

# Preparation for Quantitative Finance Interviews

Rex C. Liu  
Tepper School of Business, Carnegie Mellon University

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Rex Liu holds a Master's degree in Mathematics from the Courant Institute of Mathematical Sciences at New York University and is currently pursuing a Master's degree in Computational Finance from the Tepper School of Business at Carnegie Mellon University.

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### 3 Functions of a complex variable

Reference text: [Ahl79].

The formal definition of a complex number  $z = x + yi = (x, y) \in \mathbb{C} := \mathbb{R}^2$  is to consider the field  $(\mathbb{R}^2, +, \cdot)$  with addition and multiplication

$$(x, y) + (u, v) = (x + u, y + v), \quad (x, y) \cdot (u, v) = (xu - yv, xv + yu)$$

with neutral elements  $0_{\mathbb{C}} = (0, 0)$  for  $+$  and  $1_{\mathbb{C}} = (1, 0)$  for  $\cdot$ .

Note that  $\mathbb{C}$  cannot be ordered. However, with modulus defined as  $|z| := \sqrt{x^2 + y^2} \in [0, \infty)$  and conjugate defined as  $\bar{z} := x - yi$ , we have the analogous triangle inequalities

$$|z + w| \leq |z| + |w|, \quad |z - w| \geq ||z| - |w||$$

and Cauchy-Schwarz inequality

$$\left| \sum_{j=1}^n \bar{z}_j w_j \right| = \left| \sum_{j=1}^n z_j w_j \right| \leq \sqrt{\sum_{j=1}^n |z_j|^2} \sqrt{\sum_{j=1}^n |w_j|^2}$$

mentioned earlier in §1.

A complex number  $z = a + bi$  can be expressed by *polar coordinates*:

$$a + bi = r \cos \theta + i \cdot r \sin \theta$$

where  $\arg(z) := \theta \in (-\pi, \pi]$ . Upon multiplication of two complex numbers, the moduli are multiplied, and the arguments are added.

**Exercise 3.1** ([SRW19, 1.4]). Solve  $x^6 = 64$ .

*Solution.* The moduli should always be 2, and the argument  $\theta$  can be any value such that

$$6\theta = 2k\pi, \quad k \in \mathbb{N}_0, \theta \in [0, 2\pi)$$

Therefore, there are six possible solutions:

$$2 \cos(k\pi/3) + 2i \sin(k\pi/3), \quad k \in \llbracket 0, 5 \rrbracket$$

The extension of functions  $e^z$ ,  $\log z$ ,  $\sin z$ ,  $\cos z$ , etc. should be natural in the sense that many of the familiar properties of  $\sin$ ,  $\cos$ ,  $\exp$ ,  $\log$  are retained. We define the complex *exponential function* as

$$e^{a+bi} := e^a \cdot (\cos b + i \sin b), \quad z = a + bi \in \mathbb{C}$$

and the complex sine and cosine functions as

$$\sin(z) = \frac{e^{iz} - e^{-iz}}{2i}, \quad \cos(z) = \frac{e^{iz} + e^{-iz}}{2}, \quad z \in \mathbb{C}$$

**Exercise 3.2** ([SRW19, 1.1]). Calculate  $i^i$ .

*Solution.* Note that  $i = \cos(\pi/2) + i \sin(\pi/2) = e^{i\pi/2}$ . Therefore

$$i^i = \left(e^{i\pi/2}\right)^i = \boxed{e^{-\pi/2}}$$

A solution  $z$  of the equation  $e^z = w$  is called a *logarithm* of  $w$ , denoted  $z = \log w$ . Every  $w \in \mathbb{C} \setminus \{0\}$  has countably many logarithms:

$$\log(w) = \log|w| + i \cdot (\arg(w) + 2\pi n), \quad n \in \mathbb{Z},$$

and the principal value of the logarithm of  $w$  is set for  $n = 0$ .

## 4 Ordinary differential equations

### Solvable first-order ODEs

1. Separable:

$$x' = f(x)g(t) \quad \implies \quad \int \frac{1}{f(x)} dx = \int g(t) dt + C$$

**Exercise 4.1** ([SRW19, 1.14]). Find  $f(x)$  such that

$$f'(x) = f(x)(1 - f(x))$$

*Solution.* Let  $y = f(x)$ . Then the equation is separable.

2. Homogeneous of degree  $k$  for some arbitrary value  $a$ :

$$f(at, ax) = a^k f(t, x)$$

For example, take  $k = 1, a = 1/t$ :

$$x' = f(x/t)$$

Let  $y = x/t$ , we get

$$y' \cdot t + y = f(y)$$

which reduces to case 1, a separable equation.

