
written and oral	
only written	
only oral	X
project discussion	X
other	

COURSE DETAILS
"QUANTUM OPTICS"
SSD – FIS/03 "PHYSICS OF MATTER"

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

YEAR OF THE DEGREE PROGRAMME (I, II, III): II
SEMESTER (I, II): I
CFU:6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")
Foundations of quantum mechanics

PREREQUISITES (IF APPLICABLE)
None

LEARNING GOALS
Students are expected to learn the key concepts and main methods of quantum theory and applications of electromagnetic radiation.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding
Ability to explain and use the principles of quantum theory of electromagnetic radiation and illustrate the main experimental methods.

Applying knowledge and understanding
Capability of calculating the evolution of the quantum state of a given photonic system. Ability to sketch the schematic layout of an optical system implementing the most important tasks of quantum information and communication.

COURSE CONTENT/SYLLABUS
Quantum theory of electromagnetic radiation. Coherent and squeezed states. Field-field and photon-photon interference. Elements of quantum computation using photons. Experimental methods of quantum optics.

READINGS/BIBLIOGRAPHY

TEACHING METHODS
Live lectures on theory for 70% of frontal time, exercises for 30% of frontal time.

EXAMINATION/EVALUATION CRITERIA

s) Exam type:

Exam type	
written and oral	x
only written	
only oral	
project discussion	
other	

In case of a written exam, questions refer to: (*)		
	Multiple choice answers	
	Open answers	x
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
"QUANTUM SIMULATORS"
SSD – FIS/03 "PHYSICS OF MATTER"

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

YEAR OF THE DEGREE PROGRAMME (I, II, III): II
SEMESTER (I, II): I
CFU:6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

Foundations of quantum mechanics

PREREQUISITES (IF APPLICABLE)

None

LEARNING GOALS

Students are expected to learn the concept of quantum simulation and the various technological platforms for quantum simulation, with their main underlying physics.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

Ability to illustrate the various technological platforms for quantum simulation, with their main underlying physics.

Applying knowledge and understanding

Ability to sketch the schematic layout of a physical system implementing a quantum simulator suitable for describing specific class of phenomena.

COURSE CONTENT/SYLLABUS

This course will introduce key concepts of quantum simulation, focusing on strongly correlated many-body systems and their implementation with cold atoms, quantum dot systems, ions, superconducting circuits and photons.

READINGS/BIBLIOGRAPHY

TEACHING METHODS

Live lectures on theory for 70% of frontal time, exercises for 30% of frontal time.

EXAMINATION/EVALUATION CRITERIA

t) **Exam type:**

Exam type	
written and oral	x
only written	
only oral	
project discussion	
other	

In case of a written exam, questions refer to: (*)	Multiple choice answers	
	Open answers	x
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
" QUANTUM SOFTWARE "

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2021-22

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE (IF APPLICABLE):
MODULE (IF APPLICABLE):
CHANNEL (IF APPLICABLE):
YEAR OF THE DEGREE PROGRAMME (I, II, III):
SEMESTER (I, II):
CFU:

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

Quantum Informatics

PREREQUISITES (IF APPLICABLE)

-

LEARNING GOALS

The aim of this course is to introduce the current methodologies for implementing quantum algorithms in quantum software, both in conceptual terms by highlighting the differences with respect to classical software, and in purely experimental terms by using tools aimed at developing quantum algorithms such as graphical circuit composers or the Python Qiskit library. Furthermore, the course aims at introducing the main software execution and simulation tools, such as the IBM Quantum Experience cloud platform.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

The student is expected to demonstrate knowledge and understanding of the difference between quantum and classical software development, to know the meaning of a quantum circuit and how it can be used to implement a quantum algorithm. Moreover, the student must be aware of the current tools available to the scientific and industrial community for the implementation and execution of a quantum software.

Applying knowledge and understanding

The student must be able to implement quantum algorithms by means of quantum software. He/she should therefore be able to use the current tools available for such implementations, such as graphical composers of quantum circuits and Python libraries for their development. In addition, the student should be able to run such software appropriately, using both simulators and real quantum computing devices accessible via the cloud. Finally, the student will have to fully understand the limitations that current technologies impose on the proper execution of quantum software.

COURSE CONTENT/SYLLABUS

Programming in Python. Introduction to the Qiskit library: development of quantum circuits and manipulation of the state of one or more qubits. Introduction to the IBM Quantum Experience: analysis of real devices and available simulators. Introduction to quantum compiling. Implementation of the main quantum algorithms (Deutsch algorithm, quantum Fourier transform, Grover and Shor algorithms). Quantum error mitigation and correction. Implementation of quantum algorithms in particular areas of interest such as cryptography and quantum computational intelligence. Implementation of variational algorithms. Elements of Quantum Machine Learning and Quantum Computational Intelligence.

READINGS/BIBLIOGRAPHY

- Johnston, Eric R., Nic Harrigan, and Mercedes Gimeno Sefovia. Programming Quantum Computers: essential algorithms and code samples. O'Reilly Media, 2019.
-Jupyter Python Notebooks
- Scientific articles and slides provided by the lecturers.

