Exercise 6

In Exercises 1–26, solve the following Volterra integral equations by using the *Adomian decomposition method*:

$$u(x) = 1 - x + \int_0^x (x-t)u(t)\,dt$$

Solution

Assume that $u(x)$ can be decomposed into an infinite number of components.

$$u(x) = \sum_{n=0}^{\infty} u_n(x)$$

Substitute this series into the integral equation.

$$\begin{aligned}
\sum_{n=0}^{\infty} u_n(x) &= 1 - x + \int_0^x (x-t) \sum_{n=0}^{\infty} u_n(t)\,dt \\
u_0(x) + u_1(x) + u_2(x) + \cdots &= 1 - x + \int_0^x (x-t)[u_0(t) + u_1(t) + \cdots]\,dt \\
u_0(x) + u_1(x) + u_2(x) + \cdots &= \underbrace{1-x}_{u_0(x)} + \underbrace{\int_0^x (x-t)u_0(t)\,dt}_{u_1(x)} + \underbrace{\int_0^x (x-t)u_1(t)\,dt}_{u_2(x)} + \cdots
\end{aligned}$$

If we set $u_0(x)$ equal to the function outside the integral, then the rest of the components can be deduced in a recursive manner. After enough terms are written, a pattern can be noticed, allowing us to write a general formula for $u_n(x)$. Note that the $(x-t)$ in the integrand essentially means that we integrate the function next to it twice.

$$\begin{aligned}
u_0(x) &= 1 - x \\
u_1(x) &= \int_0^x (x-t)u_0(t)\,dt = \int_0^x (x-t)(1-t)\,dt = \frac{x^2}{2\cdot 1} - \frac{x^3}{3\cdot 2} \\
u_2(x) &= \int_0^x (x-t)u_1(t)\,dt = \int_0^x (x-t)\left(\frac{t^2}{2\cdot 1} - \frac{t^3}{3\cdot 2}\right)dt = \frac{x^4}{4\cdot 3\cdot 2\cdot 1} - \frac{x^5}{5\cdot 4\cdot 3\cdot 2} \\
u_3(x) &= \int_0^x (x-t)u_2(t)\,dt = \int_0^x (x-t)\left(\frac{t^4}{4\cdot 3\cdot 2\cdot 1} - \frac{t^5}{5\cdot 4\cdot 3\cdot 2}\right)dt = \frac{x^6}{6\cdot 5\cdot 4\cdot 3\cdot 2\cdot 1} - \frac{x^7}{7\cdot 6\cdot 5\cdot 4\cdot 3\cdot 2} \\
&\;\vdots \\
u_n(x) &= \int_0^x (x-t)u_{n-1}(t)\,dt = \frac{x^{2n}}{(2n)!} - \frac{x^{2n+1}}{(2n+1)!}
\end{aligned}$$

Therefore,

$$\begin{aligned}
u(x) &= \sum_{n=0}^{\infty}\left[\frac{x^{2n}}{(2n)!} - \frac{x^{2n+1}}{(2n+1)!}\right] = \sum_{n=0}^{\infty}\frac{x^{2n}}{(2n)!} - \sum_{n=0}^{\infty}\frac{x^{2n+1}}{(2n+1)!} = \cosh x - \sinh x \\
&= \frac{e^x + e^{-x}}{2} - \frac{e^x - e^{-x}}{2} = e^{-x}.
\end{aligned}$$