3. More generally, consider

$$x' = f\left(\frac{ax + bt + c}{\alpha x + \beta t + \gamma}\right)$$

where  $a, b, c, \alpha, \beta, \gamma$  are constants.

a) If  $c = \gamma = 0$ , rewrite it as

$$x' = f\left(\frac{ax/t + b}{\alpha x/t + \beta}\right)$$

which reduces to case 2.

b) If  $c, \gamma \neq 0$ , but  $a/\alpha = b/\beta = 1/k$ , we let  $y = ax + bt$ , then (noting that  $a$  is constant so  $a' = 0$ )

$$y' = a'x + ax' + b = af\left(\frac{y + c}{ky + \gamma}\right) + b$$

which reduces to case 1, a separable equation.

c) If  $c, \gamma \neq 0$  and  $a/\alpha \neq b/\beta$ , we solve the system

$$\begin{cases} ax + bt + c = 0 \\ \alpha x + \beta t + \gamma = 0 \end{cases}$$

which must have a solution, say  $x_0, t_0$ . Take  $y = x - x_0, s = t - t_0$ , and we have

$$\frac{dy}{ds} = \frac{dx}{dt} = f\left(\frac{ax + bt + c - 0}{\alpha x + \beta t + \gamma - 0}\right) = f\left(\frac{ay + bs}{\alpha y + \beta s}\right)$$

which reduces to case 3(a).

4. Exact:

$$M(x, y) dx + N(x, y) dy = 0$$

is exact if there exists a function  $g(x, y)$  such that

$$dg = M(x, y) dx + N(x, y) dy, \quad M(x, y) = \frac{\partial g}{\partial x}, N(x, y) = \frac{\partial g}{\partial y}$$

This happens if and only if

$$\frac{\partial M}{\partial y} = \frac{\partial N}{\partial x}$$

Then  $g(x, y) = C$  where  $C$  is some constant is the solution to this equation.

5. Integrating factors: if  $M(x, y) dx + N(x, y) dy$  is not exact but  $I(x, y) (M dx + N dy)$  is,  $I$  is called an *integrating factor*.

a) If

$$\frac{1}{N} \left( \frac{\partial M}{\partial y} - \frac{\partial N}{\partial x} \right) =: g(x)$$

is a function of  $x$  alone, then

$$I(x, y) = \exp\left(\int g(x) dx\right)$$

b) If

$$\frac{1}{M} \left( \frac{\partial M}{\partial y} - \frac{\partial N}{\partial x} \right) =: h(y)$$

is a function of  $y$  alone, then

$$I(x, y) = \exp \left( - \int h(y) \, dy \right)$$

Then it is reduced to case 4.

6. Linear nonhomogeneous equation:

$$x'(t) = k(t)x + a(t)$$

We multiply each side by

$$K(t) := \exp \left\{ - \int_{t_0}^t k(s) \, ds \right\}$$

Then

$$K(t) (x' - kx) = (Kx)' \quad \implies \quad \int d(Kx) = \int K(t)a(t) \, dt + C$$

which yields the result

$$x(t) = \frac{1}{K(t)} \left( \int_{t_0}^t K(s)a(s) \, ds + x(t_0) \right)$$

7. Some nonlinear first-order ODEs:

a) Bernoulli:

$$x'(t) = F_t x + g(t)x^n, \quad n \neq 0, 1$$

We let  $y = x^{1-n}$  and have

$$\frac{dy}{dt} = (1-n)x^{-n}x' = (1-n)x^{-n}(f(t)x + g(t)x^n) = (1-n)(fy + g)$$

b) Ricatti:

$$x'(t) = f(t)x + g(t)x^2 + h(t)$$

Suppose we already has a particular solution  $p(t)$  so that  $p' = fp + gp^2 + h$ . Subtract it from the original equation and let  $y = x - p$ :

$$\begin{aligned} x' - p' &= f(x - p) + g(x + p)(x - p) \\ y' &= fy + g(y + 2p)y = (f(t) + g(t)2p(t))y(t) + g(t)y^2(t) \end{aligned}$$

which reduces to a Bernoulli equation.



## Second-order linear ODEs

We start by considering  $a_0, a_1$  real constants for

$$y''(x) + a_1 y'(x) + a_0 y(x) = 0$$

Solve the the *characteristic function*

$$\lambda^2 + a_1 \lambda + a_0 = 0$$

and get two solutions  $\lambda_1, \lambda_2$ .