TEACHING METHODS

Front lessons (about 30% of the total time) and exercises (about 70%)

EXAMINATION/EVALUATION CRITERIA

u) Exam type:

Exam type	
written and oral	
only written	
only oral	
project discussion	X
other	

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	
	Numerical exercises	

(*) multiple options are possible

COURSE DETAILS
" SUPERCONDUCTING QUANTUM TECHNOLOGIES IN THE LAB "
SSD – FIS/03 “PHYSICS OF MATTER”

DEGREE PROGRAMME: QUANTUM SCIENCE AND ENGINEERING

ACADEMIC YEAR 2022-2023

GENERAL INFORMATION – TEACHER REFERENCES

TEACHER:
PHONE:
EMAIL:

GENERAL INFORMATION ABOUT THE COURSE

YEAR OF THE DEGREE PROGRAMME (I, II, III): II
SEMESTER (I, II): I
CFU:6

REQUIRED PRELIMINARY COURSES (IF MENTIONED IN THE COURSE STRUCTURE "ORDINAMENTO")

Foundations of quantum mechanics

PREREQUISITES (IF APPLICABLE)

None

LEARNING GOALS

Quantum hardware is what transforms the novel concepts of quantum computation and communication into reality. The key challenge is to control, couple, transmit and read out the fragile stage of quantum systems with great precision, and in a technologically viable way. This course aims at illustrating some aspects of this key challenge in realizing quantum hardware and technology, focusing on superconducting quantum devices. The idea is to simulate the student to a creative and independent path towards the planning, the design and the realization of advanced experiments.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

Ability to understand the physics of a qubit, how to measure a qubit, meaning of a quantum measurements, architecture of a quantum computer.

Applying knowledge and understanding

Ability of designing the schematic layout of a superconducting qubit; read-out and control of a quantum system and of a qubit; quantum gates; capability of measuring a superconducting qubit. Assignments will teach the basics of the Python programming language, introduce students to open source scientific software.

COURSE CONTENT/SYLLABUS

This course is characterized bylab activities focused on the measurements of superconducting qubits. Notes on Phase transitions, broken symmetry, topological defects, Ginzburg-Landau equations, phenomenology of Superconductivity, Mesoscopics with Superconductivity, Superconducting Devices, the Josephson effect, non linearity in superconducting circuits and dissipationless conversion, Andreev reflection, Dynamical Coulomb Blockade; dissipation in a Josephson junction, decoherence and noise, macroscopic quantum tunneling and its foundations on dynamics, diffusion and Langevin theory. Notes on classical superconducting electronics, superconducting quantum interference devices (SQUIDs), Quantum states superpositions, Entanglement. Qubit Hamiltonian engineering, Superconducting and hybrid qubits, Tunable qubit: Split transmon, Toward larger anharmonicity: Flux qubit and Fluxonium, Interaction Hamiltonian engineering, Physical coupling: Capacitive and inductive. Realization of a superconducting qubit and Nanofabrication techniques.. Measurements techniques for qubits, decoherence, noise and dissipation. Josephson bifurcation amplifier, SQUIDs and qubit read-out. Integration between qubits and classical superconducting electronics, Qubit - cavity coupling: Resonant coupling and dispersive coupling. Amplification and feedback. Dispersive Read-out of a Qubit in a Cavity. Quantum Control of Qubits in a Cavity. circuit-QED architecture Rabi, Ramsey fringes protocols, quantum non demolition measurements, dispersive shift; logic gates for quantum computers; Quantum state engineering and quantum gates; superconducting nanowire single photon detector (SNSPDs) dark counts, fluctuations and quantum efficiency, SNSPDs applications for Quantum Key distribution

READINGS/BIBLIOGRAPHY

- Selected papers and reviews
- Antonio Barone and Gianfranco Paternò, Physics and applications of the Josephson effect, Wiley
- Konstantin Likharev, Dynamics of the Josephson effect and circuits, Gordon and Breach
- Supriyo Datta, Electronic Transport in Mesoscopic systems, Cambridge University Press
- Yoseph Imry, Introduction to Mesoscopic Physics, Oxford University Press
- Michael Tinkham, Introduction to Superconductivity, McGraw-Hill

- M. A. Nielsen, I. Chuang, Quantum Computation and Quantum Information, Cambridge Univ. Press.
- T.T. Heikkilä, The Physics of Nanoelectronics: Transport and Fluctuation Phenomena at Low Temperatures, Oxford
- J. M. Martinis, M. H. Devoret, J. Clarke, Energy-level quantization in the zero-voltage state of a current-biased Josephson junction. Phys. Rev. Lett. 55, 1543–1546 (1985).

TEACHING METHODS

Live lectures on theory for 60% of frontal time, Lab activities for 40% of frontal time.

EXAMINATION/EVALUATION CRITERIA

v) Exam type:

Exam type	
written and oral	
only written	
only oral	x
project discussion	
other	A lab project

In case of a written exam, questions refer to: (*)	**Multiple choice answers**	
	Open answers	
	Numerical exercises	