- Case 1: if  $\lambda_1, \lambda \in \mathbb{R}, \lambda_1 \neq \lambda_2$ :

$$y = c_1 e^{\lambda_1 x} + c_2 e^{\lambda_2 x}$$

- Case 2: if  $\lambda_{1,2} = a \pm bi, b \neq 0$  (noting that roots must be conjugate pairs):

$$y = d_1 e^{(a+bi)x} + d_2 e^{(a-bi)x} = e^{ax} \cdot (c_1 \cos(bx) + c_2 \sin(bx))$$

- Case 3: if  $\lambda_1 = \lambda_2 = \lambda$ :

$$y = (c_1 + c_2 x) e^{\lambda x}$$

**Exercise 4.2** (Baruch). Solve  $4y'' - 4y' + y = 0$  with initial conditions  $y(0) = 1, y'(0) = 0$ .

*Solution.* Consider  $4\lambda^2 - 4\lambda + 1 = 0$  whose solutions are  $\lambda_{1,2} = 1/2$ . It is a Case 3 scenario, and thus we let

$$y = (c_1 + c_2 x) e^{x/2}$$

Plugging the initial conditions, we get  $c_1 = 1, c_2 = -1/2$ .

Now, suppose  $a_1 = p(x), a_0 = q(x)$ , i.e. we consider

$$y''(x) + p(x)y'(x) + q(x)y(x) = 0$$

- Case 1: Suppose  $p, q$  are analytic, then we can let  $y(x) = \sum_{n=0}^{\infty} A_n x^n$  and apply the *power series method*.
- Case 2: A *Cauchy-Euler* equation has the form

$$t^2 y'' + aty' + by = 0 \quad \Longleftrightarrow \quad y'' + \frac{ay'}{t} + \frac{by}{t^2} = 0$$

We assume  $y = t^m$  and plugging in we get  $m^2 + (a-1)m + b = 0$ . Suppose this equation has two solutions  $m_{1,2}$ .

- if  $m_1 \neq m_2 \in \mathbb{R}$ ,  $y = c_1 t^{m_1} + c_2 t^{m_2}$ .
- if  $m_1 \neq m_2 \in \mathbb{C}$ , they are conjugates, so we let  $m_{1,2} = \alpha \pm \beta i$  and have

$$y = c_1 \cdot t^\alpha \cos(\beta \log t) + c_2 \cdot t^\alpha \sin(\beta \log t)$$

- if  $m_1 = m_2 = m$ , they can only be reals, and we have

$$y = c_1 \cdot t^m \log t + c_2 \cdot t^m$$

Indeed, if it is an ODE with higher order, and  $m$  becomes a root with multiplicity  $k$ , then the basis solutions are:

$$t^m, t^m \log t, t^m (\log t)^2, t^m (\log t)^3, \dots, t^m (\log t)^{k-1}$$

- Case 3: the *method of Frobenius*: the differential equation

$$w'' + p(z)w' + q(z)w = 0$$

has an *isolated singular point* at the origin if the coefficients  $p$  and  $q$  are analytic and single-valued in a disk  $|z| < R$  except at  $z = 0$  (analytic in the punctured disk). The origin is a *regular singular point* if  $p$  has a pole of order at most one and  $q$  a pole of order at most two there. In other words, if the origin is a regular singular point then  $p(z) = z^{-1}P(z)$  and  $q(z) = z^{-2}Q(z)$  where  $P$  and  $Q$  are analytic and single-valued in the full disk, including the origin. We'll write the standard equation with a regular singular point at the origin in the form

$$z^2 w'' + zP(z)w' + Q(z)w = 0.$$

The functions  $P$  and  $Q$  then have power-series expansions

$$P(z) = \sum_{k=0}^{\infty} P_k z^k, \quad Q(z) = \sum_{k=0}^{\infty} Q_k z^k$$

convergent in this disk. Then we seek a solution of the form

$$w(z) = z^\mu \sum_{k=0}^{\infty} a_k z^k$$

Now suppose the equation is nonhomogeneous:

$$y''(x) + p(x)y'(x) + q(x)y(x) = r(x), \quad r(x) \neq 0$$

First we solve the homogeneous equation by the methods above

$$y''(x) + p(x)y'(x) + q(x)y(x)$$

and get a basis of two solutions  $b_1(x), b_2(x)$ . We calculate the Wronskian:

$$W(x) := \begin{vmatrix} b_1 & b_2 \\ b_1' & b_2' \end{vmatrix}$$

and a particular solution  $p(x)$  is given as

$$p(x) = b_1 v_1 + b_2 v_2 \quad \text{where} \quad v_1 = - \int \frac{r(x)b_2(x)}{W(x)} dx, v_2 = \int \frac{r(x)b_1(x)}{W(x)} dx$$

Therefore, a general solution is given by

$$y(x) = C_1 b_1(x) + C_2 b_2(x) + p(x)$$

**Exercise 4.3** ([SRW19, 1.13]). Solve  $y'' - 4y' + 4y = 1$ .

*Solution.* Solving  $\lambda^2 - 4\lambda + 4 = 0$  gives us  $\lambda_{1,2} = 2$ . Now, since RHS = 1, a particular solution is easy to guess:  $y_p = 1/4$ . Therefore, a general solution is given by

$$y(x) = c_1 e^{2x} + c_2 e^{2x} x + 1/4$$

for some constants  $c_1, c_2$ .

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